DEMONSTRATION REPORT

Hygroscopic Cooling Tower for Reduced HVAC Water Consumption

ESTCP Project EW-201723

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The focus of this project is to improve the trade-off between water consumption and cooling efficiency in cooling towers used for heat rejection from various processes, including building HVAC loads; data center cooling; power generation; and various other industrial purposes. Conventional wet cooling towers are a common infrastructure component at DoD facilities (estimated at over 4000 individual towers), and each can be a significant consumer of water.

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ACRONYMS AND ABBREVIATIONS

ARPA-E	Advanced Research Projects Agency – Energy
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
CERL	Construction Engineering Research Laboratory
COC	cycles of concentration
COTS	commercial-off-the-shelf
CUI	controlled, unclassified information
DCMB	DoD Center Monterey Bay
DFARS	Defense Federal Acquisition Regulation Supplement
DHRA	Defense Human Resources Activity
DoD	Department of Defense
DOE	Department of Energy
DPW	Directorate of Public Works
ECIP	Energy Conservation Investment Program
EERC	Energy & Environmental Research Center
EO	Executive Order
ESPC	energy savings performance contracts
ESTCP	Environmental Security Technology Certification Program
FY	fiscal year
gal/gsf	gallons per gross square foot
GHG	greenhouse gas
gpm	gallons per minute
HVAC	heating, ventilation, and air conditioning
kW_e/kW_{th}	kilowatt electric/kilowatt thermal
LCC	life cycle cost
LEED	Leadership in Energy and Environmental Design
NBVC	Naval Base Ventura County
NIST	National Institute of Standards and Technology
PO	performance objective
RT	refrigeration ton
SMS	Sustainment Management System
SPX	SPX Cooling Technologies, Inc.

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1.0 INTRODUCTION

1.1 BACKGROUND

The focus of this project is to improve the trade-off between water consumption and cooling efficiency in cooling towers used for heat rejection from various processes, including building heating, ventilation, and air conditioning (HVAC) loads; data center cooling; power generation; and various other industrial purposes. Conventional wet cooling towers are a common infrastructure component at Department of Defense (DoD) facilities (estimated at over 4000 individual towers), and each can be a significant consumer of water. For example, under a previous project for nonchemical cooling water treatment of DoD cooling systems (1), a single cooling tower used to cool a large HVAC chiller at Fort Irwin in California was estimated to consume up to 2.6 million gallons of water annually and produce nearly 1.5 million gallons of concentrated wastewater for disposal.

However, while cooling towers are significant water consumers, they are also valuable energy-saving devices and can be important components to meet combined energy- and water-saving goals. For instance, in drought-prone California, dry-cooled, chilled water plants are limited to 300 tons of cooling capacity (2); larger systems are mandated to use wet cooling (or seek an exception) because of the improvement to chiller efficiency with wet cooling that reduces electrical power consumption (which has its own water footprint). Therefore, this project seeks to maximize the cooling benefit from evaporative cooling, e.g., during hot summer afternoons, but curtail evaporation during cooler, off-peak times when conditions allow efficient sensible heat transfer to the air.

Hybrid cooling systems that split cooling between wet- and dry-cooled stages are currently available, and novel designs have even been fielded under the Environmental Security Technology Certification Program (ESTCP) (3). While these systems can be used for peak temperature shaving in applications where dry cooling is used, they are generally not feasible for applications that require wet cooling performance like large-tonnage HVAC chillers. For wet applications, water-saving cooling tower designs only result in modest annual water savings of up to 20% relative to conventional models and are generally selected for their plume abatement capability rather than water conservation.

The technology that will be tested under this project is a novel cooling tower that uses a hygroscopic working fluid to seamlessly vary the amount of sensible (dry) versus latent (wet evaporative) heat transfer in response to ambient weather conditions. With this mode of operation, the maximum amount of water can be saved for any combination of cooling temperature set point and ambient air conditions. In addition, the hygroscopic cooling system evaporates all makeup water to provide cooling, thereby eliminating the need for a wasteful blowdown stream. Instead of draining away a portion of the working fluid to control scaling, as is done with conventional towers, the hygroscopic tower forces the controlled precipitation of dissolved solids that are removed from the system using conventional sediment filters.

1.2 DRIVERS

There is a growing awareness regarding water use in buildings that will ensure interest in water conservation technologies. Specific examples include the following mandates and industry best practices:

- Executive Order (EO) 13693 (4), which directs that, starting in 2020, new federal buildings over 5000 sq ft must be designed for net-zero water usage.
- Leadership in Energy and Environmental Design (LEED) innovation credits for cooling tower water use and cooling tower water management.
- 2013 California Energy Commission Building Energy Efficiency Standards, Title 24 Part 6, which mandates steps to increase a cooling tower's cycles of concentration to the maximum extent possible.
- ASHRAE SPC191P, a proposed water efficiency standard passed in October 2015 that is intended to establish minimum performance levels relating to water use in many residential, commercial, and industrial areas including cooling systems.

EO 13693 in particular will incentivize a new generation of DoD users in the form of buildings that must comply with net-zero water use. According to data cited by the U.S. Environmental Protection Agency (5), cooling and heating account for 28% of water use in a typical office building. This water end use is second only to restrooms (37%), and reductions to it can have a sizeable impact on achieving net-zero goals.

1.3 OBJECTIVE OF THE DEMONSTRATION

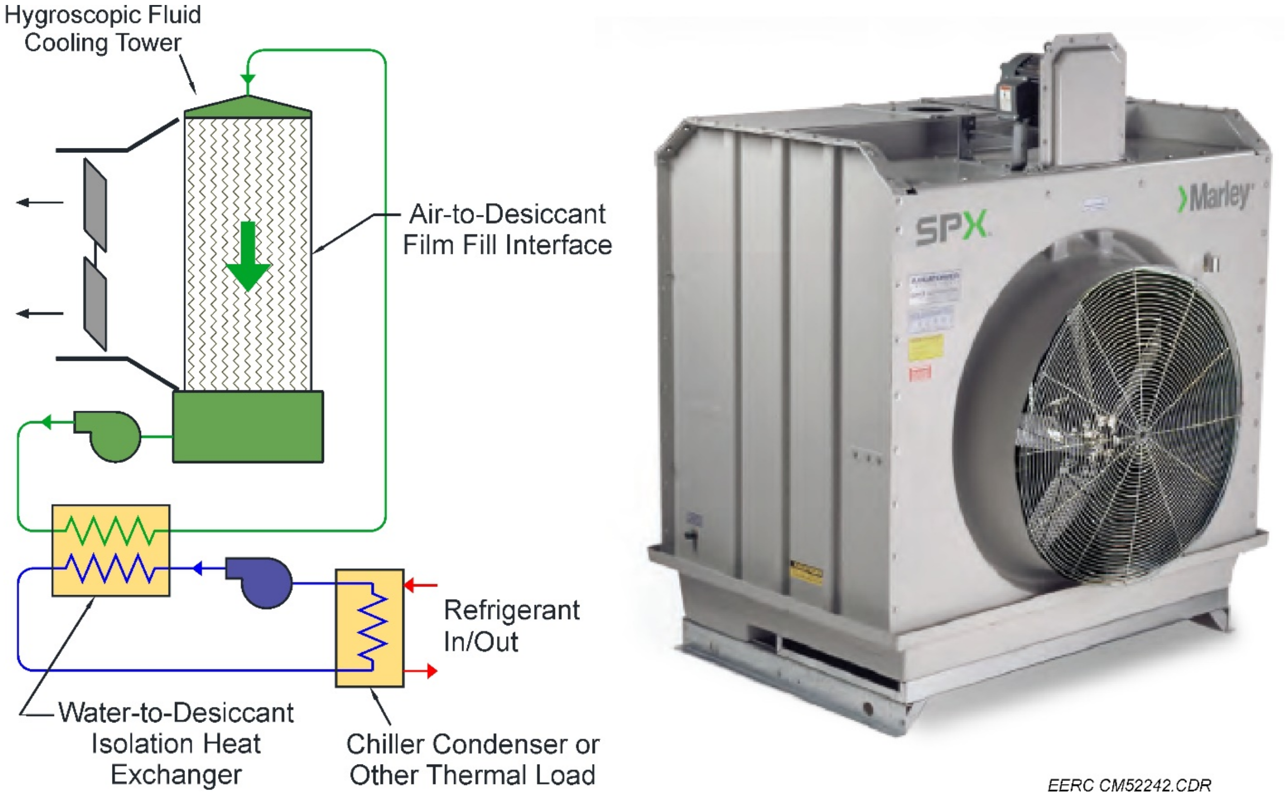
The overall objective of this project is to reduce the water intensity of DoD facilities that use evaporative cooling towers to dissipate heat from air conditioning, data center cooling, power generation, and various other industrial processes. Cooling towers are intensive consumers of water, yet they are also energy-saving devices and can be important system components to meet combined energy- and water-saving goals. The technology under evaluation in this project attempts to strike a better balance between wet and dry cooling so that the benefits of wet evaporative cooling can be applied during hot summer afternoons, but the needless evaporation of water can be curtailed during cooler times when conditions allow for efficient sensible heat transfer to the air.

Under this project, two demonstration units of a novel cooling tower technology designed to restrict water evaporation will be field-tested at sites that are characterized by hot, dry, and moderate but humid summer weather. Annual performance data will be collected and will include water savings, cooling efficacy, and operational costs. The result of a successful project will be a methodology for DoD energy managers to 1) estimate the technology's cost-saving potential, 2) understand its operations and maintenance requirements, and 3) identify potential integration strategies.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

This technology is based on the use of a hygroscopic working fluid as a direct-contact heat-transfer medium between a cooling water loop and the ambient air. The process is schematically similar to a conventional wet evaporative cooling system as shown in Figure 1. The innovation in this process comes from the fact that, unlike pure water, the hygroscopic liquid desiccant restricts the free evaporation of moisture and results in more sensible heat transfer to the air relative to pure water. In a conventional wet cooling tower, most (>90%) of the energy transfer is through evaporation, and this ratio is largely independent of outdoor conditions. With the hygroscopic tower, the amount of sensible versus latent heat transfer can be varied to maximize water savings for a given set of ambient air conditions. Water can be saved when the ambient air is cooler relative to the temperature set point, but evaporative cooling is engaged during peak air temperatures.



(a) (b)

Figure 1. a) Simplified integration schematic of the hygroscopic cooling tower technology and b) example image of an SPX Cooling Technologies (SPX) Marley Aquatower®, a conventional wet cooling system that will be converted to hygroscopic cooling operation for the ESTCP demonstrations.

Water savings come from the reduced rate of evaporation due to the hygroscopic desiccant and from the elimination of a wastewater bleed stream that is used to prevent dissolved solids buildup in conventional cooling towers. Instead of a blowdown stream, dissolved solids in the hygroscopic cooling tower are removed by forced precipitation followed by filtration of the solids. This process is based on the sharp reduction in solubility for common dissolved solids species within the liquid desiccant, a mixture of calcium chloride ($CaCl_2$) and water.

$CaCl_2$ is the preferred desiccant material for this application since it is widely available, low cost, and has few environmental concerns compared to other desiccants or salts. As evidence of its low impact, $CaCl_2$ is the primary ingredient in most ice-melting solutions that are spread on paved roads and sidewalks, and the solutions sprayed on dirt roads for dust suppression. The material can irritate the skin and eyes and is mildly corrosive to some metals, but as with conventional cooling tower waters, personnel contact should be minimized. Information regarding the general properties and handling of $CaCl_2$ solution is included in Appendix C. Copies of the product's safety data sheet will be sent with the demonstration systems and shared with each site's project point of contact.

While a liquid desiccant solution is at the core of this technology, it should not be confused with other technologies that use liquid desiccants for dehumidification in air-conditioning applications, at least two of which are being tested under ESTCP (6, 7). The hygroscopic cooling tower's primary benefit is to reduce cooling water consumption; it does not replace or change the air-conditioning system nor does it come into contact with the airstream entering a conditioned space.

Hygroscopic fluid cooling technology stems from prior work at the Energy & Environmental Research Center (EERC) to develop a large-scale dry cooling alternative for thermoelectric power plants, which are the single largest users of fresh water in the United States (8). This work has been conducted at the EERC under three previous projects: the first was cofunded by the Wyoming Clean Coal Technology Fund and the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (9), the second was funded under DOE's Advanced Research Projects Agency—Energy (ARPA-E) (10), and most recently (June 2015 to May 2016), the EERC was engaged in a privately funded project to evaluate the concept's commercialization potential for the power market.

Under these projects, the dry cooling test facility shown in Figure 2 was constructed and used to demonstrate the functionality of hygroscopic fluid cooling and collect engineering design data for the process. The test facility is essentially a small-scale cooling tower that is isolated with ductwork in order to accurately measure incoming and outgoing airflow conditions.

Figure 2. The EERC's dry cooling test facility after fabrication (left) and during an aerosol emission test (right).

The current ESTCP demonstration is based on modifying a commercial-off-the-shelf (COTS) packaged cooling tower to operate as a hygroscopic cooling tower. The COTS cooling tower that has been selected for conversion is a Marley Aquatower, an example of which is shown in Figure 1b. It is a compact, fiberglass cross-flow cooling tower with nameplate cooling capacities of up to 91 tons (400 kWth). The Aquatower is, in essence, a self-contained version of the EERC's test facility shown in Figure 2.

Hygroscopic cooling is projected to greatly expand the potential for water savings in traditionally wet-cooled applications. Since cooling towers are a common component of on-base infrastructure, the sheer number of installed units suggests significant opportunity for technology replication across DoD if hygroscopic cooling is determined to be cost-effective. An estimate regarding the number of cooling towers in service has been based on the BUILDER™ Sustainment Management System (SMS), which is a Web-based application developed by the U.S. Army Construction Engineering Research Laboratory (CERL) to help engineers, technicians, and managers decide when, where, and how to best maintain building infrastructure (11). The BUILDER SMS currently has inventory on cooling towers for the Air Force, Navy, and Marines and shows holdings of 1400, 1200, and 200 units, respectively. Inventory of units within the Army is still under way, but estimates based on individual sites suggest that there could be more than 1300 cooling towers Army-wide, resulting in a total exceeding 4000 units across the four service branches. Of the known cooling tower inventory in BUILDER SMS, approximately 80% are newer than 1990, which is in agreement with a practical service lifetime of 20–25 years. Assuming a total population of 4000 units, this lifetime distribution suggests a potential turnover rate of 130 towers per year across DoD.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Compared to other hybrid cooling system designs that simply combine conventional wet and dry cooling surfaces into a single structure, a hygroscopic tower has the following features to:

- Allow the full range of wet-to-dry performance using a single air–liquid interface instead of separate wet and dry stages.
- Approach the performance of wet evaporative cooling, which makes the technology compatible with large-tonnage chillers and adapts them to reduced water cooling when ambient conditions are suitable.
- Annual water savings in the range of 30%–50% are possible compared to less than 20% for existing hybrid cooling towers and those with plume abatement features.
- Be tolerant of poor-quality, hard water as makeup.
- Eliminate some of the burdens associated with traditional wet cooling, including microbe growth that can lead to harmful Legionella outbreaks, and freeze protection during cold weather operation.

The value proposition that hygroscopic cooling offers is a lifetime reduction in operating costs for an up-front investment in tower capital expense. This trade-off is potentially attractive for cooling towers with high water costs since the expense of makeup water alone can easily exceed the cost of the tower over its lifetime. Hygroscopic cooling reduces operational water costs in the following ways.

- Water consumption is reduced by regulating evaporation during cooler periods and from fully evaporating the makeup water instead of using a blowdown stream.
- Wastewater disposal charges are avoided by precipitating dissolved minerals and disposing of them as filtered solids.

Specific economic scenarios are presented in Section 7, but in general, the cost-effectiveness of hygroscopic cooling is governed by three factors: 1) water acquisition and disposal costs, 2) makeup water quality, and 3) annual cooling load or run time of the tower. The opportunity for savings in a hygroscopic tower comes from decreased water consumption and elimination of blowdown water; therefore, Item 1 directly scales the potential monetary savings and is the primary factor to consider. Candidate opportunities appear to be those where the combined water supply and sewer charge is approximately $10/kgal or higher.

Makeup water quality, Item 2, affects the degree to which the water can be concentrated through evaporation in a conventional cooling tower. With poor-quality water, a conventional tower may only achieve three cycles of concentration before the water must be bled from the system. This means that one-third of the makeup water is not used for evaporative cooling but is instead disposed of, incurring sewer charges in the process. Since the blowdown stream is eliminated with a hygroscopic tower, all of its makeup water is used for evaporative cooling to result in water savings and sewer charge avoidance. This benefit of hygroscopic cooling is most pronounced with poor-quality water, where achievable cycles of concentration are generally less than five.

The final factor, annual cooling load, also impacts potential water savings by dictating how much cooling is needed and under what conditions. During peak cooling times, much of the heat transfer in a hygroscopic cooling tower will still be evaporative in order to maintain its design cooling capacity. To take advantage of water-saving sensible cooling, the tower must continue to operate during conditions of cooler weather including into the evening and beyond the summer season. Increased operating hours outside of peak cooling times will increase the water-saving opportunity. Favorable applications at DoD facilities would be those that have a year-round cooling demand such as large refrigeration units or computer data centers.

Just as there are factors that highlight promising applications of hygroscopic cooling, there are also situations where it does not appear to provide a substantial benefit over conventional wet cooling. These situations include those where good-quality water is available at low cost, especially when the cooling tower is only needed during peak summer weather. Additional situations where hygroscopic cooling would be at a performance and economic disadvantage would include the following:

- Cooling loads that could benefit from the lowest possible coolant temperatures. The prime example of this type of load would be nonstandard water chillers that include added features to take advantage of low condenser temperatures. These systems are contrasted with standard chillers that generally have a higher efficiency at the design condenser temperature, but do not greatly increase in efficiency below a threshold condenser temperature (typically 75°F). Because of these trends, hygroscopic cooling will be a better fit for standard chillers since it can supply typical set point temperatures for these chillers, but not necessarily the lowest possible temperatures that would benefit a nonstandard, cold-temperature chiller.
- Applications with materials that are incompatible with the $CaCl_2$ desiccant. In general, processes compatible with seawater will be serviceable by hygroscopic cooling. However, for cases where these options are not available or are prohibitively expensive, an isolation heat exchanger will be needed which would put the hygroscopic system at a performance disadvantage if it were compared to a wet conventional tower without this interface.

The latter point of materials compatibility with the $CaCl_2$ desiccant solution also highlights a potential barrier to adoption since $CaCl_2$ can be corrosive to certain metallurgies, and this fact will raise concerns over the longevity of the hygroscopic cooling tower itself and the equipment it is cooling. The counterargument is that concentrated $CaCl_2$ brine has limited oxygen solubility compared to more dilute salt solutions; this property reduces the corrosion potential of the desiccant despite its high chloride content. In general, materials recommended for seawater contact are also suitable for use with liquid desiccant. However, projects such as this one will ultimately need to demonstrate that corrosion concerns can be mitigated before hygroscopic cooling will have widespread acceptance. Corrosion-related information from this project will include an end of test inspection of materials within the demonstration system as well as from exposure coupons for other materials of interest.

3.0 DEMONSTRATION SITE DESCRIPTION

3.1 GENERAL SITE SELECTION CRITERIA

Prototypes of the hygroscopic cooling system will be field tested at two different sites: Fort Irwin National Training Center and DoD Center Monterey Bay (DCMB), both in California. Since ambient conditions strongly affect the performance of a cooling tower, these sites were purposely selected to provide contrasting climates for data collection so that tower performance can be extrapolated over a wide geographic range.

Fort Irwin, California, is an arid location with large temperature swings between nighttime lows and daytime highs. It is representative of many DoD installations in the southwestern United States that are typified by hot temperature extremes, high evaporation potential, and generally poor makeup water quality that limits the cycles of concentrations within a conventional cooling tower.

On the other hand, DCMB in Seaside, California, is classified as having a marine climate that is characterized by ocean-moderated temperatures and humidity levels. Its day-to-night and seasonal temperature fluctuations are significantly less pronounced than at Fort Irwin and will present entirely different scenarios for cooling water savings. However, like Fort Irwin, water quality and availability is also a concern in Seaside since the local supply relies on fragile groundwater aquifers.

3.2 DEMONSTRATION SITE LOCATION AND OPERATIONS

The demonstration facility at Fort Irwin will be Building 263, which is a heating and cooling plant for several barracks and a dining facility. Building 263's cooling tower provides cooled condenser water to a large, 325-ton water chiller that supplies cooling to the barracks. A satellite view of Building 263 and its cooling tower enclosure is shown in Figure 3 and a ground-level photograph inside the enclosure is shown in Figure 4. The demonstration system is planned to be sited in the empty space in the foreground of Figure 4.

EERC CM54837.AI

Figure 3. Satellite view of Fort Irwin Building 263 cooling tower enclosure (courtesy of Google).

EERC CM54838.AI

Figure 4. Interior of Fort Irwin Building 263 enclosure.

The demonstration cooling tower will require extraction and reinjection ports within the existing condenser water piping at both demonstration sites. The proposed locations for the bypass connection points on the hot-water return line at Fort Irwin are highlighted in Figure 5. This segment of line is relatively easy to access, and it is downstream of an existing cooling tower bypass that is used for control purposes.

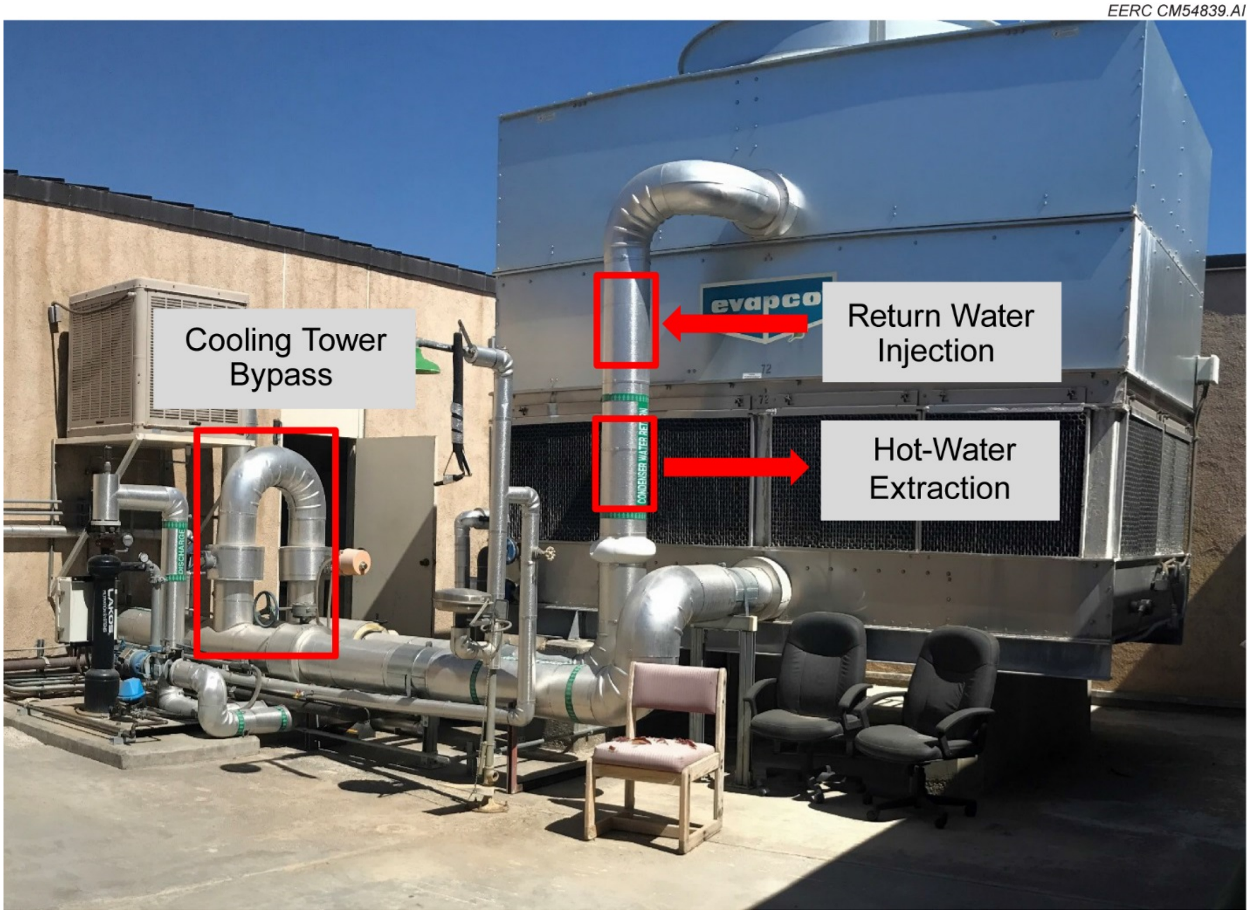


Figure 5. Proposed hot-water connection points in the walled cooling tower enclosure at Fort Irwin Building 263.

The host system at DCMB will also be a condenser water circuit that cools two chillers used for the facility's air-conditioning needs. DCMB itself is a multistory office complex that provides space for several DoD activities, including the nearby Presidio of Monterey. A satellite view of the building's cooling tower is shown in Figure 6 and a ground-level photograph of the proposed installation site is shown in Figure 7. The area surrounding the existing tower is rough ground, and a level equipment pad will be needed to site the demonstration system. The approximate pad dimensions indicated in Figures 6 and 7 are 14 feet by 14 feet.

Figure 6. Satellite view of existing DCMB cooling tower and proposed pad (courtesy of Google).

Figure 7. Site view of proposed pad location for the demonstration equipment at DCMB.

The existing cooling tower at DCMB and proposed connection points are shown in Figure 8. This segment of line has relatively open access for either adding tee connections or potentially welding on saddle-type penetrations (e.g., Weldolet® fitting). The vertical head above the proposed extraction site (roughly 10 to 12 feet) will be sufficient to keep the water booster pump flooded, and therefore, a throttling valve between the access ports will not be needed.

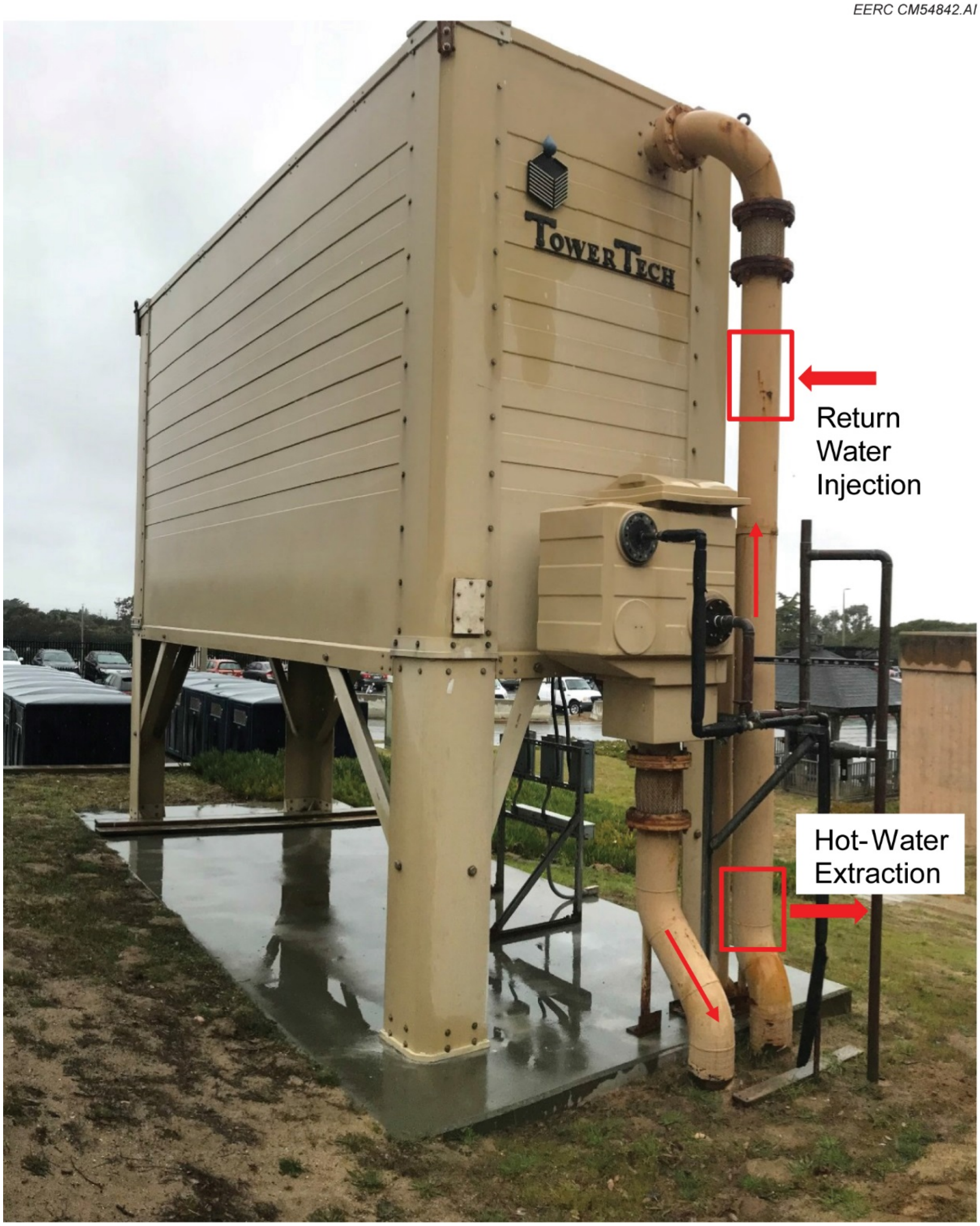


Figure 8. Existing cooling tower at DCMB and the proposed hot-water connection points for the demonstration equipment.

3.3 SITE-RELATED PERMITS AND REGULATIONS

The scope of these demonstrations falls within the jurisdiction of Fort Irwin's Directorate of Public Works (DPW) and the Mission Support Directorate, Defense Human Resources Activity (DHRA) at DCMB. The plans for modifying base equipment and temporarily siting the demonstration systems presented in this document have been reviewed and approved by cognizant installation officials at each host site as documented in each site's letter of support.

Formal work plans have been submitted to Fort Irwin DPW for approval and environmental review. Details of the equipment foundation at DCMB are being worked out; once a plan has been agreed upon, the work plans will be submitted for site approval.

Regarding network approval, the demonstration systems do not utilize network-enabled operational controllers; therefore, access is not needed to either host site's computer network. Operational data will be logged using a separate data acquisition system capable of storing and transmitting data for remote monitoring. This data transmission will be accomplished using a private, EERC-provided cellular modem. Data will be stored locally in the logger's physical memory and will be uploaded daily to a secure filer server using the modem. The collected data will be controlled, unclassified information (CUI) and will be safeguarded according to Defense Federal Acquisition Regulation Supplement (DFARS) Clause 252.204-7012 for federal contractors.

3.4 PROPERTY TRANSFER OR DECOMMISSIONING

The demonstration systems are not intended to become permanent infrastructure, and both systems will be removed from their respective sites at the conclusion of the project. Access points in the condenser water piping will be capped to prevent leaks, and the water supply and drain lines will be completely removed. Electrical services will be cut back to the nearest weatherproof connection point. All equipment skids and remaining desiccant solution will be moved from the sites.

The equipment itself will remain DoD property and will be available for follow-on demonstrations. However, in the absence of related follow-on activities, the towers will be converted back to their original factory operation (with water as the working fluid) and transported according to the wishes of the DoD.

4.0 PERFORMANCE OBJECTIVES

The key benefit of hygroscopic cooling is reduced cooling tower water consumption without introducing a performance penalty or a significant increase to cooling system parasitic power. Performance objectives (POs) for this project focus on determining the reduction in water use intensity associated with cooling tower use and the consequent impacts to energy consumption. Additional POs are also included to evaluate associated cost savings and generate an estimate for net changes to greenhouse gas (GHG) emissions. The rationale for selecting the POs with respect to energy and water security, cost avoidance, and GHG reduction is presented in the following subsections.

- Energy and Water Security: Water efficiency mandates for federal facilities are set by EO 13693 which includes goals relating to potable water use; water metering; water use for industrial, landscaping, and agricultural purposes; and stormwater management (4). Relevant to this project is the EO target for potable water use, which is to reduce "agency potable water consumption intensity measured in gallons per gross square foot by 36 percent by fiscal year 2025 through reductions of 2 percent annually through fiscal year 2025 relative to a baseline of the agency's water consumption in fiscal year 2007" (4). In addition to the potable water use goal, EO 13693 also sets an aspirational goal for new federal buildings that, beginning in fiscal year 2020, all new construction greater than 5000 gross square feet be designed to achieve net-zero water use by fiscal year 2030, where feasible (4).

  For buildings with water-cooled air-conditioning equipment, water consumption by the heating and cooling system can be a significant contributor to its water use intensity. For instance, the water consumption of the HVAC system has been estimated to be 28% of total water use for a typical office building (5). In order to directly compare the potential impact of this technology on water efficiency goals, a PO is included to determine water use intensity associated with cooling tower operation, both under baseline conditions and during the demonstration with the hygroscopic cooling tower.

  Since federal facilities also have complementary energy efficiency and energy net-zero goals, water use reductions that come with the burden of significant increases in energy consumption are counterproductive. Therefore, the POs also include cooling tower efficiency metrics to demonstrate an acceptable compromise between water savings and increased cooling tower power consumption, while maintaining equivalent HVAC system performance.

- Cost Avoidance: Several POs have been specified to determine the total cost of cooling tower operation and evaluate the life cycle cost (LCC) of hygroscopic cooling in comparison to the conventional baseline. The water use intensity PO will be used to extrapolate annual water consumption to determine the avoided costs from reduced water acquisition and wastewater disposal. Likewise, the costs associated with cooling tower energy consumption will be determined using findings from the energy usage PO. Additional POs have been identified to capture differences associated with operations and maintenance activities, and a summary PO is dedicated to evaluating the LCC comparison using a standardized methodology.

- Greenhouse Gas Reduction: As this technology is intended to reduce water consumption, it does not directly lead to calculable GHG reductions like fuel efficiency or renewable energy projects would. However, there is a carbon footprint associated with the production, delivery, and disposal of water. Because of this carbon footprint, a distinct PO has been outlined to examine water and energy use changes from the standpoint of associated GHG emissions. To accomplish this objective, the water and energy sources for each demonstration site will be investigated and assigned a specific GHG emission factor. This factor will then be used to estimate the net GHG change associated with hygroscopic cooling.

4.1 SUMMARY OF PERFORMANCE OBJECTIVES

Project POs are summarized in Table 1.

Table 1. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Cooling Tower Water Usage	Tower water use intensity (gal/gsf)	Logged value of tower makeup water supply; square footage of demonstration building	50% reduction in intensity compared to baseline
Cooling Tower Energy Usage	Tower electrical-to-thermal energy ratio (kWe/kWth)	Tower electrical power draw; logged tower thermal load and approach temperature	Threshold limit of 2 times baseline
Cooling Tower Performance	Tower cold water return temperature (°F)	Logged coolant temperatures	Cooling performance remains within 10% of the existing tower's set point temperature
System Maintenance Costs	Tower consumable expenses ($/month/refrigeration ton)	Historical expenses for baseline; log of used consumables during the demonstration	25% reduction compared to baseline
System Maintenance Effort	Service interval; time per service visit	Historical records or service provider interview for baseline; log of service intervals and maintenance conducted for the demonstration	No change relative to baseline schedule
System Economics	Simple payback (years)	Capital costs; net water, energy, and consumable expenses; operations and maintenance expenses	5-year simple payback
Net GHG Emissions	Change in emitted GHG (metric tons)	Estimated tower GHG emissions based on energy source and water supply	50% reduction compared to baseline

4.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

Cooling Tower Water Usage

- Definition: Normalized amount of makeup water used by the baseline and demonstration cooling towers.
- Purpose: Used to compare performance of the demonstration system to comparable peer structures within and outside of DoD. Directly used to determine a building's overall water usage intensity, which has mandated reduction targets under EO 13693.
- Metric: Units for this PO are annual consumed gallons per gross square feet. The FY 2007 gal/gsf benchmark referenced in EO 13693 was 53.2 gal/gsf across all federal agencies.

- Data: Demonstration-derived data for this PO is the recorded log of makeup water supplied to the cooling tower. Ancillary data include gathering the gross size of the demonstration buildings.

- Analytical Methodology: Since the demonstration tower and the baseline cooling tower have different capacities, i.e., the demonstration tower is not a drop-in replacement, water usage data for the demonstration tower will be scaled up as if it were servicing the entire building. This scale factor will be determined as information is collected about the building's existing cooling system. Furthermore, since it will not be possible to measure data from both towers simultaneously under the same building load and ambient conditions, the collected data will be used to create characteristic water consumption curves for each tower. These curves will then be used to compute water consumption for both towers under a consistent set of building load and ambient conditions to compute the gal/gsf metric.

- Success Criteria: The target for this demonstration is a reduction of 50% below the baseline established by the host site's existing cooling tower.

Cooling Tower Energy Usage

- Definition: Normalized amount of electrical energy used by the baseline and demonstration cooling towers to dissipate a thermal load.

- Purpose: Used to compare the energy efficiency of the demonstration tower to conventional cooling system types, primarily conventional cooling towers and fan-cooled condensers.

- Metric: Units for this PO are kilowatts of electrical energy per kilowatt of thermal energy dissipated by the tower. Values for conventional cooling towers vary depending on their design and the desired ambient approach temperature. A typical value for a cross-flow tower with a standard 7°F wet-bulb approach is approximately 0.01 kW_e/kWth. Fan-cooled (dry) condensers are more energy-intensive and are typically specified with higher approach temperatures. A representative energy use ratio is 0.03 kW_e/kWth for a fan-cooled condenser with a 15°F dry-bulb approach.

- Data: Tower electricity usage will be determined from a one-time measurement of power draw. Logged coolant temperatures and flow rates across the tower, along with the corresponding ambient conditions, will be used to compute the tower heat load and its approach temperature.

- Analytical Methodology: Tower energy usage is a function of the heat load and the desired approach temperature; therefore, this PO needs to be evaluated at consistent conditions for both the baseline and demonstration towers. Logged data will be used to identify periods of equivalent loading for each tower and to determine the corresponding wet-bulb approach. These trends will then be used for the comparison between the baseline and demonstration units.

- Success Criteria: The hygroscopic cooling tower relies on nonevaporative, dry cooling when ambient temperatures are low enough, but this strategy comes with some penalty to fan power since more airflow is needed for dry cooling versus evaporative cooling. A success target limiting this additional electricity consumption to 2 times the baseline value, or roughly 0.02 kW_e/kW_{th} at full load, has been selected to balance water savings and power consumption while maintaining an attractive payback period.

Cooling Tower Performance

- Definition: Tower cooling capacity at design conditions.
- Purpose: Used to compare performance of the baseline and demonstration systems and demonstrate that the hygroscopic cooling tower is functionally equivalent to the baseline tower for the purpose of condenser cooling.
- Metric: This PO is evaluated by comparing the return coolant temperature, in degrees Fahrenheit, for both towers under consistent heat load conditions. The existing host site towers vary fan speed to maintain a return coolant temperature set point, and this value will be used to equate performance of the demonstration tower without impacting chiller efficiency.
- Data: Data required for this PO consist of logged tower coolant temperatures.
- Analytical Methodology: Analogous to the energy consumption PO, the cooling performance comparison requires that the baseline and demonstration towers operate at equivalent heat load conditions. Since the towers are different sizes, the equivalent heat load will be determined as a percentage of the tower's full load rating.
- Success Criteria: Success will be achieved if the demonstration unit's return coolant temperature remains within 10% of the baseline cooling tower's value. No efficiency enhancement will be applied if the demonstration unit cools the coolant below the set point.

System Maintenance Costs

- Definition: Consumable expenses and costs associated with all aspects of cooling tower maintenance.
- Purpose: Accounts for cost differences associated with cooling tower water consumption including scale, corrosion, and microbiological control products, along with regular activities needed to keep the system in good working order.
- Metric: Units for this PO are annual costs per month, normalized on a refrigeration ton (RT) basis. Rule of thumb values for conventional systems are \$1–\$2/RT/month.
- Data: Baseline data for this PO will be determined from prior year expense logs for the host site cooling tower. An equivalent record will be created for the hygroscopic tower by maintaining a log of consumables used and maintenance activities performed during the demonstration.
- Analytical Methodology: Since the demonstration tower and the baseline cooling tower have different capacities, the maintenance costs will be normalized by each unit's nominal cooling capacity.

- Success Criteria: Hygroscopic cooling is expected to simplify makeup water treatment by reducing the number of separate conditioning products required. Success for this PO will be determined by a 25% reduction in maintenance costs relative to baseline costs.

System Maintenance Effort

- Definition: Quantified duration and frequency of time required by a maintenance technician to ensure efficient tower operation.
- Purpose: Provides a basis to compare the maintenance time required for hygroscopic cooling compared to a conventional wet cooling tower.
- Metric: Maintenance effort is quantified using the frequency of service visits, e.g. weeks or months between service intervals, along with the actual time required for service in hours.
- Data: If available, baseline service time will be determined from prior year maintenance records for the host site's cooling tower. If these records are not available, estimates will be prepared based on interviews with the host site's tower service provider. The required service records will be created for the hygroscopic system during the demonstration.
- Analytical Methodology: It is likely that the time spent on service will be conservatively high for the demonstration unit as efforts are made to preemptively identify and correct technical issues that may arise. Because of this conservative bias, some degree of data interpretation will likely be employed when comparing time spent on the demonstration unit compared to that for the conventional cooling tower with its well-established maintenance routine. No rationale is currently proposed, but any interpretation applied at the time of reporting will be clearly explained.
- Success Criteria: Cooling tower maintenance time is frequently cited as a disadvantage of water-cooled air-conditioning systems, and can be limiting factor despite their higher energy efficiency compared to fan-cooled systems. Therefore, the minimum success criteria for hygroscopic cooling is to result in no change to the level of maintenance required compared to the baseline system.

System Economics

- Definition: LCC comparison between a hygroscopic cooling tower and a conventional wet cooling tower.
- Purpose: Used to compare the technology alternatives on a financial basis.
- Metric: Simple payback time in years for the additional up-front cost of the hygroscopic system to be recouped in water consumption and other operational savings.
- Data: Data for this PO includes estimates for the up-front capital costs of a conventional cooling tower and a hygroscopic unit, along with demonstration-derived values for ongoing operations and maintenance (O&M) expenses, and any necessary design changes identified

during the project. The O&M expenses consist of water and power consumption, and maintenance related expenses, all of which are treated separately under other POs.

- Analytical Methodology: The LLC analysis will be performed using the National Institute of Standards and Technology (NIST) Building Life Cycle Cost program with the technology-specific data gathered under this project, and representative economic factors (e.g., discount rate, project life, etc.).
- Success Criteria: The hygroscopic cooling system alternative will be considered successful if it can demonstrate a 5-year simple payback for the host sites under consideration.

Net Greenhouse Gas Emissions

- Definition: Analysis of the net change to GHG emissions associated with hygroscopic cooling compared to a conventional cooling tower.
- Purpose: Used to compare the technology alternatives on a GHG emissions basis.
- Metric: The evaluation unit for this PO is the net change in annual GHG emissions in metric tons.
- Data: Input data of water and energy consumption changes will be developed under separate POs. Site-specific estimates for GHG emissions associated with water and energy consumption will be developed to support this PO.
- Analytical Methodology: GHG emission factors will be developed for both water and energy consumption that are reasonably specific to each host site. These factors will then be used to transform consumption data into a net change of GHG emissions.
- Success Criteria: The target for this demonstration is a reduction of 50% below the baseline established by the host site's existing cooling tower.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The hypothesis for this project is that hygroscopic cooling technology can reduce evaporative cooling water consumption and result in an attractive LCC savings compared to conventional cooling tower designs. This hypothesis will be evaluated by temporarily installing hygroscopic cooling towers at existing DoD facilities and monitoring their performance under actual ambient weather and building load conditions. In this scenario, the independent variable consists of the hygroscopic cooling systems themselves, while the dependent variables will include the timing and duration of the building's heat rejection load and the ambient environmental conditions under which the cooling tower must operate. In order to generate a meaningful comparison with the existing cooling tower, the controlled variable will be the magnitude of the heat load applied to the hygroscopic tower since the demonstration unit is not a drop-in replacement for the existing equipment.

Since the hygroscopic cooling tower will reduce the heat load on the existing cooling tower, it will be necessary to sequentially, rather than simultaneously evaluate the cooling performance and water consumption of the existing cooling and the hygroscopic alternative. The following test phases are envisioned to collect the necessary evaluation data.

- Phase 1: On-site characterization period for the hygroscopic cooling system. This phase will begin after each demonstration system is installed and has undergone functionality testing. The goal is to collect data with the hygroscopic systems to characterize their starting baseline performance and water consumption characteristics.
- Phase 2: Existing tower characteristics measurement. After the characterization period for the hygroscopic system, a short-duration data collection effort will be conducted around the existing cooling tower with the hygroscopic system turned off. This characterization will provide the data to which the hygroscopic cooling alternative will be compared.
- Phase 3: Duration testing of the hygroscopic cooling system. After characterizing both cooling tower systems, the hygroscopic tower will be brought back online with the intention of running for the remaining duration of the demonstration period. The goal of this test phase is to accumulate a significant run time of the system in order to monitor long-term operational trends.

5.2 BASELINE CHARACTERIZATION

Both the hygroscopic demonstration tower and the existing cooling tower will undergo a period of baseline characterization and the process will be similar for both towers. Measured data will consist of condenser water flow rate, its supply and return temperatures (i.e., the circulating water in and out of the cooling tower), and the makeup water supplied to the cooling tower. The existing conventional tower will also have the additional data requirement of monitoring the quantity of water discharged through the blowdown stream. Combined with the recorded ambient conditions (i.e., temperature, humidity, and barometric pressure) this information is sufficient to create a model of tower water consumption and cooling performance versus applied cooling load. These models can then be used during the economic evaluation to estimate the performance of either system operating in isolation under identical weather and building load conditions.

The minimum data collection period needed for cooling tower characterization is a complete daily cycle, ideally during peak summer conditions where the cooling load is minimal to zero overnight and builds in intensity throughout the day. With such a complete, recorded spectrum of operation, longer-term seasonal performance can then be modeled using this single characterization. There will be ample data collection to characterize the hygroscopic system under Phase 3 testing while data for the existing cooling tower alone will be limited to specific characterization periods under Phase 2 testing.

The demonstration tower will be fully instrumented to capture the data necessary for its characterization, including measurements of ambient air temperature, humidity, and barometric pressure. For the existing tower, a mix of existing instrumentation at the site combined with sampling associated with the demonstration unit will be used. Each host site cooling tower currently has instrumentation for the condenser water flow and inlet/outlet temperatures, and for the volume of makeup water supplied. Because the blowdown stream is intermittent and difficult to measure directly, its average flow will be estimated by determining the average cycles of concentration for the existing cooling tower using measurements of dissolved solids in the makeup water and in the circulating condenser water. The ratio of these values will provide a basis for the average amount of blowdown water released from the cooling tower. Water sampling is planned quarterly during the cooling season.

In order to evaluate the stability of the desiccant solution, samples will be collected at intervals throughout the demonstration period and each will be analyzed for cations and anions of interest. This ionic composition will be compared to a separate measure of total dissolved solids as a check to see if unidentified species are accumulating.

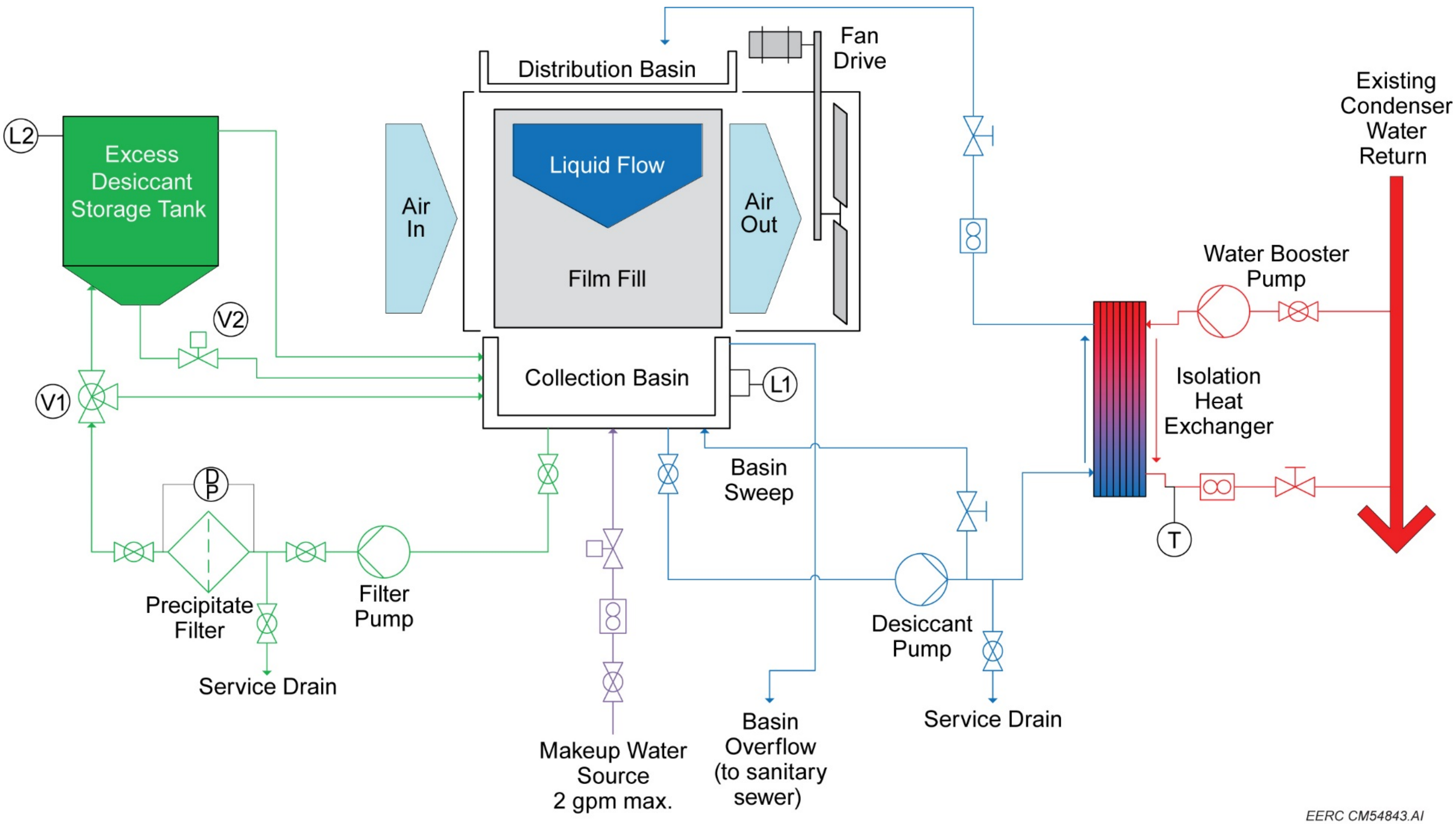
5.3 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

The demonstration system is designed around a stock cooling tower that will be modified to operate as a hygroscopic cooling tower. The starting tower will be a Marley Aquatower, Model 494K, constructed from fiberglass-reinforced plastic. This tower has a nominal cooling rating of 68 tons as designed. With the hygroscopic modifications, the maximum load will be derated by approximately 15%.

The working fluid for the hygroscopic tower is a liquid desiccant composed of $CaCl_2$ and water. The total amount of $CaCl_2$ within the system is fixed and will be approximately 680 lb for the demonstration system. However, during operation, the concentration of $CaCl_2$ in the liquid will vary in response to the cooling demand and ambient conditions. When diluted to its lowest concentration, the $CaCl_2$ will make approximately 500 gallons of solution.

An equipment schematic for the demonstration system is shown in Figure 9. There are four separate liquid flows of consequence in the system. First is the hot-water bypass circuit noted with red lines that delivers the heat load to the isolation heat exchanger. For the demonstration, this bypass will be a slipstream of the return flow to the existing cooling tower and will flow at a rate of roughly 180 gpm. The second fluid on the other side of the heat exchanger is the $CaCl_2$ solution, noted with the blue lines. It flows from the heat exchanger and over the film fill in the cooling tower for heat exchange with the air. Design flow for this circuit is approximately equal to the hot-water bypass at 180 gpm. The third fluid circuit in green is also $CaCl_2$ solution and passes between the makeup mixing tank and the tower basin to supply makeup fluid to the tower. This stream also passes through the system's particulate filter which is the location where precipitated solids and scrubbed dust are removed from the liquid. The circulation rate through the filtration system is approximately 5 gpm. Finally, the fourth liquid flow in purple is fresh makeup water mixed with the circulating $CaCl_2$ solution. Its flow will depend on the rate of water evaporation which will change as a function of cooling load and ambient conditions, but will not exceed 2 gpm.

The ultimate composition of the hygroscopic working fluid is determined by a dynamic balance between the desiccant and other species brought in with the makeup water. Each specie will concentrate until their saturation limit is reached, including less soluble chloride salts such as sodium chloride. Periodic sampling and analysis of the desiccant solution will be performed to monitor this balance and determine when a steady state composition is reached.



EERC CM54843.AI

Figure 9. Demonstration system schematic.

The hygroscopic cooling demonstration systems will be temporarily connected to existing chiller condenser water circuits at both demonstration sites. Each condenser water return line to the existing cooling tower will be tapped to install a parallel flow circuit leading to the demonstration system's isolation heat exchanger as shown in Figure 9. Cooled water from the demonstration system will feed back into the existing tower's hot-water line at a point downstream of the extraction site but before the existing cooling tower. *Since no water is allowed to bypass the existing tower, chiller cooling is never in jeopardy, even if the demonstration system is not in operation or does not meet expectations.*

As shown in Figure 9, each bypass connection point in the hot water line will have a shut off valve so that the connections can be made in advance of the demonstration system installation, and so that during the demonstration, the hygroscopic system can be completely isolated from the existing cooling system. Blind flanges or a pipe plug will be installed in the valves before the demonstration starts and after it ends to prevent accidental opening. A booster pump integrated with the demonstration equipment will be used to circulate water from the extraction site, through the hygroscopic heat exchanger, and back into the return line.

Photographs of the actual demonstration equipment during testing at the EERC are provided in Figures 10-13.

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Figure 10. Tower and pump skid with electrical cabinet.

EERC CM54845.AI

Figure 11. Front view of tower, pump skid, filter skid, and makeup tank.

EERC CM54846.AI

Figure 12. Exhaust side of tower.


EERC CM54847.AI

Figure 13. Isolation heat exchanger skid.

Figures 14 and 15 show the plan view of the equipment at Fort Irwin and a three-dimensional rendering of the layout. Since the site at Fort Irwin's Building 263 is surrounded by a walled enclosure, that demonstration system will use a vertical exhaust deflector (not shown in the photographs) to prevent exhaust recirculation.

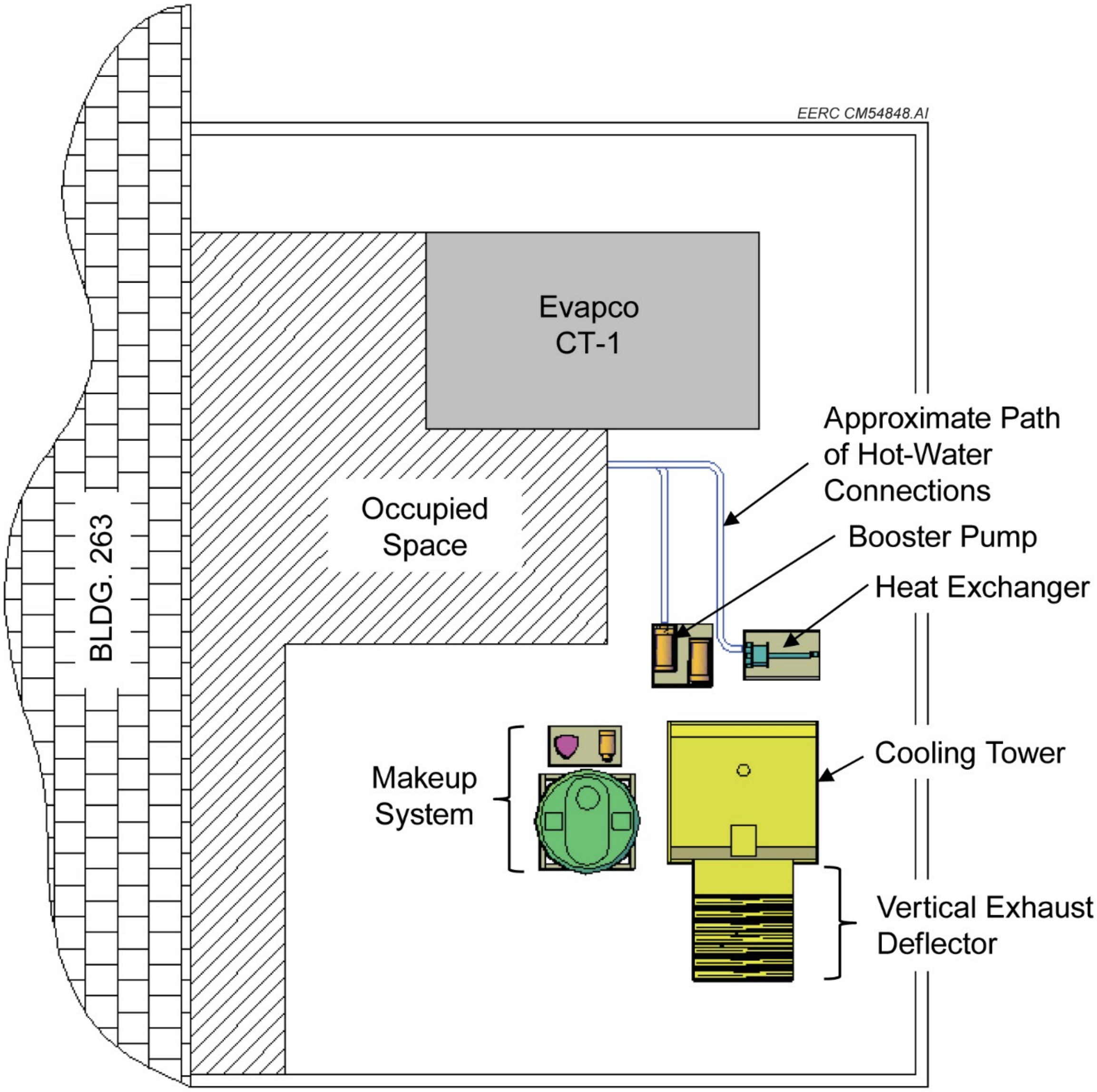


Figure 14. Plan view of Fort Irwin's Building 263 cooling tower enclosure layout (to be viewed in same orientation as what is shown in Figure 3).

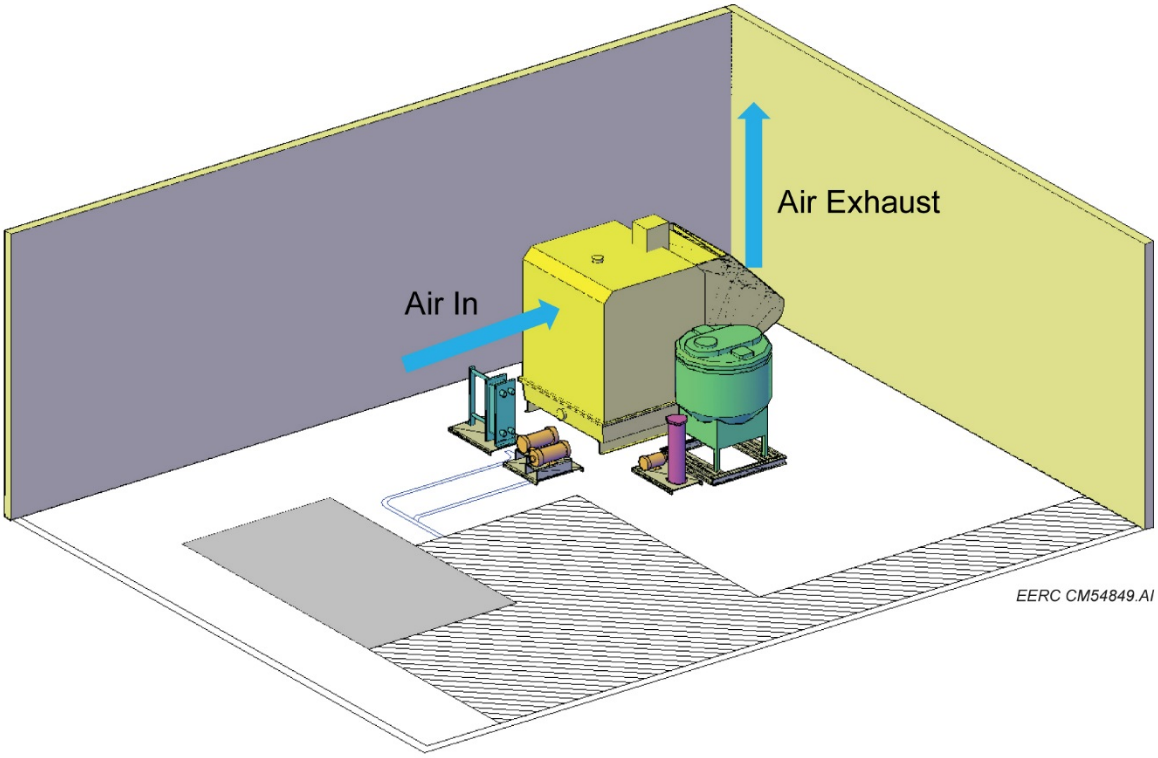


Figure 15. Three-dimensional equipment layout within the walled enclosure of Fort Irwin Building 263.

The analogous plan and layout views for the DCMB demonstration equipment are shown in Figures 16 and 17. Since there are no obstructions at DCMB, airflow through the cross-flow demonstration tower is horizontal, both intake and exhaust. The demonstration tower in Figure 17 has been oriented so that its intake side faces the prevailing wind direction, i.e., from the west.

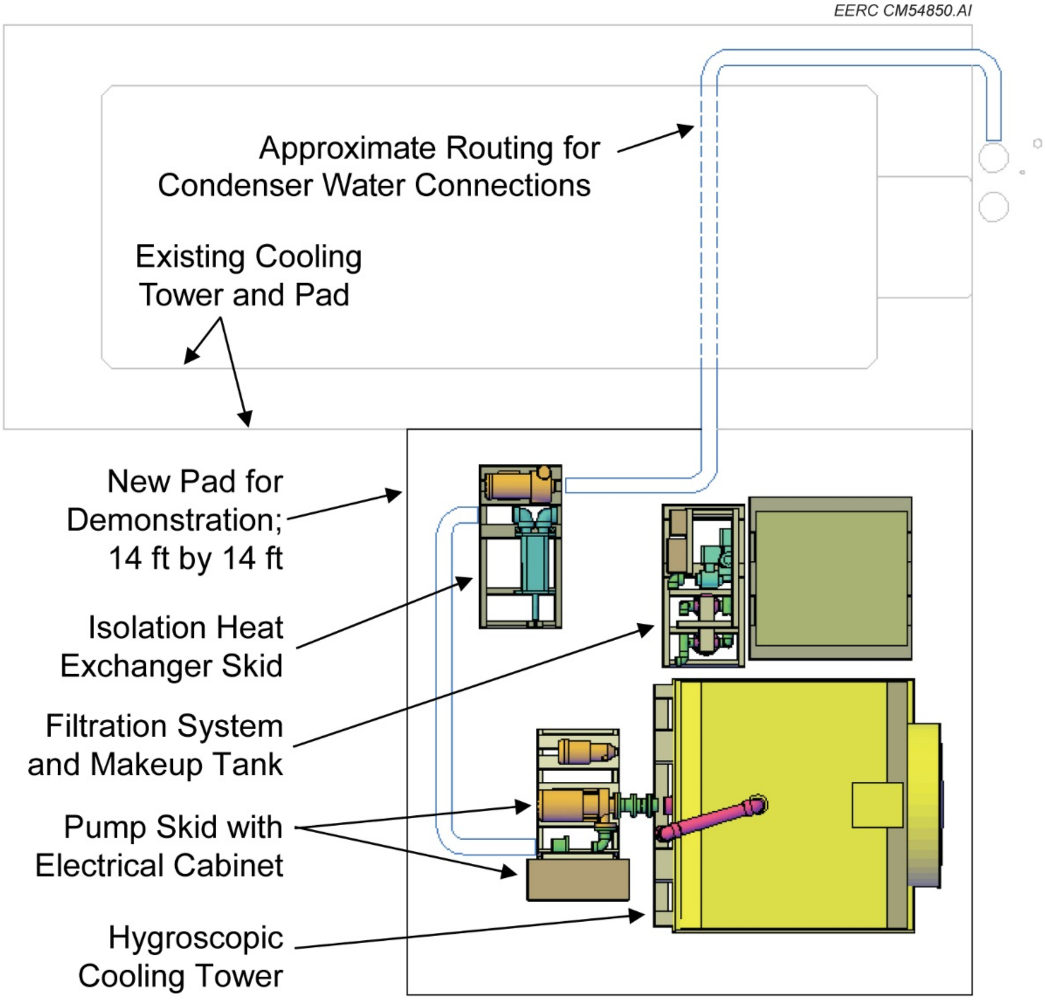


Figure 16. Plan view of the DCMB demonstration cooling tower equipment next to the existing tower and pad (shown in the same orientation as in Figure 6).

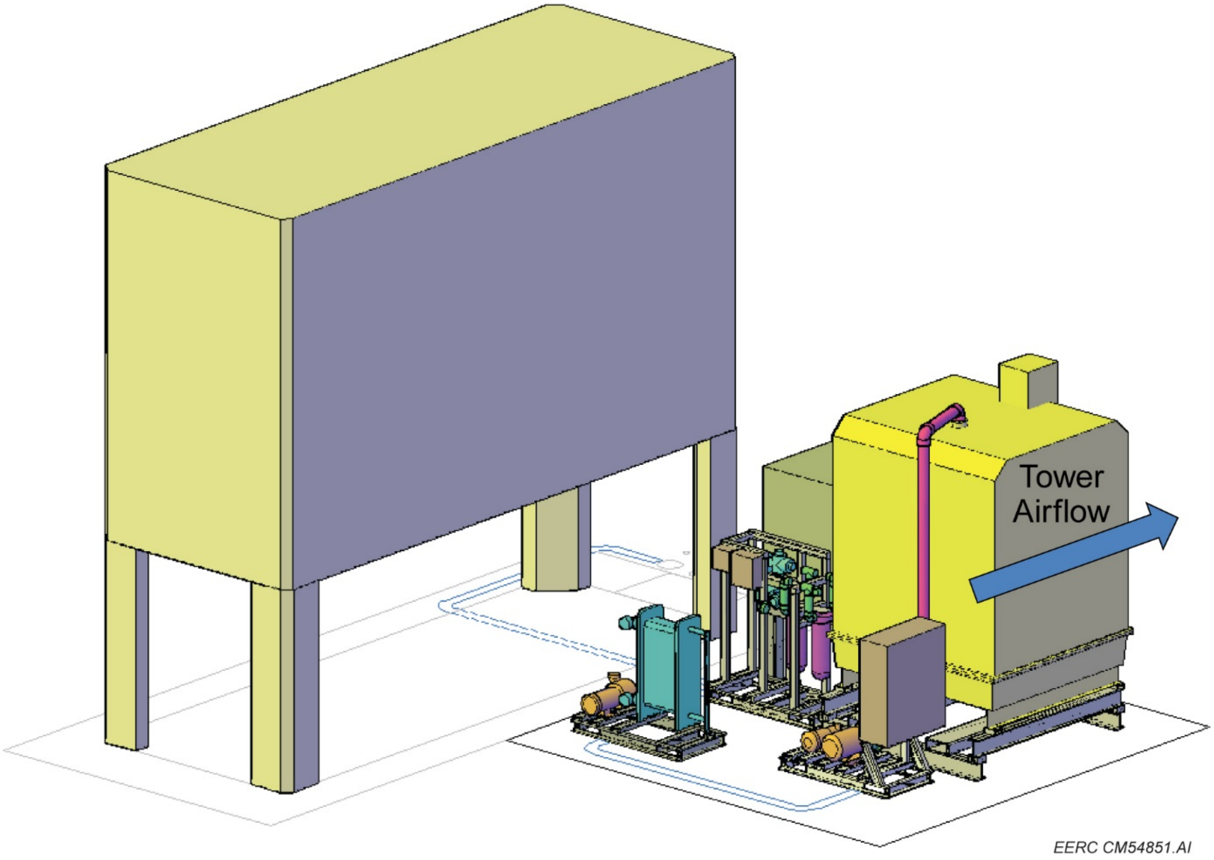


Figure 17. Three-dimensional demonstration equipment layout next to the existing cooling tower for DCMB.

5.4 OPERATIONAL TESTING

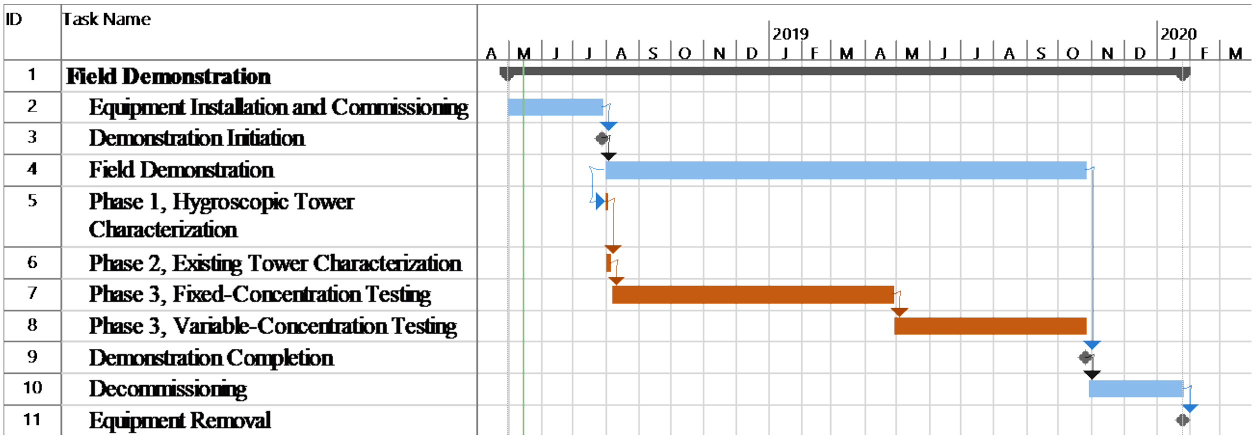
Operational testing of the hygroscopic cooling tower will consist of three distinct periods including 1) the initial start-up and system characterization, 2) fixed-concentration operation, and 3) variable-concentration operation. The initial start-up and characterization operation corresponds to Phase 1 testing, where the system will be closely supervised and operating parameters are manually controlled to capture the desired range of characterization data.

Operational Periods 2 and 3 will fall under Phase 3 testing and will differ in the way that makeup water is managed. Under fixed concentration, operation makeup water is added to maintain a constant working volume and, therefore, concentration of desiccant solution. This is the least complicated control strategy, which reduces the risk of over- or underfilling the cooling tower. However, a fixed-desiccant concentration is a compromise in that it may not provide optimal cooling when hot or save the maximum amount of water when cool.

Under variable-concentration operation, a temperature sensor in the return condenser water line will be used to trigger dilution or concentration of the desiccant working fluid. If the return temperature exceeds a set point, then more makeup water will be added to dilute the desiccant and increase the tower's evaporative cooling capacity. Similarly, when the temperature is sufficiently cool, makeup water will be withheld to concentrate the desiccant and shift toward water-saving, sensible heat transfer. The intent is that this cycle will occur once per day: during cooler evenings and early mornings the desiccant would be allowed to concentrate to a higher value in order to maximize its dry cooling contribution, but during the day the desiccant would be diluted to increase its heat transfer potential. However, this mode of operation increases complexity of the system and it remains to be seen if it will be justified through increased water savings. The outcome of this analysis will be a component of the final performance report.

The overall testing time line is outlined in Table 2.

Table 2. Demonstration Testing Time Line



ID	Task Name
1	**Field Demonstration**
2	Equipment Installation and Commissioning
3	Demonstration Initiation
4	Field Demonstration
5	Phase 1, Hygroscopic Tower Characterization
6	Phase 2, Existing Tower Characterization
7	Phase 3, Fixed-Concentration Testing
8	Phase 3, Variable-Concentration Testing
9	Demonstration Completion
10	Decommissioning
11	Equipment Removal

5.5 SAMPLING PROTOCOL

Data collection is summarized in Table 3 according to categories of: continuously logged, physical samples, host site information, and postdemonstration information. Continuously logged data consists of various measurements of the hygroscopic cooling system and the ambient conditions. These points will be logged using an electronic data logger at 1-minute intervals, and the resulting data file will be periodically uploaded to a secure server using a cellular modem. A copy of the data is also stored locally within the logger itself in the event of upload or server failure.

Physical samples primarily include items related to the condition of the desiccant working fluid and filtration system. These samples will be collected during the quarterly inspections and shipped back to the EERC for analysis. Information and data relating to the existing cooling tower and the cooling load will be requested through host site personnel and their designated service contractors; however, the EERC and CERL personnel have responsibility for collection. Finally, decommissioning activities will offer the opportunity to document the condition of various hygroscopic cooling system components, including the heat exchanger and the tower's film fill surfaces.

Table 3. Summary of Collected Data And Methods

Category	Data	Collection Method	Collector
Continuously Logged	Hygroscopic system temperatures, pressures and flow rates; ambient temperature, humidity, and barometric pressure	Automatically logged by a data logger mounted to the system	The EERC is responsible for logger setup and maintenance
Physical Samples	Desiccant solution, makeup water, and precipitate filters; existing tower circulating condenser water; corrosion coupons	Manually collected during quarterly equipment inspections	Samples will be collected by the EERC and/or CERL on-site personnel and shipped to the EERC for analysis
Host Site Information	Cooling system design information; logged temperature and flow data for existing cooling system; maintenance records and service costs for existing cooling system	Manual search for the subject data files	EERC and CERL personnel will work with host site personnel and cooling tower service providers to locate the necessary records
Post Demonstration Information	Evidence of equipment fouling and/or corrosion	Manual teardown of susceptible components	EERC personnel will document equipment condition at decommissioning

5.6 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

EERC personnel have the responsibility for testing and ensuring that all instrumentation associated with the hygroscopic cooling system is properly calibrated. The primary tool for ongoing data quality assurance is through corroboration of derived values with independently derived alternatives. For instance, water consumption by the hygroscopic cooling tower is primarily measured by a dedicated water totalizer. However, this value is validated by comparing to the measured evaporation rate across the tower, i.e., the change in humidity from air inlet to outlet. In a similar manner, heat load dissipated by the system can be compared by separate calculations of the three different system circuits, i.e., water, desiccant, and air. Laboratory-analyzed samples will adhere to established quality assurance/quality control methodologies applicable to the analysis type.

6.0 PERFORMANCE ASSESSMENT

Specific analytical approaches are discussed for each PO in Section 4. In general, the performance assessment methodology consists of two parts, the first is to develop a characteristic model of a hygroscopic cooling system based on experimental data, and the second is to document longer-term operational requirements of hygroscopic cooling. Both of these elements are needed to accurately develop LCC estimates, which are ultimately the values that will be used to justify investment in hygroscopic cooling over a conventional alternative. The external validity of the assessment is maintained by testing the technology in two distinct climates that lie at representative extremes of where cooling water savings is a concern.

7.0 COST ASSESSMENT

As discussed in Section 2.2, the cost advantage of hygroscopic cooling is based on a reduced operational cost over the tower's lifetime that will recoup the incremental up-front investment in this tower over a conventional alternative. Table 4 summarizes the key cost elements that determine the cost outlook for hygroscopic cooling and how their values will be refined using data from the demonstration.

Table 4. Inputs for Hygroscopic Cooling LCC Model

Cost Element	Initial Basis	Data Tracked During the Demonstration
Hygroscopic Tower Capital Cost	1.2 cost factor relative to an equivalent-size conventional tower	Evaluate utility of the hygroscopic tower design, identify essential features, and develop cost to implement
Isolation Heat Exchanger Capital Cost and Performance Penalty	$60 per refrigeration ton capital expense and 10°F added coolant temperature differential for scenarios with the heat exchanger	Evaluate $CaCl_2$ compatibility of various materials within the demonstration system based on an end-of-test inspection
Makeup Water Cost	$3.80/kgal at Fort Irwin; $10.19/kgal at DCMB	Validate with respective facility managers
Sewer Charges	$6.07/kgal at Fort Irwin; $5.73/kgal at DCMB	Validate with respective facility managers
Electricity Cost	$0.10/kW-hr at both sites	Validate with respective facility managers
Conventional Cooling Tower Water Treatment Expense	$1.50 per refrigeration ton per month at both sites	Validate with respective facility managers
Hygroscopic Tower Makeup Desiccant Expense	$230/yr at both sites assuming complete annual replacement	Document usage over the yearlong demonstration
Tower Water Savings	Modeled hygroscopic cooling performance using 2015 hourly weather data for both sites; assumed 3 cycles of concentration in existing towers	Measure the characteristic water consumption for the demonstration and existing cooling towers as a function of ambient conditions and applied thermal load
Cooling Performance Penalty	Added a chiller inefficiency charge at the rate of 0.005 kW/ton/°F for every degree the inlet coolant temperatures were above 75°F	Validate penalty curve based on specific chiller models
Changes to Maintenance Expense	$0 relative to wet cooling alternative	Track time spent on maintenance activities; develop a heat exchanger cleaning fee based on the end-of-test heat exchanger condition
System Lifetime	20 yrs	Revise as needed based on end-of-test system condition

Initial LCC comparisons were prepared for each demonstration site based on the cooling tower size that will be used during testing and by assuming installations with and without an isolation heat exchanger. The NIST Building Life Cycle Cost program, Version 5.3, was used to calculate the present value of the future cost elements presented in Table 4. Tables 5 and 6 summarize the LCC estimates for Fort Irwin and DCMB, respectively.

Table 5. Fort Irwin LCC Estimates Based on the Demonstration Cooling Tower Size

	Conventional Wet Cooling Without Isolation Heat Exchanger	Hygroscopic Cooling Without Isolation Heat Exchanger	Hygroscopic Cooling with Isolation Heat Exchanger
Design Information			
Cooling Load[a]	58 tons	58 tons	58 tons
Annual Run Fraction[b]	0.56	0.56	0.56
Annual Water Consumption[b]	500,000 gal	346,000 gal	346,000 gal
Annual Water Savings[b]	–	31%	31%
Life Cycle Cost Inputs			
Initial Capital	\$7700	\$10,871	\$14,339
Annual Electricity Cost[b, c]	\$2515	\$3090	\$3090
Annual Water Cost[b, d]	\$2912	\$1313	\$1313
Annual Coolant Additives[b, e]	\$520	\$230	\$230
Annual Chiller Penalty[f]	–	–	\$320
20-year Analysis[g]			
Residual Equipment Value	\$0	\$0	\$0
20-year Present Value	\$98,722	\$82,345	\$90,795
Net Savings	–	\$16,377	\$7926
Savings-to-Investment Ratio	–	6.16	2.19
Simple Payback	–	3 yr	7 yr

[a] Derived from the measured cooling capacity of a desiccant-converted Marley Aquatower Model 494K.
[b] Based on using 2015 as the reference weather year.
[c] On-base electricity rates assumed to be \$0.10/kW-hr at both locations.
[d] Water supply and wastewater disposal costs were set to the site values shown in Table 4.
[e] Cooling water additive costs were estimated according to Table 4 and include all additives for fouling, corrosion, and microbial control for the conventional tower; for the hygroscopic systems, additive costs cover the expense of makeup desiccant.
[f] Added chiller electricity consumption due to higher-temperature coolant; rationale described in Table 4.
[g] Assuming a discount rate of 3%.

Table 6. DCMB LCC Estimates Based on the Demonstration Cooling Tower Size

	Conventional Wet Cooling Without Isolation Heat Exchanger	Hygroscopic Cooling Without Isolation Heat Exchanger	Hygroscopic Cooling with Isolation Heat Exchanger
Design Information			
Cooling Load[a]	58 tons	58 tons	58 tons
Annual Run Fraction[b]	0.39	0.39	0.39
Annual Water Consumption[b]	202,000 gal	130,000 gal	130,000 gal
Annual Water Savings[b]	–	36%	36%
Life Cycle Cost Inputs			
Initial Capital	$7700	$10,871	$14,339
Annual Electricity Cost[b, c]	$1733	$2130	$2130
Annual Water Cost[b, d]	$2447	$1329	$1329
Annual Coolant Additives[b, e]	$520	$230	$230
Annual Chiller Penalty[f]	–	–	$116
20-year Analysis[g]			
Residual Equipment Value	$0	$0	$0
20-year Present Value	$79,515	$67,621	$72,903
Net Savings	–	$11,895	$6639
Savings-to-Investment Ratio	–	4.75	2.00
Simple Payback	–	4 yr	8 yr

[a] Derived from the measured cooling capacity of a desiccant-converted Marley Aquatower Model 494K.
[b] Based on using 2015 as the reference weather year.
[c] On-base electricity rates assumed to be $0.10/kW-hr at both locations.
[d] Water supply and wastewater disposal costs were set to the site values shown in Table 4.
[e] Cooling water additive costs were estimated according to Table 4 and include all additives for fouling, corrosion, and microbial control for the conventional tower; for the hygroscopic systems, additive costs cover the expense of makeup desiccant.
[f] Added chiller electricity consumption due to higher-temperature coolant; rationale described in Table 4.
[g] Assuming a discount rate of 3%.

All four hygroscopic options that were modeled in Tables 5 and 6 show a positive savings to investment ratio of 2 or higher. However, Fort Irwin's climate clearly results in a much higher quantity of water used for cooling and, in turn, results in a magnitude of water savings that is more than double the DCMB estimates. Due to its milder climate and reduced need for air conditioning, DCMB would likely not be an attractive candidate for hygroscopic cooling if it were not for the high cost of water there.

The results of Tables 5 and 6 also show the impact of adding an isolation heat exchanger to the hygroscopic system. Adding the heat exchanger increases the capital cost, and it introduces a temperature differential that raises the temperature of the condenser cooling circuit. Modeled chiller efficiency is impacted when the entering coolant rises above a threshold of 75°F, and this effect is accounted for by the annual chiller penalty cost, which is the additional electricity needed to offset the calculated drop in efficiency. From Tables 5 and 6 it is clear that the systems without the isolation heat exchanger have more attractive investment returns, meaning that such opportunities will be strong contenders for early adoption. Such opportunities include situations where the cooling circuit's materials are compatible with the desiccant solution (e.g., chillers with titanium condenser tubes), or where an isolation heat exchanger is needed even for the conventional wet cooling alternative. This last option is frequently encountered in the form of a closed-circuit fluid cooler, a popular option for separating process fluids from the potentially dirty water circulating in the cooling tower.

8.0 TECHNOLOGY TRANSFER

A successful ESTCP demonstration of this technology would naturally lead to implementation through the Energy Conservation Investment Program (ECIP) and Energy Savings Performance Contracts (ESPC). As these opportunities develop, the EERC will facilitate commercial deployment by engaging entities capable of providing equipment and after-sale support.

Technology transition deliverables include the ESTCP required reports, i.e., a final technical report, a cost and performance report, and a project outbrief. In addition, the following deliverables will also be generated to facilitate technology adoption:

- A high-level technology overview fact sheet, with a maximum of 2 pages that presents the technology's key features, a demonstration description, basic installation costs, and potential additional information sources. The target audience for this fact sheet will be the end users of the product or service.
- A technical fact sheet, with a maximum of 2 pages, that outlines the technical specifications of the technology, ESTCP demonstration results, and any specific technical references. The target audience for this fact sheet will be installation site energy managers and/or engineers.
- Technical data to complete Form 1391, which is used by DoD to submit requirements and justifications to obtain funding for many types of military construction projects.
- A briefing to be used by individual installation staff to present specific technical and economic information about the technology to support the acquisition process. The briefing will be a maximum of ten slides and targeted to installation supervisors, managers, and decision makers.

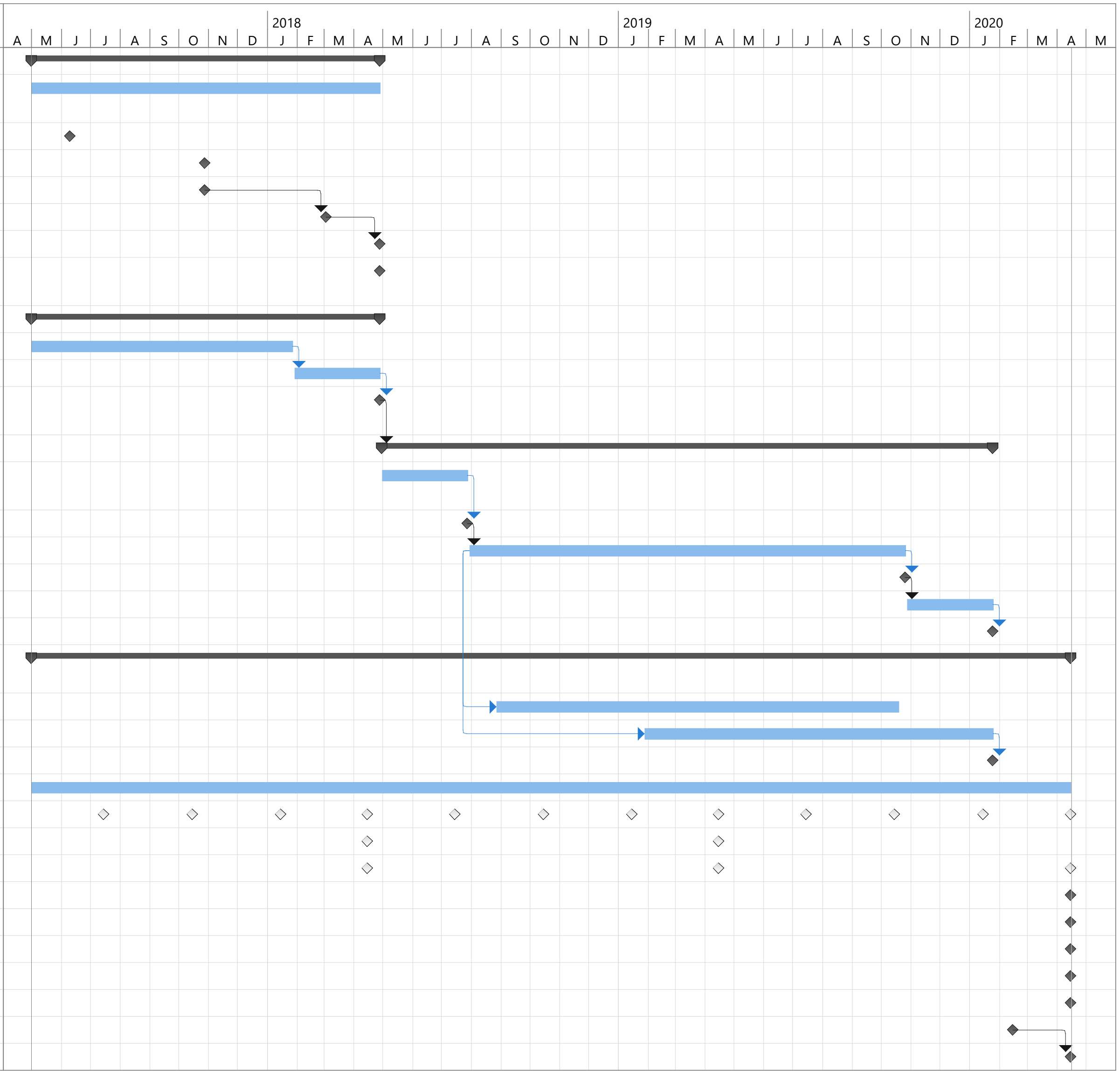
Formats for the Form 1391 input and the briefing slides will be obtained from the ESTCP program office.

9.0 SCHEDULE OF ACTIVITIES

The overall project schedule is shown in Table 7 and includes all four project Tasks from project initiation to project completion.

Table 7. Project Schedule

ID	Task Number	Task Name
1	**1**	**Host Site Preparation**
2	1.1	Host Site Selection, Demonstration Approval, and Test Plan Development
3	1.2	Kick-Off Call
4	1.3	Site Selection Memo
5	1.4	Pre-Demonstration Plan
6	1.5	Draft Demonstration Plan
7	1.6	Final Demonstration Plan
8	1.7	Completion of Permits, Approvals, Agreements
9	**2**	**Prototype Development**
10	2.1	Fabricate Prototypes
11	2.2	Prototype Acceptance Testing
12	2.3	Field Demonstration Go/No-Go Decision
13	**3**	**Field Demonstration**
14	3.1	Equipment Installation and Commissioning
15	3.2	Demonstration Initiation
16	3.3	Field Demonstration
17	3.4	Demonstration Completion
18	3.5	Decommissioning
19	3.6	Equipment Removal
20	**4**	**Technology Cost/Benefit Analysis and Reporting**
21	4.1	Data Analysis
22	4.2	Cost/Benefit Analysis
23	4.3	Cost and Performance Report
24	**4.4**	**Deliverable Preparation**
25	**4.4.1**	**Quarterly Reporting**
38	**4.4.2**	**Annual Summary**
41	**4.4.3**	**In-Progress Review**
45	4.4.4	Project Outbrief
46	4.4.5	Technology Overview Fact Sheet
47	4.4.6	Technical Fact Sheet
48	4.4.7	Form 1391 Input
49	4.4.8	Installation Technology Briefing Slides
50	4.4.9	Draft Final Report
51	4.4.10	Final Final Report



10.0 MANAGEMENT AND STAFFING

Duties regarding the demonstration are divided between the project's primary performers, the EERC and CERL. Specific demonstration and technology transfer duties for each organization are summarized in Table 8. Third-party contractors will be used at each demonstration site to assist with equipment installation and removal. However, service checks and maintenance during the demonstration are the responsibility of the EERC. Economic modeling support will also be provided by Mr. Ken Mortensen, Research and Development Manager at SPX Cooling Technologies.

Table 8. Lead Team Members and Demonstration Responsibilities

Christopher Martin, Ph.D. University of North Dakota Energy & Environmental Research Center	**Mr. Scott Lux U.S. Army Corps of Engineers Engineer Research and Development Center Construction Engineering Research Laboratory**
EERC Responsibilities: • Set up the demonstration systems at each host site and perform characterization testing. • Conduct quarterly on-site equipment checks and collect physical samples, i.e., precipitate filters desiccant solution, and makeup water. • Remotely monitor performance data from the demonstration systems. Reduce data for LCC analysis. • Supervise the transition between test phases. • Decommission equipment and prepare for removal. • Report project findings through technical meetings and conferences, as appropriate.	**CERL Responsibilities:** • Coordinate planning and contracting local services necessary for equipment installation and removal. • Collect operations and maintenance data and develop an economic model for these activities. • Synthesize the LCC comparisons using performance data and the model of O&M activities. • Prepare technology transfer deliverables and report project findings through technical meetings and conferences, as appropriate.

11.0 REFERENCES

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10. Advanced Research Projects Agency—Energy. *Novel Dry Cooling Technology for Power Plants*; Project Overview. http://arpa-e.energy.gov/?q=slick-sheet-project/water-efficient-power-generation (accessed March 2016).

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APPENDICES

Appendix A: Health and Safety Plan

- What are the applicable local, state, and federal health and safety laws and regulations?
    - Operation of this cooling tower is not directly regulated by government authorities at either host site. However, there are Federal and California state guidelines regarding the safe operation of cooling towers that this demonstration will adhere to. Specifically, the tower uses high efficiency drift eliminators to curtail inhalable aerosol formation, and the microbial activity within the cooling tower will be monitored and corrective action taken if necessary.
- What is the potential for worker exposure to hazardous materials and/or other hazards?
    - The key concern for this demonstration is personal contact with the calcium chloride desiccant solution. The desiccant is a concentrated salt solution of calcium chloride and water. Calcium chloride is classified as a Serious Eye Irritation, Category 2 hazard. It is recommended to avoid contact with skin, eyes, or clothing. The following steps will be taken during the demonstration to reduce the risk of accidental exposure.
        - Maintenance will be limited to EERC personnel trained in the necessary precautions for calcium chloride exposure. Requests of host site personnel will be limited to making inspections or turning the system on/off.
        - Facility managers at both sites will be briefed regarding the properties of calcium chloride solution and the appropriate response actions if a problem develops. A safety data sheet will be provided to the facility managers and a backup copy will be kept within the control cabinet of each demonstration system.
- What physical requirements are expected of workers?
    - Workers will be required to wear personal protective equipment including safety glasses with splash shields and non-leather protective gloves. A respirator will not be required.
- How many people are required to operate the technology?
    - The system will normally operate unattended. However, one person is sufficient to change operating conditions and perform maintenance.
- What is the technology's history of breakdowns or accidents?
    - The demonstration equipment is, as a prerequisite for the ESTCP, an early stage, pre-commercial system with limited operating history. During testing at the EERC, no breakdowns or accidents were observed that were outside events considered normal for new equipment, e.g. minor leaks.
- Will there be any potential effects from the transporting of equipment, samples, wastes, or other materials associated with the technology?

  - No effects are anticipated since calcium chloride solution is not regulated by the United States Department of Transportation.

- What impact will this technology have on the surrounding environment?
  - Environmental impacts of this technology are expected to be minimal. No water or air emissions occur under normal operating conditions. Solid waste will be produced from the precipitation of dissolved minerals in the makeup water, but this material is non-hazardous and can be disposed of through conventional means.
  - Effects from an accidental release of calcium chloride solution to the immediate environment are likewise expected to be minimal since calcium chloride poses little ecotoxicity risk and does not bioaccumulate.
- Where is the closest medical facility with emergency services?
  - At Fort Irwin: Weed Army Community Hospital, 390 N. Loop Rd., Fort Irwin, CA.
  - At DCMB: Community Hospital of the Monterey Peninsula, 23625 Holman Hwy., Monterey, CA.
  - Directions to both centers are provided in Figures A-1 and A-2.

- Emergency Directions for Fort Irwin
  - Despite being in a remote location, Fort Irwin has its own hospital with emergency services on post. From the location of the demonstration site, the driving distance is under 0.5 miles, as noted in the map below.

from 271 7th St, Fort Irwin, CA 92310
to 390 N Loop Rd, Fort Irwin, CA 92310

2 min (0.4 mile)
via 7th St and B Ave
Fastest route
⚠ This route has restricted usage or private roads.

271 7th St
Fort Irwin, CA 92310

↑ Head northwest on 7th St toward B Ave
⚠ Restricted usage road
0.1 mi

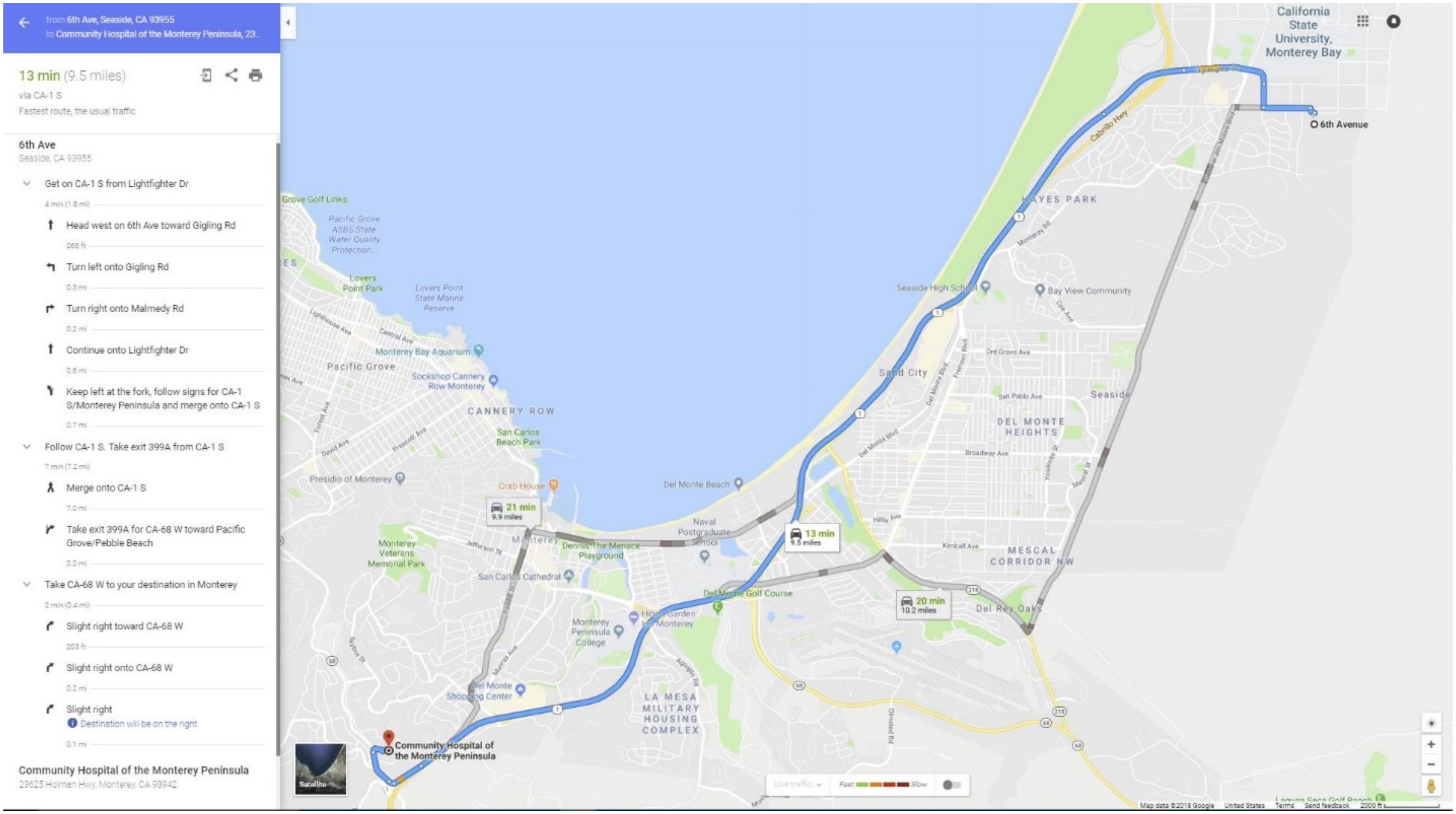
↱ Turn right onto B Ave
⚠ Restricted usage road
0.3 mi

390 N Loop Rd
Fort Irwin, CA 92310

These directions are for planning purposes only. You may find that construction projects, traffic, weather, or other events may cause conditions to differ from the map results, and you should plan your route accordingly. You must obey all signs or notices regarding your route.

Figure A-18. Map of Fort Irwin with directions from demonstration site to the on-post hospital. Note, at the time of imaging from Google Inc. the hospital did not exist, but it has since been constructed.

- Emergency Directions for DoD Center Monterey Bay
  - The demonstration site in Monterey is approximately 9.5 miles to the nearest community hospital and emergency center, as noted in the figure below with map and directions



from 6th Ave, Seaside, CA 93955
to Community Hospital of the Monterey Peninsula, 23...

13 min (9.5 miles)
via CA-1 S
Fastest route, the usual traffic

6th Ave
Seaside, CA 93955

Get on CA-1 S from Lightfighter Dr
4 min (1.8 mi)

- Head west on 6th Ave toward Gigling Rd
  266 ft
- Turn left onto Gigling Rd
  0.3 mi
- Turn right onto Malmedy Rd
  0.2 mi
- Continue onto Lightfighter Dr
  0.6 mi
- Keep left at the fork, follow signs for CA-1 S/Monterey Peninsula and merge onto CA-1 S
  0.7 mi

Follow CA-1 S. Take exit 399A from CA-1 S
7 min (7.2 mi)

- Merge onto CA-1 S
  7.0 mi
- Take exit 399A for CA-68 W toward Pacific Grove/Pebble Beach
  0.2 mi

Take CA-68 W to your destination in Monterey
2 min (0.4 mi)

- Slight right toward CA-68 W
  203 ft
- Slight right onto CA-68 W
  0.2 mi
- Slight right
  Destination will be on the right
  0.1 mi

Community Hospital of the Monterey Peninsula
23625 Holman Hwy, Monterey, CA 93942

Figure A-19. Map and directions from DCMB to the closest hospital (Courtesy of Google Maps).

Appendix B: Points of Contact

Point of Contact	Organization	Phone & E-Mail	Role in Project
Christopher Martin	EERC	701-777-5083 cmartin@undeerc.org	Technology Principal Investigator
Scott Lux	CERL	217-373-4438 Scott.M.Lux@usace.army.mil	Evaluation Principal Investigator
Christopher Woodruff	Fort Irwin DPW	760-380-4987 Christopher.A.Woodruff4.civ@mail.mil	Fort Irwin Point of Contact
John Wallingford	Mission Support, DHRA	831-583-4106 John.M.Wallingford.civ@mail.mil	DCMB Point of Contact

Appendix C: Desiccant Solution Product Data Sheet

Liquid Calcium Chloride PDS

LIQUID CALCIUM CHLORIDE

Product Data Sheet

General Description

Liquid calcium chloride (CaCl2) is an odorless, slightly alkaline, colorless fluid. TETRA's liquid calcium chloride is available in a variety of concentrations and grades, including food grade and NSF certified.

With our proprietary manufacturing process, TETRA Chemicals is the only manufacturer that uses food grade quality hydrochloric acid and high purity limestone as raw materials to produce CaCl2. This results in CaCl2 with very low levels of alkali metals, iron, and other impurities when compared to other manufacturers that produce CaCl2 from brines.

Applications

TETRA liquid calcium chloride is used in various applications to retard cold weather hazards, including snow and ice control on roadways (meets or exceeds ASTM D98-95 and AASHTO Ml 44-86 standards). It is also used as an accelerator for ready-mix concrete curing, and as an anti-freeze for coal storage and transportation.

This product is widely used in oilfield applications as completion and workover fluids, and as a drilling mud additive to increase density and prevent clay hydration.

Liquid CaCl2 also can be used as:

- A fugitive dust control agent and roadbed stabilizer,
- A weighting fluid for tractor tires to improve traction,
- An inexpensive source of calcium in wastewater treatment to remove fluoride and break oil/water emulsions,
- A low-temperature brine in refrigeration systems, and
- An additive in many other industrial applications.

TETRA Chemicals
24955 Interstate 45 North
The Woodlands, Texas 77380
Phone: 281.367.1983
Customer Service: 800.327.7817
Fax: 281.298.7150

Availability

Liquid calcium chloride is available from over 20 plant and terminal locations throughout North America. For the location nearest you, refer to the plant and terminal map available on our website (www.tetrachemicals.com) or contact your TETRA sales or customer service representative.

Safety and Handling

Liquid calcium chloride is a strong salt solution. Wear appropriate protective, impervious clothing. Wear safety glasses with non-flexible side shields or chemical goggles for proper protection of the eyes. Wear appropriate protective non-leather protective gloves and boots. Chemical protective gloves and boots such as PVC or Nitrile are recommended. Leather products do not offer adequate protection and will dehydrate with resultant shrinkage and possible destruction. This product should be handled in areas with proper ventilation. Before using this product, refer to the SDS which is available on the Company's website for complete safety and handling guidelines.

PHYSICAL PROPERTIES	
Appearance	Colorless liquid
Odor	None
Assay	28 to 40% by weight $CaCl_2$
Crystallization Temperature	-38°F (-39°C) to 55.9°F (13.3°C)
Specific Gravity @ 68°F (20°C)	1.264 to 1.403
Bulk Density	10.53 to 11.69 lb/gal

CHEMICAL PROPERTIES	
Chemical	$CaCl_2$
pH	Slightly alkaline
Impurities (on 100% $CaCl_2$ basis)	
Alkali Chlorides	< 0.1% by weight
Magnesium (as $MgCl_2$)	< 0.1% by weight
Other impurities (not H_2O)	< 1.0% by weight

www.tetrachemicals.com

Appendix D: Facility Letters of Support

Fort Irwin Demo Plan Support Letter

Monterey Host Site Support Letter

DEPARTMENT OF THE ARMY
DIRECTORATE OF PUBLIC WORKS, UNITED STATES ARMY GARRISON
FORT IRWIN, CA 92310-5000

December 6, 2017

Tim Tetreault, CEM
ESTCP Energy and Water Program Manager
4800 Mark Center Dr., Suite 17D08
Alexandria, VA 22350-3605
(571) 372-6397

Subject: Hygroscopic Cooling Tower for Reduced HVAC Water Consumption

Reference: Department of Defense Environmental Security Technology Certification Program (ESTCP) Project Number EW-201723

Dear Mr. Tetreault,

Fort Irwin, California is submitting this letter as evidence of commitment to host the subject demonstration project being conducted by the Energy & Environmental Research Center (EERC) and the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), and that is sponsored by the ESTCP. This project will demonstrate the installation, operation, performance, and maintenance of an advanced cooling tower technology.

Fort Irwin is an ideal representation of an extreme hot and arid climate with operational challenges due to the remote location and limited access to water resources. This project will enhance the ability of DoD and Fort Irwin to improve energy security and operational resilience by reducing water usage and intensity. Key points regarding the demonstration are summarized below. Further integration details are provided in the attached enclosure.

- The demonstration cooling tower will be sited at Fort Irwin Bldg. 263, which is a heating and cooling plant for barracks and a dining facility.
- The demonstration is planned to commence by summer 2018 and run through summer 2019.
- The demonstration tower will be installed upstream of the existing cooling tower in Bldg. 263, thereby reducing the cooling load on this tower but not replacing it. As a result, cooling will not be in jeopardy even if the demonstration tower is not in operation or does not meet expectations.
- Manual shut-off valves will be installed to isolate the demonstration system if required.
- The EERC and ERDC-CERL team will be responsible for data collection and maintenance of the demonstration equipment.
- Data will be logged using an independent instrumentation system and will be relayed offsite using an EERC-provided cellular internet modem.
- All equipment will be removed from Bldg. 263 at the conclusion of the demonstration. Fort Irwin may choose to keep the equipment.

Fort Irwin will support the demonstration by coordinating installation access for EERC and

ERDC-CERL team members and associated contract support, by assisting with project planning, and by providing feedback to support the objectives of the demonstration. Fort Irwin's primary point of contact for this project will be Mr. Christopher Woodruff, Project Manager, Directorate of Public Works. We look forward to working with EERC and ERDC-CERL on this project.

Sincerely,

Muhammad A. Bari, P.E.
Director of Public Works

HEADQUARTERS
DEFENSE HUMAN RESOURCES ACTIVITY
4800 MARK CENTER DRIVE, SUITE 06J25-01
ALEXANDRIA, VA 22350-4000

March 8, 2018

Tim Tetreault, CEM
ESTCP Energy and Water Program Manager
4800 Mark Center Dr., Suite 17D08
Alexandria, VA 22350-3605
(571) 372-6397

Subject: Hygroscopic Cooling Tower for Reduced HVAC Water Consumption

Reference: Department of Defense Environmental Security Technology Certification Program (ESTCP) Project Number EW-201723

Dear Mr. Tetreault,

As the cognizant installation official for DoD Center Monterey Bay, I submit this letter as evidence of commitment to host the subject demonstration project being conducted by the Energy & Environmental Research Center (EERC) and the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), and that is sponsored by the ESTCP. This project will demonstrate the installation, operation, performance, and maintenance of an advanced cooling tower technology.

DoD Center Monterey Bay presents a marine climate with moderate year-round temperatures and is representative of many coastal locations with limited access to water resources. This project will enhance the ability of DoD to improve energy security and operational resilience by reducing water usage and intensity. Key points regarding the demonstration are summarized below. Further integration details are provided in the attached preliminary demonstration plan.

- The demonstration cooling tower will provide heat rejection for two, water cooled chillers that meet the air conditioning needs of DoD Center Monterey Bay.

- The demonstration tower will be installed upstream of an existing cooling tower, thereby reducing the cooling load on this tower but not replacing it. As a result, chiller cooling will not be in jeopardy even if the demonstration tower is not in operation or does not meet expectations.

- Manual shut-off valves will be installed to isolate the demonstration system if required.

- The EERC and ERDC-CERL team will be responsible for data collection and maintenance of the demonstration equipment.

- Data will be logged using an independent instrumentation system and will be relayed offsite using an EERC-provided cellular internet modem.

- The demonstration is planned to commence by summer 2018 and run through summer 2019.

- All equipment will be removed at the conclusion of the demonstration.

DoD Center Monterey Bay will support the demonstration by coordinating installation access for EERC and ERDC-CERL team members and associated contract support, by assisting with project planning, and by providing feedback to support the objectives of the demonstration. The primary point of contact for this project will be Mr. John Wallingford, Facility Manager, Mission Support Directorate, Defense Human Resources Activity. We look forward to working with EERC and ERDC-CERL on this project.

Sincerely,

Elizabeth A. Mazik
Chief, West Coast Operations
Mission Support Directorate