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For Immediate Release

Contact: Chairman, CTI Multi-Agency Testing Committee

Houston, Texas
2-September-2015

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I hope that everyone is enjoying Summer 2015 and I want to offer my sincere appreciation for all of the member companies for supporting attendance at our recent Committee Workshop at the Tradewinds Island Resort in St. Pete Beach, Florida. We had an excellent turnout with over 100 attendees which resulted in significant progress being made by each of our three (3) standing committees; Performance & Technology, Engineering Standards and Maintenance and Water Treating, updating and completing several standards and guidelines.

The sphere of technical influence of CTI codes and standards continues to expand worldwide as demonstrated in growth of our international membership, Cooling Tower Certification Program, collaboration with Eurovent and recent discussions with the Chinese Cooling Tower Industry Association during the CTI 2015 Committee Workshop.

The CTI is 65 years old in 2015. I am pleased to report that the Cooling Technology Institute continues to produce Codes, Standards and Guidelines that are referenced in specifications and procurement documents world-wide and is financially sound which is a testament to the hard work of its many volunteer members and office staff in Houston, Texas.

Planning for the CTI 2016 Annual Technical Meeting scheduled for February 7-11, is well under way. Our program Committee has received a number of excellent abstracts for potential presentation and many of the available 56 table top exhibit spaces have been reserved. If your company has not yet reserved a table, please do so while openings still are available.

Enjoy the rest of the summer and thanks again to all of the participants in our very successful Committee Workshop. As I have mentioned in past articles, please feel free to contact me if you have any ideas, suggestions and/or concerns about CTI that you would like to discuss.
Thinking...

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Dear Journal Reader,

Another progress update on key activities at CTI:

CTI Sound Testing: The Licensed Sound Testing Program by CTI is off to a good start, after the official launch on January 1, 2015. There are now three test agencies licensed, two of which are CleanAir and McHale, with whom many of you are familiar. The third is a joint license to CTTA, Tom Weast and Nick Stich, with whom many of you are also familiar, and with SSA Acoustics, a sound testing company. Contact information for these companies is on the CTI website and in this Journal. CTI strongly encourages the specification of CTI ATC-128 Licensed third party sound testing by owner/operators and EPCs, and as importantly the execution of the specified tests.

DOE Fan Rule: CTI Members should be aware that a Department of Energy rulemaking is in progress with regard to fans, which includes at this point the manufacturers of cooling towers, closed circuit coolers, evaporative condensers, air cooled heat exchangers, air cooled refrigerant and steam condensers, and any hybrid of the above that moves air with a fan or blower. A working group of CTI members under the Strategic Issues Task Force developed a position paper which was filed with the DOE, and led to CTI representation (Larry Burdick(SPX, member), and Frank Morrison (BAC, alternate) on the negotiation working group under DOE auspices which is now in progress. The target date for closure on their activity is early August, 2015. CTI has asked for exemption of heat rejection equipment from the rule, but this may or may not happen, and fans used in the equipment are likely to be included in any event. AMCA has represented fan manufacturers on the negotiation up to formation of the current working group. CTI members who produce fans for any purpose should be aware that they are likely to be affected by this rulemaking, which will set minimum fan efficiencies by equipment types. The legal basis for this goes back to the same law from the 70s which has been used to regulate motors for some time, but which included broad coverage of fans, compressors, pumps, commercial boilers, and other equipment types, not been applied until now. The rule as currently envisioned by DOE considers anyone who puts a fan or blower impellor with a drive and/or motor in some sort of housing to be a fan manufacturer, who would be expected to certify the performance of their equipment with validation testing by the DOE. A proposal by AMCA and a group of energy advocates would push much of this responsibility toward the impellor manufacturers to certify performance in various defined testable configurations. Manufacturers such as those making cooling towers could be required to use DOE certified impellors under this proposal. For more information, contact Larry Burdick, Frank Morrison, or me.

CTI Research Update: A research grant has been awarded to CleanAir, from amongst those who responded to the CTI RFP, to complete Pitot tip investigations to find a replacement for the (no longer commercially available) Simplex tip, which has been the CTI water flow measurement standard. The project has reached its first milestone, the submittal of the Project Implementation Plan. It has been reviewed and acceptable responses received to comments. CleanAir is proceeding with the project and has begun fabrication of the two tip designs being evaluated. For those who may be unfamiliar with this, it is the first research project developed under the relatively new CTI Research and Development Committee. Projects are proposed via the standing technical committees, and proceed through a process administered by the R&D committee. Funding is raised and administered via the CTI Finance Committee. Other projects are under consideration, and new ones may be proposed within the standing technical committees at any time.

There is much happening with the very active CTI volunteer technical organization; we encourage you to get involved in the CTI technical committees.

Respectfully,

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Cooling Tower Support Framing Systems: Distress and Repair

Narendra Gosain, Ph.D., P.E.
Ray Drexler, P.E.
Walter P. Moore and Associates, Inc.

Abstract
Other than specifying the loads and support points for the cooling towers, the cooling tower manufacturer has very limited involvement in the structural design of support framing for commercial type cooling towers. Over a period of time, the cooling towers themselves undergo the required maintenance, but their support framing is often neglected. As such, extensive deterioration and distress is frequently observed in cooling tower support structures.

Restoring the integrity of the cooling tower support framing becomes very costly and time consuming. In order to continue operations of the cooling towers, temporary shoring of the support framing may be needed while the severely distressed framing members are being strengthened or replaced. Work often includes replacement of the deteriorated vibration isolation springs and damper boxes making the restoration work even more complex. Three case histories are presented that illustrate the varying degrees of distress, why the distress occurred and the methods used to restore the structural integrity of the support framing.

Design Of New Cooling Tower Framing
The process of starting the structural design of a new cooling tower framing begins with the assistance of a mechanical engineer who must consider the geographical region, occupancy, usage, type of construction, and volume of space to be conditioned before performing building heat load calculations which will ultimately determine the heat rejection that the cooling tower will see. The mechanical engineer will then select a cooling tower with the assistance of cooling tower manufacturers that will meet the needs of the project based on the calculated entering and leaving water temperatures from the cooling tower as well as the ambient air temperature for the project location. The cooling tower manufacturer will provide cut sheets for various types of cooling towers (Fiberglass, Wood, Field Erected, Pre-Manufactured, etc.) that meet the mechanical engineer’s requirements. Once a cooling tower is selected that meets the capacity requirements and the type of cooling tower to be used is determined, the mechanical engineer, structural engineer, and the manufacturer work collaboratively to get the following information that will be required for the structural design of the cooling tower support framing:

- Number of cooling tower cells and the overall plan dimension of the cooling tower.
- Gravity loads, snow loads, and lateral loads from wind and seismic forces that will be imposed on the support framing from the cooling tower.
- Support locations of the cooling tower and how the cooling tower will be mounted to the support framing, including tower anchorage bolt sizes and bolt spacing.
- Obstructions and clearances required for the related Mechanical, Electrical, and Plumbing (MEP) layouts such as power, piping, and controls.
- Deflection criteria of the support framing, if critical.
- Vibration isolation requirements.

Typical information from the cooling tower manufacturer’s engineering data book may have the information as shown in Table 1 to assist the mechanical engineer and the structural engineer for their preliminary design work.

When the manufacturer’s data book does not provide information on the location or details of the cooling tower support points, the applied gravity and lateral loads at the supports are then specifically requested by the structural engineer from the manufacturer along with the required cooling tower anchorage details.

Regardless of whether the cooling tower is made of wood, steel, concrete, or composite fiber reinforced polymer material, the supports are typically made of reinforced concrete or steel framing or a hybrid system of steel framing supported on concrete pedestals or stub columns.

Figure 1 shows an example of a cooling tower supported on a steel frame with concrete stub column supports. Such a hybrid framing system is very typical of ground supported and roof mounted cooling towers for reinforced concrete buildings and garages. The building columns are generally extended above the roof level to support the cooling tower. In parking garages where the columns are spaced further apart, transfer girders may be used to support the cooling tower or certain members of the garage roof framing designed for heavier loads to accommodate the cooling tower framing.

In steel framed buildings, the steel columns may be extended above the roof for the cooling tower support framing or stub columns may be mounted to the steel roof girders or transfer beams. Such framing drawings will often have general notes accompanying the structural plans and details. The notes describe the cooling tower manufacturer and model for which the framing has been designed along with the locations of support points and loading. Other relevant and important items pertaining to the framing not covered in the project technical specifications are given in these notes. Considering that the cooling tower is exposed to the environment and constantly subjected to moisture, the structural steel must be well protected from corrosion.

In certain instances where there are architectural constraints and a conventional cooling tower is not acceptable from an aesthetic point of view, a customized concrete box cooling tower may be preferred. The structural engineer of record performs this type of design working collaboratively with the mechanical, electrical, plumbing (MEP) engineer of record. Figures 2a, 2b, 2c and 2d show...
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an example of such a concrete cooling tower. The general notes in Figure 2d highlight some steps taken to provide durability to the water retaining structure and the cooling tower framing. Additionally, there are other precautions that provide enhanced durability for such concrete framed cooling towers.

Another important aspect of the conventional cooling tower is the design of base vibration isolation system. The structural framing has to accommodate such a system as well as its mounting requirements. If not isolated, the vibrations can be a nuisance to the occupants of the facility or interfere with other operations.

Noise control is another important aspect of design. Cooling towers are often close to the property line or office windows, where noise from the cooling tower fans can cause a problem. For a roof mounted cooling tower, the structure borne noise needs to be mitigated in the design phase of the project. Noise control can be rather difficult once the structure is built.

Even though the design of the framing is considered simple, the work has to be well coordinated between the various disciplines of engineering and contractors involved with the project to accommodate the various piping, wiring, mechanical controls, electrical equipment, access requirements, and service clearances.

**Design For Strength And Serviceability**

All structures are designed for strength and serviceability. Understandably, there are two types of issues that can occur when cooling tower support structures are not adequately designed:

- **Failure**: A mishap that combines human error with mechanical or material malfunction. This mishap results in the collapse of the structure and is generally strength related either due to some shortcomings in the materials of construction or structural design of the support structure, or changes in the cooling tower loadings that were not communicated to the structural engineer prior to construction.

- **Performance**: This is a lack of fulfillment of a deed or promise in which the owner’s serviceability expectations of the structure are not met. Such performance issues could be due to excessive deflections, vibrations, sway during wind events, corrosion of steel elements, and corrosion of reinforcing bars in concrete that lead to damaging spalls in concrete. When not addressed and corrected in a timely manner, such performance related issues have the potential of causing collapse of the cooling tower support structure.

Although there are no documented failures of cooling tower support structures, there are several examples of performance related issues associated with deferred maintenance. Three cases will be discussed for illustration purposes.

**Durability And Maintenance**

Upon project completion and as per the requirements in the project specifications, the owner is provided with a warranty for the cooling tower. Also included are manuals for the cooling tower operation and maintenance requirements. These manuals describe the scheduled maintenance requirements for mechanical and electrical equipment as well items such as drift eliminators and fill material.

The facility maintenance personnel generally keep up with the operational aspects of the cooling tower but its support structure is often forgotten. This “forgetfulness” may be due to lack of funding by management or the failure to recognize the operational importance of keeping up with the support structure maintenance to prevent disruption of services normally expected from a cooling tower. This lack of a “maintenance manual” for the structure may also be a significant part of the “forgetfulness”. A “maintenance manual” is traditionally not provided by the structural engineer of record since it is generally not considered to be within the scope of their services. Such a document can be provided by the engineer for a nominal additional fee. Having such a document will provide a road-map to the facility management group for maintaining the support structure as well. This will save the owner a significant amount of money and other valuable resources in the future if the maintenance items specified in the manual are diligently executed on an ongoing basis and not deferred until a problem is observed.

It needs to be emphasized that it is not just the maintenance personnel that have the responsibility for ensuring satisfactory performance of the supporting structure; the task really starts with the design professional designing the structure not just for strength and deflection limits but also for durability.

A durable structure is expected to perform satisfactorily with minimal maintenance over its anticipated life. Regrettably, in the process of design, the term “minimal maintenance” is often times forgotten by the design professional. There is a belief that all matters pertaining to maintenance is the responsibility of the building owner once the project is completed and hence not important in the original design. However, this thinking is not rational. Designing for durability is a collaborative process involving the owner, structural engineer, MEP engineer, vibration and acoustic consultant, as well as the facility maintenance staff that will have overall responsibility to maintain the facility once it is built. Contrary to the common misconception that the cost of the supporting structure will increase substantially by incorporating some durability aspects into the structure, the actual cost differential is generally nominal. Some simple features in the original design that can extend the useful service life of the support structure are as follows:

- **Steel Structures**
  - Hot-dip galvanize structural steel for all steel framing members and connections after the steel is cut and fabricated.
  - All steel plates and other such steel elements embedded in concrete for connections not exposed to circulating water from the cooling tower should also be hot-dip galvanized after fabrication with their anchors. Embedments exposed to circulating water shall be of stainless steel or other non-corrosive materials appropriate for use with the water chemistry. In order to prevent galvanic corrosion action, there shall be no direct contact of stainless steel or other such material used as embedments with galvanized structural steel.
  - All bolts, washers, and nuts shall be galvanized.
  - In boxed steel sections or steel sections where the webs of wide flange and channel sections are horizontal and in areas where there is a potential for stagnation of water, provide drainage holes and slopes for water to drain.
  - Eliminate weld connections were possible.
  - All field welds shall be coated with zinc rich or cold galvanizing paint.
  - Do not use intermittent fillet welds. All welds need to be continuous to prevent entrapment of water.
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  o Use the largest size aggregate permissible for the size of element cast.
  o Use shrinkage reducing admixtures (SRA) to control cracking due to shrinkage.
  o Use air entraining agents (AEA) in regions susceptible to freeze-thaw conditions.
  o Use moisture curing or cover concrete with moisture retaining cover in accordance with ACI 301 (Reference 2).
  o Use clear covers to reinforcing bars that exceed the typical covers provided in ACI 318 (Reference 3). Some recommended covers based on the authors experiences are as follows:
    • Structural slabs: 50 mm (2”) top and bottom
    • Beams and girders: 70 mm (2.75”) top; 50 mm (2”) bottom and sides
    • Columns: 50 mm (2”)
    • Walls: 50 mm (2”)
  o Depending on the exposure condition and water chemistry, consideration should be given to the use of epoxy coated reinforcement conforming to ASTM A184 (Reference 4).
  o Use only plastic or stainless steel bar support chairs. Stainless steel chairs should not contact carbon steel or galvanized steel bars.
  o Tie wires shall be non-corrosive. Use stainless steel tie wires with stainless steel reinforcing bars or galvanized wires with galvanized bars to minimize the potential for galvanic circuits (corrosion).
  o Remove all wall form ties and nails used in formwork.
  o Consider the use of coatings, penetrating sealers, or other crystalline waterproofing materials on exposed concrete surfaces for additional protection against moisture infiltration into the concrete.
  o For additional durability requirements for concrete used in a cooling tower environment, refer to CTI document ESG-153 (Reference 5).

• Quality Control during Construction: In most contracts, the site visits by the structural engineer of record during the construction phase is very nominal, generally once or twice a month. It is recommended that the engineer be retained to provide more frequent site visits. In addition, it is also important to engage a testing laboratory to perform material testing of the various elements as specified in the technical specifications prepared by the structural engineer. Some important items that need to be observed at the construction site are:
  o Structural Steel: Proper galvanizing, bolting, and welding of steel.
  o Reinforced Concrete: Use of the right concrete mix; use of proper bar support chairs and tie wires; proper placement and cover provided for the reinforcing bars; proper placement and compaction of concrete; proper curing of concrete.
  o General Construction: For both roof mounted and ground supported cooling towers, ensure that there is adequate drainage away from and around the support columns. This is particularly important in steel column supports where the stagnant water can corrode the steel section.

High Cost Of Deferred Maintenance

Once a scheduled maintenance plan is developed for the support structure, it should be funded adequately and executed faithfully. Not performing the maintenance as scheduled or postponing for a later date is often referred to as “deferred maintenance”. This is true for even those structural elements that are designed with built-in durability. The difference may be the frequency and extent of maintenance requirements.

It is to be understood that in spite of the built-in durability and best practices followed in the design and construction, if the support structure is not adequately maintained, the aggressive environmental conditions can and will attack the best designed support. Cracks and spalls in concrete elements and corrosion of unprotected or poorly coated structural steel elements and connections will occur without proper maintenance. There is also the potential of shift and movement of reinforcement during concrete placement which may result in smaller concrete covers than specified.

Cost of deferred maintenance is best described conceptually and qualitatively in Figure 3 taken from Reference 6. This has been slightly modified by the authors. All structures deteriorate over time. This is shown by the curve marked X. The degradation rate of a structure designed for durability deteriorates at a slower rate shown by the curve marked Y. The curve marked ABCD shows that if the structure is not maintained proactively, the deterioration/repair cost will escalate exponentially. If there is intervention at an early stage of its life at point A, the repair cost will be much lower than that indicated by curve ABCD. If intervention is at the later stage point B, then the repair cost will be greater than A’ curve but lower than the curve ABCD.

It is regrettable that the development of proactive maintenance plans for exposed structures is often not a priority with most facility managers. David Geaslin of the Geaslin Group (Reference 7) has developed a simple rule that shows that the time and cost to recover from problems caused by deferred maintenance...
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is huge compared to time and cost to avoid the problem. This is called the Inverse Square Rule for Deferred Maintenance which states that “If a part is known to be failing and the repair is deferred and allowed to remain in service until the next level of service, the resultant expense will be the square of the failed part” as illustrated in Figure 4. Geaslin essentially developed this rule for mechanical equipment. However, an example of such cost of deferred maintenance for a structural condition is given in Reference 8. “If a missing bolt is found in a beam connection supporting a floor, and the cost to replace this is $100 but not done in a timely manner, then the cost of fixing the entire connection due to consequent failure of other bolts due to overstress and other related cost may be as much as $100 x 100 = $10,000”. Figure 4 also illustrates the observation made by Geaslin that the “deferred cost of repair is 15 times the cost of parts and labor when problem is first detected.” Some additional comments on deferred maintenance are also presented in Reference 8.

Case Histories

Three examples given below describe case histories of cooling tower support structures where intervention was done at various stages of their service life to extend their functionality. The degree of deterioration varied from moderate to extreme with the commensurate levels of required repairs.

Case History 1: Customized Concrete Cooling Tower

Figures 5a, 5b, 5c, and 5d (respectively) show the Lower Level, Level 2, Roof Level, and a longitudinal section of a 4 cell cooling tower constructed in 1987. Level 2 is 7.30m (21'-0") above the Lower Level; Fan Level or Level 3 is 5.50m (18'-0") above Level 2 and the Roof Level (Grating Level) is 2.70m (9'-0") above the Fan Level. The Lower Level is approximately 4.30m (14'-0") below grade. All perimeter walls and interior walls are 30 cm (12") thick.

This cooling tower had several of the built-in durability features as described above in the section on Durability and Maintenance. No SRA or epoxy coated bars were specified for this concrete cooling tower. CTI document ESG-153 (Reference 5) was also not published at the time the cooling tower was designed.

Other than the standard construction administration services, no enhanced site visits were performed by the engineer of record. The testing laboratory also provided just the routine material testing. The owner performed routine maintenance only on a regular basis.

Detailed specifications were provided for waterproofing the concrete walls, slabs, beams and foundation basin within the cooling tower. Some clauses in the specification are described below:

- Water Test: Prior to application of the waterproofing material, the general contractor shall fill the four cells of the cooling tower with water up to a depth of 4.30m (14'-0") feet prior to backfilling behind the cooling tower walls. The chemical waterproofing applicator shall supervise the water test and determine water-tightness of the cells prior to application of waterproofing. Waterproofing applicator shall provide appropriate details for water-tightness at any detected leaks.
- Material used for waterproofing shall be a cementitious coating containing catalytic chemicals which migrate into the concrete using moisture present in the concrete as the migrating medium, and which cause the concrete to react causing the growth of non-soluble crystals to prevent passage of water.
- Material shall be effective in providing waterproofing against no less than 3.60m (12'-0") static head of water.
- Concrete surfaces to be waterproofed shall be free of defects such as honeycombing, rock pockets, and cracks.
- Concrete surfaces shall be free from scale, form oil, lacquer, and other foreign matter.
- Surfaces to be treated with waterproofing shall be wetted such that the moisture is absorbed into the concrete. All free water shall be removed prior to the application of the waterproofing material.
- Apply one slurry coat of the waterproofing material at the rate of about 0.80 Kg per square meter (1.50 pounds per square yard) of the concrete surface. After the first coat has set but while it is still green, apply a second coat at the same rate as the first coat.
- Curing shall begin as soon as the waterproofing material has set up sufficiently so as not to be damaged by the moisture curing methods.
- Curing shall continue for a minimum of 3 days and then shall be allowed to set for 12 days before filling the structure with water or installing any equipment in the cooling tower.
- Use fans for air circulation within the cooling tower to aid in curing of the waterproofing material.

In 2013 approximately 27 years after it was built, the facility management staff noted some corrosion and spalling of concrete. The original engineer of record was engaged by the owner to do an assessment of the noted distress and then provide restoration services. Use was made of Non Destructive Evaluation (NDE) procedures to determine the extent of the noted distress and the reason for such distress. Ground Penetrating Radar (GPR) was used to check for concrete cover in areas of noted distress and non-distressed areas to establish a benchmark. Half-cell potentiometer was used to check for the potential rate of corrosion. Figures 6a, 6b, and 6c show photographs of some typical distressed areas in walls and beams. It was noted that where the spalls in concrete had occurred in the floors and walls, the reinforcement cover was inadequate and not as specified in the drawings. Wall concrete spalls were primarily between the Lower Level and Level 2. However, the spalls in beams appeared to be random in nature and no clear pattern was seen. No distress was observed at Level 3 which is the Fan Level.

The extent of the distress noted was minimal. Only a total of about 39.00 square meters (420 SF) of wall surface and 8.40 square meters (90 SF) of beam surfaces needed repair. Repair
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locations at lower, second, and roof levels (respectively) are shown in Figures 5a, 5b, and 5c. All the deteriorated concrete nodes at the intersection of walls and intersection of walls with slabs were specified to have new concrete joint sealants in the repair documents. Typical repair details of concrete spalls in floor, beams and walls are shown in Figures 7a, 7b, and 7c (respectively). Where the reinforcement cover was found to be deficient, additional repair work was provided to build-up the cover as shown in these details. This changed the profile of the surface which was acceptable to the owner. Prior to performing repairs, surface preparation was performed in accordance with the project documents and ICRI Guidelines (Reference 9). Several task items were identified on the plan drawing shown in Figure 5a, 5b and 5c and are also listed in Table 2.

**Case History 2: Repair of Moderately Maintained Hybrid Cooling Tower Support Framing**

This is a roof mounted cooling tower support system with concrete pedestals supporting steel framing as shown in Figure 8. This cooling tower is located in the environmentally aggressive region of the Gulf Coast close to the shoreline. An overall photographic view of the cooling tower is shown in Figure 9a. Even though some of the wooden elements of the cooling tower itself had some problems (Figure 9b), the structural steel support framing was in a reasonably good condition. This 28 year old structure appeared to have been well designed in the sense that all structural steel was hot dip galvanized. However, some omissions were observed which appeared to be generally construction related:

- Bolts, nuts, and washers were either not galvanized or were inadequately galvanized (Figure 9c).
- Shim plates were not galvanized (Figure 9d).
- Field welds not protected by zinc rich paint (Figure 9e).
- Spalls in concrete pilaster caused by corrosion of non-galvanized embedded plate (Figure 9f).
- Use of non-galvanized structural steel for miscellaneous framing (Figure 9g).
- Inadequate concrete cover to reinforcing bars in concrete pilasters supporting steel framing (Figure 9h).

On noting the spalls in the concrete pedestals, the facility management recognized that some repairs were needed to maintain the integrity of the cooling tower support framing. Engineers were retained in 2010 to perform an evaluation of the existing distressed conditions and develop drawings for repair and restoration of the framing system. Several task items identified on the plan drawing (Figure 10) by the engineers are listed in Table 3. Figures 11a through 11c show typical repairs required which were included in the bid documents along with detailed repair specifications.

**Case History 3: Repair of Poorly Maintained Steel Cooling Tower Support Framing**

A partial view of the cooling tower is shown in Figure 12a. This is a roof mounted cooling tower support system with steel pedestals supporting two levels of steel framing as shown in Figure 12b. This 30 year old structure is located in the Gulf Coast region. The upper level steel grillage was specified as hot dip galvanized wide flange beams with bolt holes and was designed to support the specified cooling tower. This upper level steel grillage was supported by 20 hot dip galvanized isolator springs. These springs sat on a lower level steel frame (that for unknown reasons were not called out to be hot dip galvanized) supported by 8 columns. Figures 12a and 12b illustrate the two level framing configurations.

The upper level steel grillage is painted gray with galvanized isolator springs and boxes that are not painted. The unprotected lower level steel frame, interior columns, and the K-bracing are also shown in these figures. Following the limited observations of the corrosion related distress at the cooling tower support structure, as well as a brief review of the structural drawings, the engineers opined that the structural integrity of the cooling tower support framing had been significantly compromised. The engineers further recommended the cooling towers be expeditiously shored to restore a safe load path for the supported cooling towers until a permanent repair solution could be designed and implemented. The original outer 4 corner columns sat on roof beams while the original inner 4 columns were extensions of the building columns through the roof. K-bracing was provided between the extended building columns to transfer the lateral loads from the lower level steel frame level to the roof diaphragm level. The cooling tower cells still sit on the original hot dip galvanized upper level steel grillage but the original, non-galvanized, lower level steel frame, 8 columns, bracing, and isolator springs required removal.

After several decades of less than optimal maintenance a significant domino effect had occurred. In addition to the damage to the cooling tower framing structure (Figure 13a), the springs and their housings (Figure 13b) as well as the roof deck penetration points (Figure 13c) exhibited structural distress that required repair. Additionally, part of the roof metal deck and steel framing below the concrete slab exhibited evidence of light corrosion damage. Fortunately, this distress below the roof slab that would normally have remained hidden was discovered during the investigation phase and the required corrective actions were relatively minor at this stage.

Rather than hot dip galvanizing the structural steel or providing periodic repainting of the lower level steel frame, the originally selected “waterproofing system” for the lower level steel frame consisted of styrofoam type blocking between the steel section flanges held in place by a grease/tar impregnated cloth (similar to a fiber based duct-tape) wrapped around the full steel section (Figures 14a and 14b). Rather than keeping moisture out, the wrap and foam effectively trapped moisture and promoted corrosion. Additionally, the wrap concealed the ongoing distress which remained hidden from view for many years.

The engineers performed structural analyses to determine potential shoring solutions that maintained the cooling tower in place and minimized the impact of repairs on tower and tenant operations. This included performing field verification of the roof level framing condition from the occupied level below at night to assist in the structural analyses for the implementation of the
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selected shoring system. The engineers also worked collaboratively with a construction contractor to vet the constructability for the proposed shoring and repairs as they were being developed based upon the results of the engineering analyses and assessments. After reviewing the field conditions and existing drawings, construction drawings and specifications were developed to provide the roof framing strengthening required for supporting the temporary shoring loads. This would then allow the installation of a new lower level cooling tower hot dip galvanized steel frame support between the roof and existing upper level steel frame that was remaining. The major repair steps included:

- Provide temporary piping to maintain cooling tower operations.
- Strengthen roof framing to support temporary shoring and new cooling tower framing (Figures 15a, 15b, and 15c).
- Provide temporary shoring between existing cooling tower framing and roof deck (Figures 16a and 16b). This shoring was provided to maintain integrity of the load path between the upper level cooling tower framing and the roof deck framing while repair solutions were being developed and installed.
- Fabricate and install new structural frame to support existing cooling tower (Figures 17a and 17b).
- Fabricate and install new hot dip galvanized cooling tower vibration isolation boxes (Figure 18a and 18b).
- Structural testing and inspections of welds and bolting.
- Remove temporary shoring.
- Demolition and disposal of original lower level cooling tower support framing (Figures 17a and 17c).
- Install piping and control wiring in their final locations.

Figures listed above show typical required repairs included in the bid documents for repair as well as typical repaired conditions. Note the increased clearance below the lower level steel frame supporting the upper level steel grillage and cooling tower cells (Figure 19). This allows for easier inspection of the support frame and access for future maintenance. In order to maintain this clearance (Figure 19), the new lower level steel framing members were placed at two different levels (Figure 18b).

**Conclusions**

Structural design of cooling tower support structures is not complex once the gravity and lateral load conditions are determined. What requires careful consideration is how to design for durability in both steel and concrete framings. Even though the cooling tower may not be located in a coastal region, the fact is that the supporting structures are in humid and potentially aggressive environments that promote corrosion.

Some simple techniques for preventing corrosion of embedded reinforcement in concrete structures include the use of normal weight concrete with low water cement ratio, galvanized or epoxy coated reinforcing bars, proper curing techniques, and the use of shrinkage reducing and/or permeability reducing admixtures.

In steel framing, the use of hot dip galvanizing is a very economical method to add durability. In such steel structures, all bolts, nuts, washers, connection plates and shim plates should also be protected by galvanizing. All field welds also need to be coated with zinc rich paint or other similar protective coating.

It is imperative that cooling tower support structures also have scheduled maintenance to avoid high costs of emergency repairs.

**Acknowledgements**

The authors gratefully acknowledge the help given by Mr. Karim Zulfiqar, P.E., Principal, and Enrique Vaca, Ph.D., P.E., Senior Associate of Walter P Moore in discussing some of their experiences in designing and repairing some cooling tower support framing. We also appreciate the review done by Marvin Leach P.E., LEED AP of I A Naman + Associates, Inc. on the process used in designing a cooling tower from the perspective of a mechanical engineer. Examples used to describe the cooling tower support framing and the case histories discussed are from the archives of Walter P Moore with the exception that the original cooling tower support framing of Case History 3 was designed by others.

**References**

2. ACI 301-10: Specification for Structural Concrete
3. ACI 318-11: Building Code Requirements for Structural Concrete and Commentary
5. “Recommended Guidelines for Portland Cement Concrete for Mechanical Draft Cooling Towers”, Cooling Tower Institute, ESG-153 (07)
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1. The cooling tower support framing has been designed for Model XYZ manufactured by Best Cooling Tower Company. General Contractor shall coordinate with the mechanical contractor to verify model used for the project. Structural engineer of record shall be notified immediately of any deviations from this requirement prior to fabrication of structural steel.

2. Cooling tower support points for the cooling tower referenced above are noted as A.

3. Loads at these support points
   a. Vertical: 16 Kips
   b. Horizontal: 3 Kips both north-south and east-west directions

4. Placement of cooling tower on frame: The center-line of cooling tower support legs shall coincide with the center-line of the support points of framing

5. Notify structural engineer of record immediately of any deviations from the requirement of placement of cooling tower supporting legs after erection of cooling tower

6. All structural steel, connection plates and angles shall be hot-dipped galvanized after fabrication

7. All bolts and washers shall be hot dipped galvanized

8. All field welds and field-cut surfaces of steel shall be coated with zinc-rich paint
General Notes
1. All reinforcing used in the concrete elements of the cooling tower shall be epoxy coated bars.
2. Concrete strength shall be 28 MPa (4,000 PSI) at 28 days
3. Water cement ratio for concrete shall be limited to 0.4
Figure 4 - Geaslin’s Inverse Square Rule for Deferred Maintenance

Figure 5a - Customized Concrete Cooling Tower Lower Level Repair Plan

Figure 5b - Customized Concrete Cooling Tower Level 2 Repair Plan

Figure 5c - Customized Concrete Cooling Tower Grating/Roof Level Repair Plan

Figure 5d - Customized Concrete Cooling Tower Longitudinal Section

Figure 6a - Typical Wall Distress Photograph identified in 2013

Figure 6b - Typical Wall and Cove Joint Distress identified in 2013
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Figure 6c- Typical Beam Distress Photograph identified in 2013

Figure 7a- Typical Concrete Floor Spall Repair

Figure 7b- Typical Concrete Beam and Girder Spall Repair

Figure 7c- Typical Concrete Wall Spall Repair

Figure 8- Hybrid Cooling Tower Support

Figure 9a- Overall View of Cooling Tower

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Figure 9b- Wood Elements of Cooling Tower supported on Galvanized Steel Frame

Figure 9c- Corroded Nuts and Bolts

Figure 9d- Corroded Shim Plates

Figure 9e- Inadequately Protected Field Welds

Figure 9f- Corrosion of Non-Galvanized Embedded Plate in Concrete Causing Spalling

Figure 9g- Use of Non-Galvanized Steel Bracing Angles

Figure 9h- Inadequate Cover to Reinforcing Bars
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 Field Erected, Counter Flow, Steel Tower
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Figure 10- Repair Required to Cooling Tower Support Framing

Figure 11a- Concrete Pilaster Repair/Repair of ΩConnection of Steel Beam W14 to Pilaster

Figure 11b- Corroded Bolt Replacement

Figure 11c- Corroded Bolt Replacement, Repair of Steel Beam to Pilaster Connection and Brace Angle Connection Repair

Figure 12a- Partial View of Cooling Tower

Figure 12b- Partial View Showing General Layout of Cooling Tower Framing and Offset Building Framing (Column Stubs Above Roof Line)
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Figure 13a- Typical Distress of Cooling Tower Framing

Figure 13b- Typical Cooling Tower Spring and Housing Distress

Figure 13c- Typical Cooling Tower Stub Column Corrosion at Roof Deck

Figure 14a- Original “Waterproofing” Consisting of Styrofoam Type Blocking Between Steel Section Flanges Held in Place by a Grease/Tar Impregnated Cloth

Figure 14b- Original “Waterproofing” Remnant of Lower Level Steel Framing

Figure 15a- Roof Frame Strengthening to Support Temporary Shoring and New Cooling Tower Framing (See Figure 15b for Kicker Connection Section Detail)
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Figure 15b- Roof Frame Strengthening and Bracing to Support Temporary Shoring and New Cooling Tower Framing (See Figure 15a for Locations)

Figure 15c- Installed Roof Frame Strengthening and Bracing to Support Temporary Shoring and New Cooling Tower Framing (See Figure 15a for Locations)

Figure 16a- Temporary Shoring between Existing Cooling Tower Lower Level Framing and Roof Deck to Maintain Structural Integrity

Figure 16b- Installed Temporary Shoring and Roof Penetration for new Stub Column (Not Yet Installed)

Figure 17a- New Hot Dip Galvanized Lower Level Steel Frame and Original Non-Galvanized Lower Level Steel Frame Prior to Removal

Figure 17b- Installation of New Hot Dip Galvanized Lower Level Steel Frame to Support Existing Cooling Tower
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Figure 17c- Demolition and Removal of Original Non-Galvanized Lower Level Steel Frame

Figure 18a- New Cooling Tower Vibration Isolation Spring Box and Column Assembly

Figure 18b- Installed New Cooling Tower Vibration Isolation Spring Box and Column Assembly

Figure 19- View Below New Lower Level Steel Framing Showing New Vibration Isolation Spring Box, Column Assembly, and Increased Headroom Below Framing
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Wind can have deleterious effects on air-cooled condensers of utility scale including both degradation of thermal performance and physical damage to fans and fan blades. Approaches to mitigation of wind effects include wind screens and wind barriers. This study seeks to develop general guidelines for the arrangement of wind screens and estimates of their effectiveness through field testing of a full-scale utility air-cooled condenser (ACC) coupled with physical (wind tunnel) and computational (CFD) modeling of the field conditions. A description of the scope and methodology of the study and preliminary example results are presented.

Background
The adverse effects of wind on the performance of large air-cooled condensers (ACCs) have been recognized for many years. Kröger [1], in a chapter entitled “Effect of Wind on Air-Cooled Heat Exchangers” states the situation succinctly:

In general, winds have a negative effect on the performance of mechanical-draft heat exchangers. Plume air recirculation tends to increase while fan performance is usually reduced during windy periods”.

In his ensuing discussion, Kröger cites 16 references dating from 1958 dealing with the problem.

More recently, the EPRI ACC Guidelines [2] state “the impact of ambient wind on ACC performance is not well understood by owner/operators or their representatives in the specification and bid/evaluation process” and “this area of wind effects in total represents the major challenge associated with ACC specification, design, and performance”.

Figure 1 illustrates the effect of wind on the performance of one ACC in the Southwestern U. S. under windy conditions. In this example, wind speeds above about 20 mph (~ 9 m/s) result in turbine exhaust pressures that are 1.5 to 2. in H2O (~ 5 to 7 kPa) higher than those at the same ambient temperature and steam load at wind speeds below 4 mph (~1.75 m/s). Furthermore, the wind speeds shown on Figure 1 are one hour average values and not instantaneous. Wind gusts, if they occur when the ACC is operating near the trip point of the turbine, can cause a rapid excursion to pressures high enough to trip the turbine. A sudden trip, from which it may take several hours to recover, can have a significant effect on plant revenue when the plant is at full load, the network demand is at its peak and the price for power is high.

Approaches to mitigation
The mitigation of high wind effects on ACCs has not usually been addressed in the initial design stage. While this might be done with additional heat transfer surface per cell, additional cells, additional fan power or some combination of all three, this would likely lead to a higher cost which many purchasers would be reluctant to accept to ameliorate conditions which may arise only occasionally. EPRI [2] addresses this issue at some length from the point of view of both the purchaser and the vendor in the introductory chapter of the report.

While recently some units have been equipped with wind screens as part of the original design, the usual situation has been that attempts are made after the fact to retrofit the ACC with some sort of wind screen or barrier after operating experience had shown the effects of wind to be sufficiently severe that corrective action was warranted. This is sometimes to mitigate reduced thermal performance and sometimes to protect the fans from excessive wind buffeting leading to blade failure.
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Figure 3 shows a similar set of conditions with windscreens in place. Smoke injected below the bottom of the screen is similarly carried across the fan inlet without being entrained. However, air passing through the screen is sufficiently slowed that the fan is capable of turning the flow into the inlet zone and through the cell.

![Figure 3: Smoke stream traces below fan (with screening) above: Flow entering below screen below: Flow entering through screen](image)

**Description and Objectives**

To assist in addressing this issue, a study has been initiated on the use of wind barriers on large-scale ACCs at electric power generating plants. The objective of the study is to develop technically sound guidance for the specification, design, installation and use of wind barriers for the prevention of ACC performance degradation and ACC fan damage from wind.

**Approach/Methodology**

The study will consist of several elements; specifically

- A comprehensive review of the existing knowledge and experience base for air-cooled condensing equipment.
- Computational fluid dynamics (CFD) modeling of air flow patterns around ACCs with and without wind barriers. A range of barrier types, locations and configurations will be modeled under conditions of varying wind speed and directions. Particular emphasis will be placed on modeling the air flow to each of the individual ACC cells and the inlet velocity distribution at the fan inlets.
- Physical (wind tunnel) modeling of a representative multi-cell ACC. The model will simulate recirculation patterns around an ACC equipped with a range of barrier types, locations and arrangements under varying wind speeds and directions. Field measurements of air flow patterns, air flows into individual cells, fan inlet velocity distributions and stresses on individual fan blades under varying wind conditions.
- Analysis of CFD, physical model and field test results to calibrate and validate the CFD model.
- Use of the CFD model to compare the relative performance of a range of wind barrier designs to provide selection criteria applicable to specific sites with known expected wind conditions for use with existing or proposed ACC installations.

**Field tests**

- Field testing is being conducted at the Caithness Long Island Energy Center, a 350 MWe gas-fired, combined cycle plant located in Yaphank, NY. An aerial view of the plant site and the 18-fan ACC is shown in Figure 4. The ACC is equipped with peripheral, retractable wind screens.

Extensive instrumentation was installed on and around the ACC to monitor the air flow and temperature patterns as well as the performance of selected fans and stresses on the fan blades in one cell (Cell 3.4). Specifically, 65 measurements are recorded at 4 millisecond intervals (and reported as one minute averages) including

- Inlet air temperatures in all 18 cells and at the top of an adjacent tank
- 8 air inlet velocities on each of two adjacent Cells 2.4 and 3.4
- Static pressure measurements (4 locations plus average in Cell 3.4 and average in Cells 2.4 and 1.4)
- Motor current measurements in 9 cells
- Blade force measurements on 6 of 9 blades in Cell 3.4
- Blade position in Cell 3.4
- Wind screen position
- Wind speed and direction in two locations
- Fan shaft speed in Cell 3.4
- “Overhead voltage” (a measurement to monitor the load cell operation on Cell 3.4 fan blades)

A sketch showing the location of the instrumentation is shown in Figure 5.

![Figure 4: Caithness Long Island Energy Center](image)
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Figure 5: Location of field test instrumentation

Figure 6 shows the inlet velocity anemometers for obtaining critical information on the air flow into Cell 3.4 and the velocity distribution at the fan inlet as affected by wind conditions and wind screen position. Figure 7 shows the data acquisition system “dashboard” with which project personnel and plant personnel can monitor the output of the various instruments in real time.

Figure 6: Inlet velocity instruments at Cell 3.4 inlet

Figure 7: Data acquisition system “dashboard”

In addition to measurements obtained on and around the ACC, concurrent data from the plant control room are obtained. These data consist of readings at one minute intervals of plant and steam turbine output (MW), turbine backpressure, steam flow to the ACC, ambient temperature, wind speed and direction from plant instrumentation, and the status of all 18 fans (full speed, half speed and off).

Physical modeling

The 1:120 scale model of the plant site and ACC which was constructed for testing in the atmospheric boundary layer wind tunnel at UC Davis is shown in Figure 8. It is mounted on a rotatable turntable for tests at varying wind direction. Wind speed, controlled with the tunnel fan, can be varied from modeled speeds of 0 to 8 m/s (~18 mph). Fan status (on/off/half speed) in each of the 18 model cells can be controlled individually. Wind speed and direction under and around the ACC is measured with a precision hot-wire anemometer and can produce detailed streamline patterns from the “far-field upstream region” to directly under the fan inlet planes.

Figure 8: Wind tunnel model of Caithness site

CFD Modeling

Computational Fluid Dynamics (CFD) modeling of air flow patterns around ACCs with and without wind barriers is to be performed. The first step will be to model the external geometry of a single ACC unit in its entirety with a viscous ground plane. As much of the relevant physical geometry as possible will be modeled. The fan will be replaced with an actuator disk model to represent the pressure change across the fan plane. The heat exchanger/radiators will be modeled using a second pressure jump condition to represent the aerodynamic losses created by the fins. This ACC geometry will be used with a periodic boundary condition to model an infinitely long row of repeating units in cross flow (with the external flow passing perpendicularly across the row axis). The second phase would be to model multiple (5 or 6) ACCs across, again repeated periodically in the cross wind direction. This will effectively physically represent multiple, infinitely long, rows of cooling devices with the external flow going across them. The third phase will be to model an actual grid array of units isolated on a ground plane. This will significantly increase the size of the problem, as each unit will be modeled completely without the use of any periodicity conditions.

A numerical grid representation of the ACC and the important surrounding structures has been assembled. A CAD/CAM model of the site, provided by Siemens and shown in Figure 9, was used to estimate the important geometric features and dimensions. Representations of the ACC structure and the cell walls and fan shroud are shown in Figures 10.
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Preliminary results

Field tests

While data collection has been underway for several months, it is only since early summer that steady state plant operating conditions have been sustained. “Steady state” in this context implies constant steam turbine output, constant steam flow to the ACC and all fans running continuously at full speed. Under those conditions changes in ACC performance, recirculation and fan blade stress can be attributed solely to ambient wind conditions and screen position. Although careful scrutiny of the data and detailed analysis remains to be done, a few example plots are presented in Figures 12 through 15 for illustrative purposes.

Figure 12 shows the wind speed and direction for August 19, 2014. Measurements are made at three separate locations: the top of the water tank south of the ACC (21A and 23D in Figure 3); the west side of Cell 3.4 at fan deck level (20A and 22D in Figure 3); the top of the turbine building at the west end (plant instrumentation).

From some directions, there is significant disagreement among the three readings. This is believed to be attributable to interference from neighboring structures. Attempts will be made to resolve some of these differences with the help of the physical and CFD modeling efforts.

Figure 13 shows the variation in the inlet air velocity to Cell 3.4 for the same day. Note that the changes in the inlet air velocity distribution across the inlet plane of Cell 3.4 at approximately 3 am and 9 am correspond reasonably well to shifts in wind direction at those same times.

The grid representation developed in the first step to represent the external geometry of a single ACC cell is shown in Figure 11.
Some comparisons were made of the inlet air flow to Cells 3.4 and 2.4 under similar wind conditions between operations with the wind screens both fully deployed and fully retracted. While much more attention to this important issue is required, Figure 14 gives a preliminary indication that the air flow to Cell 3.4 increases with the screen deployed, while Figure 15 suggests that the air flow to Cell 2.4 is only minimally affected.

**Wind tunnel tests**

Wind tunnel tests were run for a range of wind speeds coming from the West (normal to the long side of the ACC) with and without windscreens in place. Figure 16 shows a comparison of flow patterns from the undisturbed upwind region to the inlet plane of the Cell 3.4 fan. Without screens present, much of the air entering the western ACC air inlet plane, bypasses Cell 3.4 while, with the screens present, more air turns and flows into Cell 3.4. This is qualitatively consistent with the smoke stream traces obtained in the early flow visualization tests shown in Figures 2 and 3.

**CFD modeling**

Some preliminary CFD runs have been made on a single free-standing cell as shown in Figure 17. Cases with no screen and with a fully extended screen were compared at a wind speed of 4m/s (~9 mph) normal to the screened side.

![Figure 13: Inlet air velocity to Cell 3.4](image1)

![Figure 14: Effect of screen position on air flow to Cell 3.4](image2)

![Figure 15: Effect of screen position on air flow to Cell 2.4](image3)

![Figure 15: Streamline patterns from upstream to under fan without screen](image4)

![Figure 16: Streamline patterns from upstream to under fan with screen](image5)

![Figure 17: Single cell CFD comparison of air velocity patterns with and without screen](image6)
Qualitatively the results are consistent with both the field measurements and the wind tunnel results.

**Conclusions**

The material presented in this paper is intended primarily to introduce the existence of the project to the ACC community and to describe some illustrative preliminary results as examples of the potential outcome of the study. After the remaining testing, computational modeling and analysis are completed, it is hoped that they will serve as a basis for a sound understanding of the effect of wind barriers on ACCs and for some general guidelines for the selection, design and arrangement of wind barriers suitable for specific situations.

**References**


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1. Introduction

The air wet-bulb temperature entering a cooling tower can be measured with several different technologies. Some European standards, dedicated to cooling tower thermal tests such as EN 14705, historically recommend capacitive hygrometers for cooling tower acceptance tests for more than 20 years now, while the CTI-ATC 105 (and also 140) standard only recommends the use of mechanically-aspired psychrometers. The goal of this paper is to compare the measurement of wet-bulb temperature results from capacitive hygrometers with CTI-approved psychrometers for cooling tower tests, and to compare the strengths and weaknesses of these two instruments.

Field tests have been conducted in various environments with both capacitive hygrometers and psychrometers. These tests have been performed on the air inlet of cooling towers, gas turbines, and other air flow scenarios. Results of these tests are provided in Section 4 and summarized in Section 6.

2. Definitions

- Water vapor pressure: the pressure saturated water vapor would exert at thermodynamic equilibrium with its condensed state.
- Relative humidity: the ratio of the actual vapor pressure to the saturation vapor pressure, expressed in percentage.
- Hygrometer: an instrument used to measure the moisture content of air.
- Psychrometer: an instrument used to measure the wet-bulb and dry-bulb temperatures of air.
- Pt100 RTD sensor: an instrument used to measure temperature by correlating the resistance of the RTD element with temperature.
- Dew-point: the temperature at which condensation begins when air is cooled at constant pressure.

3. Moisture Content Measurement Technology

3.1. Technologies Overview

Air moisture content can be determined with various instruments measuring different psychrometric parameters such as: relative humidity, dew-point temperature, wet-bulb temperature, dry-bulb temperature, and barometric pressure.

Three common technologies are:

- Dew-point hygrometers: high quality laboratory instruments based on dew-point condensation and a separate temperature measurement. The measurement principle consists in gradually cooling a small mirror surface until moisture condenses onto the surface. The cooling is stabilized to maintain the stable equilibrium between air water vapor and condensation onto the mirror. The temperature of the mirror is measured, which is the dew-point temperature. Optical dew-point hygrometers are often used in reference standards laboratories for calibration and in this case their uncertainty can achieve ±0.1°C to ±0.2°C. However, these instruments are not suited for field use.

- Psychrometers: consist of two temperature sensors over which an air flow is drawn. The measured parameters are the wet-bulb and dry-bulb temperatures. The relative humidity can be determined using psychrometric calculations. Details of a typical psychrometer are displayed in the following paragraph.

- Electronic hygrometers (probes): consist of a resistance, capacitive or impedance sensing element that can be correlated with relative humidity. The characteristics of the capacitive hygrometer that has been used in these tests are detailed in the following paragraphs.

3.2. Wet-Bulb Measurement With Psychrometer

3.2.1. Principle

As previously described, the psychrometer consists of two temperature sensors. One sensor end is equipped with a wick (or wet sock, usually constituted of cotton fibers) that is soaked into a water reservoir for constant capillarity.

The sensor equipped with a wet wick measures the wet-bulb temperature. When dry air passes over the wet wick, some of the water in the wick evaporates causing an evaporative cooling effect. The temperature of the probe stabilizes when the evaporative cooling effect reaches equilibrium. This is defined as the wet-bulb temperature.

In addition to the temperature sensors, a fan is added that creates the proper air flow for the wet-bulb measurement. The fan characteristics depend on the design of the psychrometer, but the right air flow should be between 2 to 6 m/s (4.5 to 13.5 mph).

Psychometric properties of the ambient air can be determined by measuring wet-bulb temperature, dry-bulb temperature, and barometric pressure. The chosen parameter usually depends on the industry or cultural habits. In the cooling tower industry, both relative humidity and wet/dry-bulb values are commonly used.

3.2.2. Psychrometer used for tests

The psychrometers used for the tests are shown below in Figure 3.1. They consist of two Pt100 (platinum RTD’s) of class A accuracy 0.05°C. The calibration certificates are in Annex 2. The air flow is maintained with a small fan at the rear of the box. The psychrometer is design to shield the RTD’s from thermal radiation.
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3.3. Humidity Measurement With Hygrometer

3.3.1. Principle
Capacitive hygrometers (used for this test) are equipped with a capacitive sensing element, see Figure 3.2. The dielectric of the capacitor is constituted of a hygroscopic substance (polymer) of a few micrometers. This substance absorbs the water in the air until reaching the equilibrium with the water vapor of the humid air. As a consequence, the variation of the dielectric constant inside the polymer varies, as do the capacitance. The capacitance is measured and correlates with the relative humidity of the air. Some hygrometers contain integrated dry-bulb measurement sensors. However, for most tests, the dry-bulb temperature must be measured separately due to the difficulty in calibrating the integrated temperature sensor.

3.3.2. Hygrometer used for tests
The capacitive hygrometer used in this test is a Rotronic HC2-S3. It is a small and portable instrument equipped with a filter to protect against pollution, see Figure 3.3. The output signal is a voltage that directly correlates with relative humidity. These Rotronic hygrometers are among the best hygrometers on the market. The manufacturers specify the accuracy of this instrument to be 2% RH. Other good capacitive hygrometers also exist but have not been tested for this paper; however, the one used is representative of the performance of this kind of instrument.

4. Field Tests Program
4.1. Equipment
4.1.1. Location and Use
The tests have been conducted with the psychrometer and hygrometer installed next to each other in the same air stream. When possible, several pairs of instruments have been used at various heights and positions.

4.1.2. Calibration
The hygrometers have been dually calibrated (RH and temperature) before the tests by certified laboratories. Temperature sensors have been checked at various relative humidity’s at 23°C (73.4°F). Calibration certificates samples are in Annex 2.

4.1.3. Data acquisition and use
For all test, the wet-bulb and dry-bulb temperatures are recorded with an Agilent. Based on the instruments and the data acquisition system used in this test, the estimated deviation between the two instruments should not exceed 0.6 °C (1.1 °F), see Section 5 for uncertainty analysis.

The psychrometric tables used for the calculations are detailed in the standard NF X15-110 [3].

4.2. Mistral Bench Test
4.2.1. Description of Test
Measurements have been performed at EDF test facility called MISTRAL on the nuclear power plant of Bugey (France). This test facility is a one cell mechanically induced draft cooling tower with a counter-flow and a cross-flow part. The filling capacity is 50 m². The air inlet of MISTRAL is equipped with three stages of instruments. There is one temperature sensor and one hygrometer at each stage. A barometric pressure sensor is also available on the top of the tower. The facility is also equipped with meteorological sensors for wind (direction and speed) and for rain detection. Other sensors are displayed inside the cooling tower but are of no use for the test.
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Each psychrometer box has been placed at one stage of the air inlet, next to one EDF hygrometer. The hygrometers are connected directly to the bench command center. The psychrometers were connected to an independent data acquisition system (Agilent).

The bench is located inland, a plain region of the south-east of France where the climatic conditions are continental. In winter, temperatures lies between -10°C (14°F) / 10°C (50°F) (dry) and during summer between 20°C(68°F) / 35°C(95°F) (dry). Precipitations are quite constant over the year, around 100mm each month.

4.2.2. Results

The results of the Mistral Bench test are present in Figures 4.2 through 4.4 below. In general for all three cases, the wet-bulb trends for both technologies followed one another fairly well. The deviation range and average deviation in wet-bulb is presented in Section 6.

Figure 4.2: Results for the Mistral Bench Test, Center Equipment

Figure 4.3: Results for the Mistral Bench Test, Top Equipment

Figure 4.4: Results for the Mistral Bench Test, Bottom Equipment

4.3 Coastal site

4.3.1. Description of Test: Coastal Site 1

The air inlet of a gas turbine is similar to the air inlet of a cooling tower. The inlet air relative humidity is commonly measured for performance test for gas turbines. For this reason, a field test on gas turbines has been performed.

The air inlet was equipped with 2 pairs of instruments. Each pair consisted of 1 psychrometer and 1 hygrometer installed after the shutters on the guardrail upstream of the filters. One pair of instruments (pair 1) was on the top area of the air inlet, the other pair (pair 2) was on the lower area.

This gas turbine belongs to a coastal power plant located in the south of France. In winter, temperatures range between 0°C(32°F) / 15°C(59°F) (dry) and during summer between 20°C(68°F) / 35°C(95°F) (dry). The weather is quite dry and windy. There are scarce precipitations in summer (below 30mm per month) and a little more during the autumn and winter (around 50mm per month).

4.3.2 Results: Coastal Site 1

Tests have been performed during two days. The ambient characteristics are detailed Table 4.1. The results are presented in Figures 4.6 through 4.13. In general for all four test, the wet-bulb trends for both technologies followed one another fairly well. The deviation range and average deviation in wet-bulb is presented in Section 6. The wick in the psychrometer for Equipment 2 Test 1 went dry which cause a major divergence in wet-bulb.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Date/Time</th>
<th>Weather</th>
<th>Average ambient dry-bulb temperature</th>
<th>Average ambient wet-bulb temperature</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27/06/2014 16:53:38</td>
<td>Sunny – No clouds – No wind</td>
<td>21.8°C (71.3°F)</td>
<td>18.4°C (65.1°F)</td>
<td>Psychrometer 2 out of water during the night (around 4:30am)</td>
</tr>
<tr>
<td>2</td>
<td>28/06/2014 09:11:13</td>
<td>Sunny – No clouds – No wind</td>
<td>22.4°C (72.3°F)</td>
<td>16.2°C (61.2°F)</td>
<td>Psychrometer 2 titeld with water at the beginning of the test</td>
</tr>
<tr>
<td>3</td>
<td>28/06/2014 10:17:43</td>
<td>Sunny – No clouds – No wind</td>
<td>24.2°C (75.5°F)</td>
<td>16.9°C (62.4°F)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>28/06/2014 11:35:04</td>
<td>Sunny – No clouds – No wind</td>
<td>25.3°C (77.5°C)</td>
<td>17.4°C (63.5°F)</td>
<td></td>
</tr>
</tbody>
</table>
4.3.2.1. Test 1
Figure 4.6: Results for Test 1, Equipment 1

4.3.2.2. Test 2
Figure 4.7: Results for Test 1, Equipment 2

4.3.2.3. Test 3
Figure 4.10: Results for Test 3, Equipment 1

4.3.2.4. Test 4
Figure 4.12: Results for Test 4, Equipment 1

Figure 4.8: Results for Test 2, Equipment 1

Figure 4.9: Results for Test 2, Equipment 2

Figure 4.11: Results for Test 3, Equipment 2

Figure 4.13: Results for Test 4, Equipment 2
4.3.2.5. General conclusion about Site 1 tests
The air velocity at the air inlet is very high. The main difficulty with using the psychrometer was the constant capillarity of the wick, but no problem occurred. At the same time, the maintenance of this instrument (water filling, wick insertion) in these extreme conditions of air aspiration is difficult and the hygrometers were much easier to install and maintain. The hygrometers ran normally and no impact of the surrounding conditions was noticed.

4.4. Inland Sites
4.4.1. Description of Test: Inland Field Site 1
This test was performed on the inlet of a cross flow cooling tower located in Oklahoma on August 2014. The wind speed was very high and the instruments were exposed to recirculation from the tower exhaust. The average dry-bulb temperature was around 90 °F. The wet-bulb results of the two technologies are presented below.

4.4.2. Results: Inland Field Site 1
The results of this test are present in Figure 4.14 below. In general, the wet-bulb trends for both technologies followed one another fairly well. The deviation range and average deviation in wet-bulb is presented in Section 6.

4.5. Test At Edf Laboratory
4.5.1. Description of Test:
First tests have been performed inside the EDF laboratory where the air is only controlled by the building air conditioning (no climatic room). The average dry bulb-temperature was 28.4°C (76.6°F).

4.5.2. Results:

4.6. Test At McHale Laboratory
4.6.1. Description of Test 1
This test was performed inside the McHale laboratory in Knoxville Tennessee where the air humidity is only controlled by the building air conditioning (no climatic room). The average dry-bulb temperature was around 71°F.

4.6.2. Results of Test 1
The results of this test are present in Figure 4.17 below. After the initial unsteady period, the two instruments measured a consistent trend. The deviation range and average deviation in wet-bulb is presented in Section 6.

4.6.3. Description of Test 2
This test was performed outside the McHale laboratory in Knoxville Tennessee day where the wind was speed was very low and the average dry-bulb temperature was around 65°F.

4.6.4. Results of Test 2
The results of this test are present in Figure 4.18 below. The two instruments measured a consistent trend. The deviation range and average deviation in wet-bulb is presented in Section 6.

Note that the deviation in this test is not as steady as the test performed indoors. This is expected due the unsteady nature of weather.
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However, the average deviation on this test was lower than the test performed indoors.

Figure 4.18: Results for the McHale Laboratory Test 2

### 5. Uncertainty Analysis
#### 5.1. Uncertainty In Wet-Bulb Temperature Using A Capacitive Hygrometer

An uncertainty analysis was performed on determining wet-bulb temperature from the two technologies used in these tests and is described below.

The uncertainty in determining wet-bulb temperature using a psychrometer is simply based on the systematic uncertainty of the RTD and the data acquisition system. For the equipment used in these tests, a conservative approximation of the total uncertainty for determining wet-bulb temperature using a psychrometer is 0.15 °F.

The uncertainty in determining wet-bulb temperature using a capacitive hygrometer is based on the systematic uncertainties of measuring relative humidity, dry-bulb temperature, and barometric pressure. For the uncertainty analysis that follows, the systematic uncertainty for measuring relative humidity is assumed to be 2%, which is representative of the best capacitive hygrometers commercially available at the time of publication. The systematic uncertainty for measuring dry-bulb temperature is assumed to be 0.15 °F, and the systematic uncertainty for measuring barometric pressure is assumed to be 0.325% of reading.

Figure 5.1: Uncertainty in Wet-Bulb Temperature Using a Capacitive Hygrometer

A plot of the total uncertainty in determining wet-bulb temperature using a capacitive hygrometer for several relative humidity’s and dry-bulb temperatures is provided in Figure 5.1. The uncertainty analysis was determined from a sensitivity analysis on psychrometric calculations with the assumed systematic uncertainties described above.

### 6. Results Summary And Discussion
#### 6.1. Main Results

A summary of the results is presented in Table 6.1 below.

#### Table 6.1: Summary of the Results

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Deviation Range</th>
<th>Average Absolute Deviation</th>
<th>Test Notes</th>
<th>Figure #</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISTRAL, Bench Test Center</td>
<td>-1.11 to 0.92 °C</td>
<td>0.91 °C</td>
<td>Cooling Tower Inlet</td>
<td>4.2</td>
</tr>
<tr>
<td>MISTRAL, Bench Test Top</td>
<td>-0.03 to 0.46 °C</td>
<td>0.23 °C</td>
<td>Cooling Tower Inlet</td>
<td>4.3</td>
</tr>
<tr>
<td>MISTRAL Bench Test Bottom</td>
<td>-0.61 to 0.51 °C</td>
<td>0.52 °C</td>
<td>Cooling Tower Inlet</td>
<td>4.4</td>
</tr>
<tr>
<td>Coastal Site 1, Test 1, Equipment 1</td>
<td>-0.77 to 0.65 °C</td>
<td>0.65 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.6</td>
</tr>
<tr>
<td>Coastal Site 1, Test 2, Equipment 2</td>
<td>-0.77 to 0.53 °C</td>
<td>0.53 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.7</td>
</tr>
<tr>
<td>Coastal Site 1, Test 2, Equipment 3</td>
<td>-0.43 to 0.56 °C</td>
<td>0.45 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.8</td>
</tr>
<tr>
<td>Coastal Site 1, Test 3, Equipment 1</td>
<td>-0.20 to 0.90 °C</td>
<td>0.91 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.9</td>
</tr>
<tr>
<td>Coastal Site 1, Test 3, Equipment 2</td>
<td>-0.46 to 0.19 °C</td>
<td>0.42 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.10</td>
</tr>
<tr>
<td>Coastal Site 1, Test 3, Equipment 3</td>
<td>-0.72 to 0.89 °C</td>
<td>0.89 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.11</td>
</tr>
<tr>
<td>Coastal Site 1, Test 4, Equipment 1</td>
<td>0.45 to 0.66 °C</td>
<td>0.52 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.12</td>
</tr>
<tr>
<td>Coastal Site 1, Test 4, Equipment 2</td>
<td>0.67 to 2.14 °C</td>
<td>1.08 °C</td>
<td>Gas Turbine Inlet</td>
<td>4.13</td>
</tr>
<tr>
<td>Inland Field Site 1</td>
<td>0.67 to 1.26 °C</td>
<td>1.01 °C</td>
<td>Cooling Tower Inlet</td>
<td>4.14</td>
</tr>
<tr>
<td>EDF Lab. Equipment 1</td>
<td>0.21 to 0.90 °C</td>
<td>0.67 °C</td>
<td>Indoors</td>
<td>4.15</td>
</tr>
<tr>
<td>EDF Lab. Equipment 2</td>
<td>0.35 to 0.86 °C</td>
<td>0.81 °C</td>
<td>Indoors</td>
<td>4.16</td>
</tr>
<tr>
<td>Mokuleke Lab. Test 1</td>
<td>0.21 to 0.59 °C</td>
<td>0.53 °C</td>
<td>Indoors</td>
<td>4.17</td>
</tr>
<tr>
<td>Mokuleke Lab. Test 2</td>
<td>0.56 to 0.42 °C</td>
<td>0.56 °C</td>
<td>Outdoors</td>
<td>4.18</td>
</tr>
</tbody>
</table>

Excluding the initial stabilization period of certain test runs, the maximum instantaneous deviation between the two instruments was found to be 1.96 °C (3.53 °F). The maximum average absolute deviation between the two instruments for all tests reported was found to be 0.72 °C (1.3 °F), and the average absolute was found to be 0.47 °C (0.85 °F).

In general, the psychrometer determined a higher relative humidity than the hygrometer. CTI standard performance curves correlate cold water temperature with range and wet-bulb temperature; psychrometers directly measure the wet-bulb temperature. Furthermore, psychrometers have lower uncertainties in measuring wet-bulb than hygrometers. However, hygrometers are easier to use and do not require continuous monitoring during the test. Because hygrometers do not have to be refilled with water, they are well suited for long test periods like performance monitoring applications where a tradeoff in accuracy for usability is warranted.

In order to help the end user decide which technology is the best one to use for their specific application, a summary of the observed strengths and weaknesses of the two technologies is provided in the next section.
6.2. Strengths And Weaknesses Of Both Instruments

A summary of the observed advantages and disadvantages of psychrometers and capacitive hygrometers is provided below in Tables 6.2 and 6.3. The goal is not to choose in the end between the two in all cases but to give people an overview of what they can expect of each technology depending on their needs.

Some international codes require short term testing periods as well as long term testing periods. The long term testing period can last several months or up to 1 year in duration for performance monitoring, see ISO 16345:2014 Water-cooling towers – Testing and rating of thermal performance. We believe capacitive hygrometers are well suited for long term testing applications like performance monitoring.

Furthermore, we believe that psychrometers are well suited for short term testing applications, like typical CTI thermal performance test on mechanically induce draft cooling towers where the test period is a minimum of one hour.

7. Conclusion

This paper is based on on-site tests to determine if capacitive hygrometers or psychrometers are preferred for measuring wet-bulb temperature for cooling tower applications. Both technologies have strengths and weaknesses. Ultimately, the end user will have to decide on which technology to use.

8. References

[2] La mesure de l’humidité dans les gaz (the measure of humidity in gas), Collège Français de Métrologie.

Annex 1: Rotronic Hc2-S3 Characteristics

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity sensor</td>
<td>RROTOMIC Hygrometer Hc2-S3</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>PT100 Class A</td>
</tr>
<tr>
<td>Accuracy at 23 °C, ±5 K</td>
<td>±0.8 %rh / ±0.1 K</td>
</tr>
<tr>
<td>with Standard adjustment profile</td>
<td>at 23 °C und 10, 35, 80 %rh</td>
</tr>
<tr>
<td>Accuracy at 23 °C, ±5 K</td>
<td>±0.5 %rh / ±0.1 K</td>
</tr>
<tr>
<td>with High Precision adjustment profile</td>
<td>at 23 °C und 10, 20, 30, 40, 50, 60, 70, 80, 90 %rh</td>
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<tr>
<td>Long-term stability, humidity sensor</td>
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<tr>
<td>Humidity response time t&lt;sub&gt;63&lt;/sub&gt;</td>
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<td>Measurement range</td>
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<td>(depending on probe type)</td>
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</tr>
<tr>
<td>Electronics operating range</td>
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<tr>
<td>Analog output signals</td>
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<tr>
<td>(standard, user scalable)</td>
<td>0...1 V = 40...60 °C</td>
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<tr>
<td>Interface</td>
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</tr>
<tr>
<td>Alarm function</td>
<td>Yes, analog &amp; digital, programmable</td>
</tr>
<tr>
<td>Audit Trail / Electronic Records</td>
<td>FDA 21 CFR Part 11 and GAMP compliant</td>
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<tr>
<td>Current consumption</td>
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<tr>
<td>Housing/probe material</td>
<td>Polycarbonate, PEEK or stainless steel (depends on probe type)</td>
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<tr>
<td>Filter</td>
<td>Polyethylene / wire mesh filter</td>
</tr>
<tr>
<td>Standards</td>
<td>CE-compliant 2007/108/EG</td>
</tr>
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</table>

Annex 2 : Calibration Certificates (Sample)

Report of Calibration
COMpte rendu d'étaLonnage

N° HR14-004

Délivré à : EDF DTG EET
21, Avenue de l'Europe
38040 CEZENOBLE
FRANCE

INSTRUMENT ÉTAISONNE

Désignation : Humidité Relative

Constructeur : ROTRONIC

Type : MP402H-080300/HC2-03

N° de série : 01071000/0102526

N° d'Identification : 01071000/0102526

Co certificat comprend 4 Pages

Date d'émission : 20/02/2014

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44th Turbomachinery
31st Pump SYMPOSIA

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Empirical Methods For Inspecting, Analyzing And Converting Large Field Erected Wood Cooling Towers To Fiberglass Structure

Al Feltzin, Linde Gas
Philip Poll, OBR Cooling Towers, Inc.

Abstract:
A series of empirical methods for inspecting, analyzing and converting large field erected wood cooling towers to fiberglass structure. Methods of inspecting and documenting the existing conditions, evaluating and selecting new materials and performance of respective repairs will be explained.

Introduction
The use of fiberglass reinforced plastic materials for repairs to existing wood cooling tower structures has become common practice in the cooling tower industry. Advances in pultruded fiberglass reinforced plastics (FRP) coupled with the diminishing supply of high grade structural lumber material has accelerated the use of FRP structural materials in “Stick by Stick” cooling tower repairs. Mechanical property differences between wood material and FRP requires well planned methods for executing repairs that differentiate significantly from traditional wood repairs. The execution of these repairs requires a dynamic process that involves a well-trained field repair crew in constant communication with a project engineering group to ensure that all repairs are conducted in a safe and reliable well documented manner.

This paper highlights the process of identifying the need for a repair, implementation of appropriate design and engineering principals, while maintaining due diligence in identifying deviations from proposed design in the field. The process includes an understanding from the end user of the potential pitfalls and associated remedies that may be implemented in the field. Two example projects are used to discuss issues that were discovered and the means and methods that were employed to solve the problems.

Methodology of Repairs and Reconstruction
All successful repair projects require a methodology for execution. When considering minor “In Kind” repairs, the methodology only requires a simple execution plan. This consists of the identification of developed deficiencies and review of the scope of work, a job safety analysis (JSA), procurement of “In Kind” material and finally, execution of the project scope. Within the execution phase, individual means and methods of repair construction are implemented where productivity and quality are direct reflections of the field crews experience and training. As project scope increases, or when global structural integrity of the existing tower is questionable, more detailed methodology for repair is needed to confirm a proper solution is implemented.

When “In Kind” material replacements become impractical, a more sophisticated approach to the repair and reconstruction method must be implemented. Using different material grades of lumber, steel or the substitution of FRP for traditional materials, requires thorough analysis of the repair. The first step of the process should always be a detailed cooling tower inspection. The inspection is the foundation of a good repair, in that it identifies the current condition of the cooling tower, documents deviations from the original design, and identifies areas where the original design may have been deficient. A proper inspection should be well documented and deliver a report that is effective in communicating the cooling tower’s condition to all parties involved in the repair project.

Once a good inspection is performed, the engineering and design team should work with the inspection team to identify a proper scope of work for the repair. Many site specific items need to be considered in addition to, local building codes, seismic and wind load requirements. It is often the case that repairs are proposed as solutions to other indirect operating conditions such as: poor water quality, increased system loads or environmental conditions. It is important that the source of the problem be identified so that the proposed repair not only alleviates the failed condition, but addresses the initial source of the problem. An example of this is failed structure caused by fouled fill material or damaged components from excessive ice loading.

All repairs should include a written repair plan that considers the means and methods of construction, the materials used and end user constraints, such as site conditions, project schedule...
and process demands. It is imperative that the engineering/design team, the inspection team and the execution forces work together to properly complete and document the final proposed repairs. A diagram of the relationship between these three groups is located in figure one.

Figure 1: Relationship of Engineering/Design, Inspection Team and Execution Forces.

The final component of a properly executed repair project is completing the appropriate documentation, which is commonly referred to as the Management of Change (MOC). This documentation should be extremely detailed and provide the proper evidence needed to allow future involved parties to clearly understand the changes made. At a minimum the MOC paperwork should include the original design criteria of the tower, identify issues that were corrected, materials that were used and the location of the changes that were made. Depending on the type of repair that is performed, detailed AS-Built drawings and calculation packages should be included to demonstrate that proper research and discovery was performed. The MOC process is a very effective method to confirm that proper engineering standards and methods are being implemented.

Cases of identified issues and executed repairs

The subject cooling tower repair projects involve two separate counterflow cooling towers at a large industrial plant operating in a remote location. The plant utilizes sea water for the bulk recirculating water that is used in the cooling tower. The two towers were built as part of two individual erection projects that were separated by approximately six years.

Case #1 Field Erected Tower operating with Seawater – Structural Degradation

The first cooling tower to be erected and placed into service consisted of two thirteen cell banks built in parallel and were designed to operate with bulk recirculating sea water that collects in a central pump collection basin. The tower was designed and constructed utilizing Douglas Fir structural material coupled with silicon bronze hardware. The fill material was PVC film heat transfer media and the distribution was composed of fiberglass reinforced plastic (FRP) header with PVC lateral piping. An image of one of the thirteen cell banks is located in figure two.

The tower was placed in operation in 1999 and experienced significant issues from the original startup date. The initial problems included excessive amounts of suspended solids which resulted in accelerated erosion of both the structure and connecting hardware. The local operating team implemented short term repairs that consisted of covering the interior structure and hardware with plastic covers to delay the aggressive erosion. Images of the structure and hardware covers are located in figures three and four. The covers were effective in slowing down the aggressive erosion but were unsuccessful at eliminating or totally protecting the structural system from the aggressive bulk water.

Figure 2: One of the thirteen cell banks built during the initial construction of the plant.

Figure 3: Internal tower structure covered in PVC plastic sleeves that were installed to protect from erosion.
After twelve years of operation, the plant commissioned a full inspection of the tower structure in December of 2011. The intent of the inspection was to identify the current overall condition of the equipment and specify needed repairs to establish the reliability of the tower. The initial inspection was performed and identified the visual issues with the tower structure and associated components. The initial recommendations of the inspection report was to immediately repair the tower structure in-kind, to mitigate the chances of failure in heavily loaded areas. In March of 2012 the plant commissioned an alternate inspection to provide a second opinion on the overall condition of the equipment. The second inspection was performed with the goal of extending the life of the tower for three to four years in an effort to allow the plant to properly budget for a full plant relife operation.

The second inspection concurred with the findings of the first inspection but differentiated in that a full structural analysis was performed to quantify the remaining capacity of the original structure as compared to the original design. The structural analysis revealed that when design loads were applied, the structure had limited capacity in the lower level tie lines and columns located directly below the fill section. The inspection and engineering team reviewed the existing conditions and developed a short term repair that included the installation of reinforcing “Construction Blocks” to reduce the unbraced lengths of the tie lines from six feet to three feet. The installation of the blocks improved the slenderness ratio of the tie lines providing additional structural capacity to both tie lines and stabilizing columns through reduced slenderness ratios. The installation of construction blocks along with annual follow up inspections allowed for a confident life extension that allowed for proper planning on the overall cooling tower relife project. Images of the construction block design plan and final installation are located in figures five and six.

Following the installation of construction blocks in 2012, a reconstruction plan was developed during the following twelve months with a follow up inspection scheduled to be performed during the summer of 2013. The reconstruction plan focused on alternative materials that could be implemented to allow for an efficient and effective long term solution. The proposed reconstruction material was pultruded fiberglass reinforced plastic members coupled with 304 stainless steel hardware. The intent of the follow up inspection was to document the rate of deterioration in one year and install sample material “coupons” to verify the viability of different construction materials. Due to the previous deterioration that was recorded on the original design materials, it was deemed necessary to verify the reliability of the newly proposed FRP material.

The follow up inspection was performed in June of 2013. Four sets of FRP structural coupons were produced of known weight and dimensions to allow for empirical analyses of material reliability. The coupons were installed to substitute for the previously installed construction blocks and were orientated in numerous arrangements to allow for exposure to all areas of the cooling tower. In addition to the installation of material coupons, it was the intent of the follow up inspection to verify the condi-
tion. The overall structural condition of the tower was verified to be consistent with the previous year. A discovery was made during the follow up inspection with regards to the condition of the recently installed 304 stainless steel hardware. Removal of a construction block installed one year prior, revealed that the 304 stainless steel hardware had deteriorated in an accelerated fashion. Images displaying the deterioration of a 304 stainless steel bolt, the cooling tower structure and the installed FRP coupons are located in figures seven, eight and nine respectively.

![Figure 7: 304 Stainless Steel bolt displaying significant deterioration from corrosion after one year of exposure in the bulk recirculating sea water.](image)

![Figure 8: The removal of a construction block after one year of exposure revealed the deterioration that occurred to a wood member over one year.](image)
The findings from the follow up inspection were assembled in a detailed report and presented to the owner/operator for review and analyses. The discovery of the limited resistance of 304 stainless steel hardware to the corrosivity of the recirculating seawater brought an elevated concern with regard to the reconstruction plan. The owner/operator was adamant about developing a method to provide similar feedback to that of the one year hardware exposure. After discussion and review with the inspection and engineering teams, it was decided that a corrosion coupon rack of numerous bolting materials should be installed to obtain applied results for the resistive ability of a given material. An FRP corrosion rack was designed and produced to give an accurate representation of ten different metallurgies when installed in the FRP shapes. The individual metallurgies that were used were; 304 Stainless Steel (Control), 316 Stainless Steel, 317L Stainless Steel, 2507 Duplex Stainless Steel, AL6XN, Zeron 100, I825, C276, K500 and Titanium. Images of the corrosion coupon assembly design and the final produced coupon rack are located in figures ten and eleven.

The corrosion coupon rack was produced and installed in February of 2014. Due to the quick recovery of the overall business climate, the start of the overall relife project was pushed forward to start in the winter of 2014/2015. This quick acceleration of the project start date required the corrosion coupon rack to be removed after only five months of exposure. The rack was removed in August of 2014 and was sent back to the independent laboratory for analyses. The relatively short exposure time contributed to a legitimate concern that the materials were not exposed long enough to display any measurable results. After full analyses, the compiled data was received with results that displayed significant corrosion to over half of the tested metals. Corrosion rates are illustrated in figure twelve with the relative data compiled in table one.
Review of the corrosion data revealed that the bulk recirculating sea water was significantly more aggressive than originally perceived. During the initial project specification writing phase, the end user's team used 316 stainless steel for the base specification because it was believed to have enough corrosion resistant properties to operate in the cooling water system. The corrosion coupon study revealed that the 304 stainless and 316 stainless steel material had relatively the same corrosion rates under exposure to the sea water and recirculating temperatures. In addition the 317L stainless steel, AL6XN, I835 and K500 were all found to display corrosion rates that would undermine the expected service life of the tower. All of the corrosion was found to be localized and occurred at both the interface of the bolt and fiberglass member wall and the bolt and securing nut interfaces. An image displaying the localized corrosion to a 316 stainless steel bolt is located in figure thirteen. The owner is currently conducting a feasibility study to determine which material should be used for the final construction of the tower.

### Table 1: Compiled corrosion data from coupon test and experiment, the highlighted items showed acceptable resistance to the water source

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<tr>
<th>Material</th>
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<th>Pre-Exposure Weight</th>
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<th>Weight Change</th>
<th>Post Exposure After Cleaning Weight</th>
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<td>(-1.23)</td>
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<td>(-1.64)</td>
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<td>258.06</td>
<td>(-1.69)</td>
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<td>Titanium</td>
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<td>0.50</td>
<td>136.67</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figure 13: A 316 Stainless steel nut with corrosion on the threads where contact with the bolt occurred.

### Case #2 Field Erected Tower operating with Seawater – Excessive Fill Fouling that exceeds the original tower design criteria.

The second cooling tower to be erected and placed into service consisted of one six cell bank that was designed to operate with the same bulk recirculating sea water as the tower described in the first case. The tower was designed and constructed utilizing Douglas Fir structural material coupled with silicon bronze hardware. The fill material was PVC film heat transfer media and the distribution was composed of a fiberglass reinforced plastic (FRP) header with PVC lateral piping. The second tower was designed and built with a smaller footprint cell size than the original towers and used a different structural design that was more economical from a first cost analysis.

The tower was placed in operation in 2006 and experienced similar issues during the initial startup as the tower described in case #1. Being that the local operating team was familiar with the operating environment and related issues the preventative maintenance program was designed to accommodate the relative concerns. The towers operated without any unplanned operating interruptions until February of 2014 when a storm introduced a significant amount of suspended solids into the bulk recirculating sea water. Due to the second cooling tower being installed downstream from the first towers, and toward the end of the water system, the majority of the solids were recirculated through the smaller six cell cooling tower.

The large amount of suspended solids that were introduced into the bulk water in a short amount of time led to excessive fouling of the heat transfer media. This excessive fouling exceeded the original design criteria of the tower structure resulting in failure of the fill support system. This failure was found in the center fourth cell, of the six cells, with all of the cells displaying signs of overloaded structural conditions. Images of the failed section of structure and overloaded fill supports are located in figures fourteen and fifteen.
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Electronic Vibration Switches
Series 685B

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Figure 14: The fill supports were found to have failed at the connection point to the structural columns.

Figure 15: A fill support that has begun to fail in shear at the connection to the structural column.

Immediately after the fouling incident, the plant implemented a cleaning crew to begin carefully cleaning the tower from the exterior to remove the foulants causing the excessive loading. In conjunction an emergency inspection was commissioned to provide an opinion on the overall condition of the equipment and develop a solution for a short term and long term repair. The inspection was performed in conjunction with an emergency repair to stabilize the structure and perform a full structural analysis. The inspection and structural analysis consisted of identifying the developed fouling loads, reviewing the original design criteria and analyzing the effects of the applied loads. To properly identify the failure mode, weights of the fill material packs were recorded. The recorded weights relative to the original clean fill packs are located in table two.

Utilizing the recorded weights in table two a full structural analysis was performed. The structural analysis found that in an effort to cut costs on the second towers construction, the second tower fill supports were designed with less capacity than the original twenty six cells. The point of failure was found to be at the single bolted connection of the fill support to the column, which was a double bolted connection on the original design. A summary of the structural analysis is located in table three.

<table>
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<th>Structural Member</th>
<th>Summary of Analysis (Before Cleaning)</th>
<th>Summary of Analyses (After Cleaning)</th>
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<tbody>
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<td>3&quot; x 6&quot; Transverse Tie Line</td>
<td>Failed 2.5 times over capacity on bending stress</td>
<td>Failed 1.6 times over capacity on bending stress</td>
</tr>
<tr>
<td></td>
<td>2.0 times over capacity on deflection</td>
<td>1.3 times over capacity on deflection</td>
</tr>
<tr>
<td>4&quot; x 4&quot; Fill Support</td>
<td>Failed 2.2 times over capacity</td>
<td>Passed (within capacity for deflection)</td>
</tr>
<tr>
<td>3/8&quot; Bolts Connection</td>
<td>Failed 1.1 times over capacity</td>
<td>Failed</td>
</tr>
<tr>
<td>4&quot; x 4&quot; Column</td>
<td>Passed</td>
<td>Passed</td>
</tr>
</tbody>
</table>

Table 3: Summary of Structural Analyses

The information from the inspection and structural analysis were assembled into a root cause failure report and presented to the owner/operator for review and evaluation. Following the review of the inspection findings, the project and operating team had to discuss the difficult task of repairing the overloaded structure. Due to the conditions of the tower, it was deemed unsafe to remove any existing structure without removing the fill above. The cleaning method had proven to be successful so the tower was found to have limited load when compared to the conditions of failure. Full analysis revealed that the most economical way to repair the existing structure and extend the life expectancy was to reinforce the failed fill supports with an additional double bolted support. Images of the original design along with the proposed repair solution are located in figures sixteen and seventeen.

<table>
<thead>
<tr>
<th>Date of Sample</th>
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</tr>
<tr>
<td>February 11, 2014</td>
<td>125 kg</td>
</tr>
<tr>
<td>February 12, 2014</td>
<td>147 kg</td>
</tr>
<tr>
<td>February 12, 2014</td>
<td>121 kg</td>
</tr>
<tr>
<td>February 12, 2014</td>
<td>123 kg</td>
</tr>
<tr>
<td>February 12, 2014</td>
<td>117 kg</td>
</tr>
<tr>
<td>Average Weight</td>
<td>133 kg</td>
</tr>
</tbody>
</table>

Table 2: Fill pack recorded weights – A new clean fill pack weighs 23 kg.

Figure 16: Original fill support and structural design that failed from excessive fouling.
Figure 17: Proposed structural repair that reinforced the existing supports to extend the life expectancy of the cooling tower fill support system.

Once a final repair design was agreed upon, the project team had to evaluate the use of associated construction materials. Considering the aggressive nature of the water, the owner/operator desired to use FRP material for the repairs. After review with the field construction team, it was determined that the use of FRP was not feasible due to the inconsistencies in the existing structure. To effectively reinforce the existing structure, the new tie line would have to be “wedged” into place using jacking apparatuses which would locally damage the fiberglass material. Considering this information, it was decided to install douglas fir material utilizing FRP shear bushings to increase the capacity of the bolted connections. Images of the prepared existing columns and the installed reinforcing fill supports are located in figures eighteen and nineteen.

Figure 18: Tower Structure prepared for the installation of reinforcing supports

Figure 19: Tower Structure following structural repair

Conclusion

The use of empirical methods for inspecting, analyzing and repairing cooling towers when using alternative materials, is not only required for proper design, but essential for adequate project execution. Identifying the source of the problem along while reviewing the viability of proposed materials, is cost effective and prudent to ensure a successful project outcome. Any repair project should involve detailed review by all of the parties involved and employ effective communication between the design team, the construction team and the inspection team. Utilizing these methods will increase the probability of a successful project and will ensure proper documentation of the means and methods used in the repair.

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Can Total Bacteria Measurement Be Used To Predict Legionella Presence?

Janet E. Stout, Scott Special Pathogens Laboratory

Abstract
Microbiological growth in cooling water systems presents several challenges for water treatment providers. Culture methods such as heterotrophic plate count (HPC) and “dipslides” provide valuable information related to general microbiological water quality but require several days to produce results. Alternative methods using adenosine triphosphate (ATP) measurement provide faster results and have been applied when rapid water quality assessment is necessary. Our evaluation reviewed potential applications for ATP analysis in cooling water systems. We also assessed whether total bacteria measurement using culture methods or ATP analysis can predict the presence/absence using both experimental data and data collected from field observations.

Introduction
Standard culture methods have been used for decades to quantify microbiological populations in cooling towers. Monitoring cooling towers for excessive growth of bacteria is essential for verification that the applied treatment program is working successfully and for protection of system components from fouling and corrosion associated with microorganisms. Culture methods such as heterotrophic plate count and use of dipslides have been adopted by many water treatment providers for routine analysis of bacterial concentrations in cooling water.

While culture methods provide reliable information regarding bacterial growth in cooling water systems, results for these analyses require several days of incubation in order to achieve accurate results. An alternative method for enumeration of microbial populations in cooling water samples, adenosine triphosphate (ATP) measurement, offers results in a much shorter time period (≤1 hr) using a simple test method performed on-site. While ATP measurement offers faster results than culture methods, little data is available comparing this method with established culture methods. The data presented in this report evaluates the correlation between HPC concentrations and microbial populations as approximated by ATP analysis for cooling water samples.

Measurement of total bacteria concentrations in cooling towers using both culture methods and ATP measurement has been proposed for use as an indicator of Legionella presence/absence. This report includes an evaluation of the ability of each testing method (ATP analysis and HPC) to correctly predict Legionella positivity in cooling water samples. Additionally, the variability of each testing method was assessed to evaluate the usefulness of each method as an indicator of Legionella positivity.

Materials & Methods

Sampling Locations
Sampling locations for this evaluation included two pilot-scale model cooling towers and the associated make-up water supply. Make-up water for each of the two cooling towers was dechlorinated using activated carbon and stored in four 125-gal. storage tanks. The maximum residence time of these tanks was approximately 48 hours, and the tanks were refilled with dechlorinated water daily.

Each of the two cooling towers operated at approximately 4-5 cycles of concentration with sump temperatures ranging from 95 – 105°F. The model cooling towers and make-up water supply evaluated in this study were previously described in Duda, Vidic, and Stout 2011.

Water samples were collected from two pilot-scale model cooling towers and their combined make-up water supply over an eight month period. One of the cooling towers (T1) remained untreated for the duration of the evaluation, while the remaining tower was treated sequentially with five non-chemical treatment devices. Devices evaluated during the investigation included magnetic, pulsed-power, electrostatic, ultrasonic, and hydrodynamic cavitation water treatment technologies. Each device was applied to the treated tower (T2) for a period of several weeks. A total of 54 samples were collected from the make-up water supply, while 108 samples were collected from the two cooling towers. All water samples were collected in sterile 250 mL HDPE bottles containing sodium thiosulfate for oxidant neutralization.

HPC Culture
HPC culturing of cooling water samples was done according to the Standard Methods for the Examination of Water and Wastewater pour plate method (9215B) using plate count agar (PCA). A series of four dilutions was prepared for each sample (10-2 – 10-4 for make-up water samples, 10-3 – 10-5 cooling tower samples), plated on PCA, and incubated at 36°C for three days prior to enumeration.

ATP Measurement
Measurement of ATP was performed in accordance with the procedure provided by the test kit manufacturer. A volume of 50 mL was filtered for each sample analysis, and ATP extraction and measurement was performed within 24 hours of sample collection. The concentration of ATP in each sample was measured as relative light units (RLUs) using a photometer, and the concentration of bacteria present in the sample was estimated using the following equation:

\[
\text{cATP (MEQs/mL)} = \frac{\text{RLU}_{\text{Sample}}}{\text{RLU}_{\text{Standard}}} \times \frac{10,000 \text{ pg ATP}}{V_{\text{Sample}} \text{ (mL)}} \times \frac{1 \text{ MEQ}}{0.001 \text{ pg ATP}}
\]
Legionella Culture
Samples were cultured Legionella based on ISO Standards 11731:1997 and 11731:2004. Legionella spp. culture media was laboratory-prepared buffered charcoal yeast extract (BCYE) agar and a selective dye-containing media supplemented with glycine, vancomycin, and polymyxin B (DGVP) (Ta et al., 1995).

Statistical Analysis
HPC bacteria concentrations from samples were transformed to log 10 data and analyzed using a Shapiro-Wilk test to verify normal distribution. A paired t-test was used to compare ATP and HPC data from cooling water samples, and a p-value below 0.05 was considered statistically significant.

Receiver Operating Curves (ROCs) were prepared for all ATP and HPC data for evaluation of the relationship between total microbial concentration and Legionella positivity. F-tests for analysis of variability were performed for all data to determine which microbial measurement (ATP or HPC) demonstrated greater stability (i.e. lower variability).

Results & Discussion
ATP/HPC and Legionella Presence
All cooling water data for samples collected from model cooling tower sumps were combined and analyzed to determine whether or not a correlation between heterotrophic bacteria concentration (HPC) and Legionella positivity was observable. Statistical data are summarized in Tables 1 and 2.

An ROC curve area >0.5 indicates that the tests being evaluated (use of HPC or ATP concentrations to predict Legionella positivity) is valid, while an ROC curve area <0.5 indicates that the test is not useful. The data collected during this evaluation demonstrated an ROC Curve Area <0.5 and no statistical significance (p>0.05). Neither HPC nor ATP concentrations were predictive of Legionella presence in the model cooling towers.

### Table 1: Relationship between total bacteria counts as determined by HPC and Legionella positivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cooling Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPC ROC Curve Area</td>
<td>0.28</td>
</tr>
<tr>
<td>HPC Geometric Log Mean (Positive for Legionella)</td>
<td>5.00</td>
</tr>
<tr>
<td>HPC Geometric Log Mean (Negative for Legionella)</td>
<td>5.60</td>
</tr>
<tr>
<td>p-value</td>
<td>&gt;0.05</td>
</tr>
</tbody>
</table>

### Table 2: Relationship between total bacteria counts as determined by ATP and Legionella positivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cooling Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP ROC Curve Area</td>
<td>0.44</td>
</tr>
<tr>
<td>ATP Geometric Log Mean (Positive for Legionella)</td>
<td>5.73</td>
</tr>
<tr>
<td>ATP Geometric Log Mean (Negative for Legionella)</td>
<td>5.83</td>
</tr>
<tr>
<td>p-value</td>
<td>&gt;0.05</td>
</tr>
</tbody>
</table>

ATP/HPC Measurement Variability
For all samples collected from the model cooling tower sumps, ATP had significantly lower variation than HPC (p = 0.026), indicating that ATP measurements demonstrated lower variability than traditional HPC culture methods.

ATP/HPC Correlation
Statistical analyses were performed to evaluate the correlation between HPC and ATP microbial concentrations measured in cooling water samples, and the results of these analyses are shown in Table 3. Correlation coefficients for samples collected from the model cooling tower sumps ranged from 0.52 – 0.54, demonstrating a very weak correlation between the two measurement methods. A weaker correlation (coefficient of correlation = 0.38) was observed for samples collected from the make-up water supply.

ATP measurements demonstrated higher microbial concentrations than HPC measurements. Lower HPC values (<10,000 CFU/mL) were extracted from the cooling water sample data and analyzed separately. This analysis showed that the correlation between HPC and ATP measurement was stronger for HPC concentrations >10,000 CFU/mL than for concentrations <10,000 CFU/mL (coefficient of correlation = 0.64 vs. 0.43).

Field Observations
Field data collected from a cooling system serving a large healthcare facility were also evaluated as part of this analysis. The facility cooling system included a total of five cooling towers served by a common sump. The cooling system is treated with sodium hypochlorite and a polymer corrosion inhibitor, and the water treatment provider performs routine monitoring of microbiological growth using ATP analysis. ATP analysis was being performed as a surrogate for both HPC and Legionella culture. The ATP analysis test kit used for evaluation of this tower was produced by a different manufacturer than the test kit used to collect data presented in the previous section.

Upon evaluation, samples collected from the each of the five cooling tower sumps for ATP analysis demonstrated unmeasurable levels of ATP. Subsequent evaluation of samples collected from the combined sump demonstrated the presence of Legionella pneumophila serogroup 1 at a concentration of 80 CFU/mL and an HPC concentration of 65,000 CFU/mL.

While these results are very limited in scope, they are indicative of the potential pitfalls associated with use of ATP analysis as a surrogate for culture methods. Routine monitoring of the towers consistently demonstrated undetectable quantities of ATP despite the presence of HPC concentrations in excess of 104 CFU/mL and Legionella pneumophila serogroup 1.

Conclusions
The data collected during this investigation did not indicate that there is a statistically significant correlation between HPC, ATP, and Legionella positivity in samples collected from the model cooling tower sumps. ATP measurement for cooling tower water quality analysis may be useful for fast evaluation of the efficacy of biocide application, but the weak correlation between ATP and HPC in cooling tower samples indicated that HPC may prove more useful for routine monitoring, particularly for regulatory compliance. Field observations where ATP was used as a surrogate for Legionella and HPC culture indicated that culture methods provide a better indicator of the microbiological quality of cooling water systems.

References


Eydal HSC and K Pedersen. 2007. Use of an ATP assay to determine viable microbial biomass in Fennoscandian Shield groundwater from depths of 3-1000 m. J. Microbiol Meth. 70:363-373.


Acknowledgements

Materials for ATP measurement and analysis were donated by Dave Tracey and Pat Whalen of LuminUltra Technologies Ltd. We would like to acknowledge Marilyn Wagener for her assistance with performance of statistical analyses. Additionally, we would like to thank Special Pathogens Laboratory for their assistance with processing of microbiological samples.
Hybrid Cooling Towers Water Savings Calculations and Measurements

Jean-Pierre Libert, John Lane, Andrew Carl and Micheal McCarrell; Evapco, Inc

Abstract
In many areas of the globe, water has become a critical natural resource. To address this, a variety of non-conventional cooling towers have been developed to consume less water, while still meeting the cooling capacity of a traditional evaporative tower. The variety in the design and operation of these hybrid cooling towers results in a wide spectrum of water savings potential, which is further amplified when considering the climate in which the hybrid cooling tower will be installed. Currently, there is no generally-accepted method for estimating the expected water savings from a specific hybrid design at a specific site; nor is there a generally-accepted method for verifying that the estimated water savings was realized. This paper proposes methods for both standardization of hybrid water savings calculations and verification of water savings by field measurements.

Introduction
It has become apparent that water, like energy, is a critical natural resource, not only in the arid southwest of the US, but throughout the world. The electric power generation industry is one of the largest users of water, with the main water consumption occurring in cooling. In the industry, both once-through and closed-cycle cooling (cooling towers) are used. Once-through cooling involves withdrawing cool water from a source – typically a river – and returning the same quantity of warm water back. It is generally accepted that very little water is consumed in this cooling process, as the only loss is from a slight increase in evaporation rate from the warmer discharged water. However, the thermal pollution of the source water can be an environmental issue. In addition, the thermal pollution of the source water can be an environmental issue. In addition, the newest regulations of the Clean Water Act §316 (b) imposes requirements on the water intake to minimize the impact to aquatic fish and shellfish, as well as mammals such as manatees. Cooling towers draw significantly less water into the facility than a once-through system but also ‘consume’ more water through evaporation.

Hybrid Cooling Systems
The cooling industry has developed a variety of hybrid cooling systems that conserve water. These hybrids combine dry cooling with evaporative cooling, providing less water usage than a conventional wet cooling tower, without sacrificing Rankine-cycle steam condensing temperature. A synopsis of current hybrid cooling tower technologies is shown below. For more information on these technologies, please reference TP14-19 [L11].

Parallel Condensers – This design consists of a smaller air-cooled condenser connected in parallel to a water-cooled condenser and a cooling tower. The system is self-balancing as the steam will travel to the lowest pressure unit. The wet cooling tower is typically sized to handle the full design load for when the ambient dry bulb is high.

Parallel Path Wet-Dry – This design is considered primarily for plume abatement. Finned coils, located in the plenum walls, are fed a portion of the hot circulating water. Ambient air is drawn through these coils and sensibly heated. This warm, dry air is then mixed in the plenum with the humid air from the evaporative heat exchanger, which reduces the cooling tower’s exhaust relative humidity and plume. Since some cooling is done by the coils, some water will be saved; however, the evaporative section must be large enough to handle the entire cooling load. This system is generally much taller than a conventional cooling tower.

Series Path Wet-Dry – This design is considered for higher water savings. Finned coils, located across the plenum, above the fill and nozzles and below the fan, are fed all of the hot circulat-
ing water, which is then sprayed over the evaporative heat exchanger. Ambient air first passes through the evaporative heat exchanger, then is heated sensibly through the finned coils, which minimizes plume. Since cooling is done by the coils, water will be saved. An added advantage in hot, dry climates, is that the dry bulb temperature of the evaporative exhaust may be lower than the ambient dry bulb, which allows for additional dry cooling, thus more water savings.

**Side-Stream Air Cooling** – This is another form of parallel path wet-dry technology. A side-stream dry cooler is fed a portion of the hot circulating water, which is then mixed and sent to an evaporative tower. Since some cooling is done by the coils, some water will be saved. The evaporative tower needs to be full sized, and there is no plume abatement.

**Air-to-Air in Plenum** – This design places an air-to-air heat exchanger above the wet cooling tower. The exhaust air from the cooling tower passes on one side of the heat exchanger while ambient air passes on the other. In some conditions, the cool ambient air condenses a portion of the evaporative exhaust air, returning the condensate to the basin. Since no cooling of the hot circulating water is done by the air-to-air heat exchanger, the wet tower must be full sized. This design is usually much taller than a conventional wet tower.

**Wet/Wet-Dry** – This design places sparsely finned coils side by side with a traditional evaporative section in the same airstream. On hot days, the coils are used as splash fill (no fluid in the coils), with a portion of the circulating water flow sprayed over them. In cool weather, however, the circulating water flow can be redirected to flow through the coils, allowing for dry cooling. The dry exhaust would then mix with the evaporative exhaust in the plenum, providing plume abatement. Since a portion of the cooling is done by the coils, some water will be saved. Since the dry coils are on the same level as the evaporative section, this design is much shorter than hybrid systems, and because the dry coils also double as splash fill, the footprint is only slightly larger than a conventional cooling tower.

Each of these hybrid cooling tower designs have different water savings potentials, costs, parasitic energy demands, reliability considerations, and space issues. A potential purchaser must evaluate using their site requirements and experience. And if that is not complicated enough, there is no accepted methodology for calculating the key requirement, how much water will be saved. This leaves each equipment supplier providing their own assumptions and calculations, and a potential purchaser buried in unverifiable information. The result is that the estimated water savings between two differing technologies is not comparable.

This leaves two quandaries:

1. How can a potential purchaser evaluate the water savings of different technologies when there is no industry-accepted method for doing so?
2. How can a potential purchaser verify that the cooling equipment supplied meets the advertised water savings when there is no industry-accepted method for doing so?

This paper proposes a method for standardization of hybrid water savings calculations and an additional method for verification of the water savings by field measurements. This insures that all cooling equipment and technologies can be assessed on a level field.

### General Approach

The authors’ proposed approach to estimating water savings is to compare the water use of a hybrid cooling tower to that of a calculated benchmark cooling tower. The calculated water usage by this benchmark will be the basis of comparison for all hybrid systems from all potential equipment providers for a given location and thermal load.

Typically, wet cooling towers for power plants operate under almost a constant load and circulating water flow, which means that as the ambient conditions change throughout the year, the cold and hot water fluctuate together to maintain a constant cooling range across the cooling tower. If energy savings is important, cooling towers may be operated at a set cold water temperature while fans are modulated to minimize power usage. Similarly, hybrid cooling towers typically operate at a constant cold water temperature set point in order to take maximum advantage of water saving modes.

For the sake of commonality and simplicity, this paper proposes that the hybrid mode of operation be used in all evaporation calculations. (Constant circulating water flow, and constant hot and cold water temperatures.) It will be shown later in this paper that this operating mode provides an accurate estimate of annual water usage even though the operating mode may differ from actual.

In summary, the proposed benchmark water consumption method includes these assumptions:

1. Constant heat loading all year long
2. Constant hot water and cold water temperatures
3. Site specific set of climate data (Typically ambient wet bulb, dry bulb and barometric pressures that reflect average annual weather conditions.)

With these assumptions, the annual water usage for a benchmark wet cooling tower can be calculated using a specific methodology, and should accurately reflect the loading and climate conditions at a specific location.

The hybrid equipment supplier will use the same assumptions outlined above to calculate any proposed hybrid technology’s water usage over a year. Equation (1) shows that the difference between the hybrid and benchmark water usages, divided by the benchmark water usage, equals the estimated hybrid water savings as a percentage.

\[
\text{Percent water savings} = \frac{P_{\text{wat}}}{Q_{\text{BEO}}} \cdot 100\% \tag{1}
\]

\[
Q_{\text{BEO}} = \text{Volume flow of evaporation (Benchmark) (l/s)}
\]

\[
Q_{\text{BEO}} = \text{Volume flow of evaporation (Hybrid) (l/s)}
\]

Note: blowdown is not included in the calculation. While all evaporative sites will require blowdown, the blowdown is assumed to be a fixed percentage of the make-up water for both the benchmark wet tower and the hybrid and thus does not affect the comparison.

The final, essential step is to validate the field performance of the hybrid cooling tower after commissioning. Unlike plume evaluation and thermal performance, there is no accepted methodology for measuring water consumption under specific conditions. A simple method of evaluating water consumption will be proposed, along with a more complex and more accurate method. The intent is that all parties involved in a hybrid cooling tower installation would agree to one of the two methods to verify water savings.
Benchmark Water Usage for a Wet cooling Tower

To create the benchmark water consumption of an evaporative cooling tower, an equation can be derived using a generalized equation of heat balance between air and water, and then manipulated to provide the exhaust air properties of enthalpy and humidity ratio. How this equation is derived and used is shown in Appendix A, but the main formula is Equation (2).

\[
\begin{align*}
\Delta \mu &= L + c_p \Delta T_w - (w_i - w_o) + c_p \Delta T_w \cdot \frac{L}{G} \\
\end{align*}
\]

\( h_w = \text{Enthalpy of exhaust air}, \quad h_i = \text{Enthalpy of inlet air} \) (J/kg)
\( c_p = \text{Specific heat of water (At average water temperatures (J/kg °C))} \)
\( T_w = \text{Temperature of cold water,} \quad \Delta T_w = \text{Change in water temperature(°C)} \)
\( w_i = \text{Humidity ratio of inlet air} \)
\( L = \text{Mass flow of hot water}, \quad G = \text{Mass flow of dry air (kg/s)} \)

From Equation (2), the known variables are enthalpy and humidity ratio of the inlet air (from climate data), the water temperatures (assumption that hot and cold water temperatures are set as constant), the mass flow of hot water (assumption of fixed 100% water flow) and the specific heat of water. Only the mass flow of dry air and the exhaust air conditions are still unknowns. The following assumptions can be made to reach a unique solution. Note: The effects and practicality of the final two assumptions will be addressed in Section 3.

1. Set the L/G ratio equal to a constant value of 1.0
2. Assume the exhaust air is 100% saturated

Knowing the exhaust air conditions will enable the evaporation rate to be calculated. Doing so for a set of climate data will yield an annualized water consumption that can be used as a benchmark for evaporative cooling towers. Appendix A explains in detail how this can be done.

Hybrid Cooling Tower Water Usage

Because of the numerous hybrid cooling tower offerings noted in Section 1.1, and the many variations of each, it is unlikely a standard evaluation can be created that works for all hybrid technologies. With that in mind, hybrid cooling tower water consumption calculations will be provided by the equipment supplier using their own (and often proprietary) rating methods. Because proprietary calculations are by nature obscured, the following provisions are proposed in order to ensure water consumption calculations are estimated on an equal basis.

1. The equipment supplier must estimate water consumption using the same climate data and assumptions (100% loading, constant hot and cold water temperature) that is used to calculate the wet benchmark. Note: This is critical. The same unit evaluated using different climate data can predict vastly different water savings.
2. The equipment supplier must provide evaporation curves that can be used to verify their hybrid cooling tower water consumption predictions.

The evaporation curves should show the evaporation rate vs. entering air wet bulb temperature for various entering air relative humidities. Since the wet benchmark cooling tower assumes constant load and constant range, evaporation curves that provide a direct comparison must (at minimum) depict the full design water flow and full design range at the appropriate altitude (or barometric pressure). An example of appropriate evaporation curves can be seen in Figure (1).

It is important that enough information be presented in the curves to evaluate every point in the appropriate climate data set. The annualized hybrid cooling tower water consumption can then be approximated by extracting the evaporation rate for each climate data point and then correcting for the number of hours or months used in the data set.

While a single evaporation graph that shows 100% water flow and cooling range is sufficient for verifying water savings compared to the benchmark, it is recommended that the equipment supplier provides more information in order to verify actual operating water consumption. The actual water consumption can be checked against the predictions using one of two proposed field tests outlined in Section 4.

For use with the field tests, it is recommended that the equipment supplier provide a set of at least nine evaporation curves, one for each of the combinations of 80%, 100%, and 120% design ranges, and 90%, 100%, and 110% design water flow (Similar to the plume characteristic performance curves from ATC-150). Since these curves are designed to estimate water consumption for actual operating conditions, it is recommended that they be calculated using full fan speed and letting the cold water temperature vary.

Note: It is possible that hybrid cooling towers can have different modes of operation, each designed to conserve more water or energy. For these cases, it is possible that evaporation curves would need to be generated for each mode of operation to verify all operating conditions.

Figure 1: Example of a generic cooling tower's evaporation at 100% water flow and cooling range. This example is based on a hot water temperature of 37.77 °C (100°F), a cold water temperature of 29.44 °C (85°F), and a volumetric water flow of 3,785.41 l/s (60,000 GPM). Sea Level.

Sensitivity Studies

In order to validate the assumptions made to simplify and standardize the evaporation calculations, studies were done to determine their effect on the resulting evaporation estimates.

Sensitivity of Annual Water Use to ‘L/G Ratio’

A significant assumption was made by setting the L/G ratio to a value of 1.0. This value was selected to simplify the benchmark equations, as well as to represent a reasonable average value of existing wet cooling tower applications. When evaluating the effect of L/G on
evaporation, it is important to remember that the load requirements of the condenser are specified for a specific water flow rate, which means changes to the L/G are really just changes in air flow rate.

While heat and mass transfer processes in a cooling tower are complex, a psychrometric chart can be used to model the air conditions within a cooling tower. The air can also be analyzed by separating the heat and mass transfer into two stages.

In the first stage, the inlet air is adiabatically saturated by following the wet bulb line to the saturation curve. This is illustrated by Curve 1 in Figure (2). Since an adiabatic path is assumed, no enthalpy is transferred from the water.

The second step involves the saturated air moving up the saturation curve (Curve 2 in Figure (2)). This is where enthalpy is transferred directly from the hot water to the air. The air will follow the saturation curve until the enthalpy lost from the water equals the enthalpy added to the air.

Since the enthalpy and humidity ratios are given per mass of air, the lower the ratio of air to water, (high L/G), the less water is needed to adiabatically saturate the air (Curve 1 in Figure (2)). However, lowering the ratio of air to water will also raise the exhaust air temperatures, forcing the exhaust air higher up the saturation curve (Curve 2 in Figure (2)).

When the air is cooler, toward the bottom-left of Figure 2, the saturation curve is flatter, which means more energy is transferred to the air via sensible cooling, heating the air, rather than using evaporation. For warmer temperatures, located in the upper right of Figure 2, the saturation curve is much steeper, which means less energy is transferred to sensibly heat the air than is transferred latently.

Knowing that the total amount of water evaporated in a cooling tower is equal to the mass flow of dry air multiplied by the difference in humidity ratio of the inlet and exhaust air (Equation A.3), it is clear that if the tower is operating where the saturation curve is steeper, more evaporation is expected. So the effect of the L/G is then dependent on where on the saturation curve the cooling tower is operating.

Figure (3) displays the effect of various L/G ratios on the total annual evaporation in four different climates. The results are normalized to the evaporation calculated for an L/G of 1.0 for each location.

At very low ratios, the amount of water required to adiabatically saturate the air dominates, and total calculated water usage artificially goes up due to the saturation assumption. At mid to high L/G ratios, the adiabatic cooling becomes less important and the effect of L/G on evaporation becomes minor. Although the outliers of Alaska (Arctic) and Arizona (Arid) show significant dependence on L/G, moderate climates begin leveling off at around an L/G value of 1.0. While not perfect, a value of 1.0 seems to provide a reasonable average benchmark.

Sensitivity of Annual Water Use to ‘Exhaust Air Saturation Assumption’

Another simplifying assumption in the benchmark water consumption calculations is that the exhaust air is fully saturated. For many inlet air conditions, that is a valid assumption, but when the inlet air is very dry (low relative humidity), this assumption may pose issues. Low L/G ratios (high air flows for a fixed water flow) will also tend to yield unsaturated air.

Using a proprietary program, exhaust air saturation was calculated for each of the weather data sets used to generate Figure (3). As can be seen in Figure (4), when the L/G value is lower, and the climate is more hot and arid, the evaporation can differ significantly if saturation is assumed.

In moderate climates, the difference in annual water consumption with an L/G of 1.0 is less than 5%; however, in hot, dry climates there is a greater error. A possible further refinement of the benchmark
Sensitivity of Annual Water Use to ‘Climate Data set’

Both hybrid and traditional cooling towers operate differently in varying climates. This cannot be clearer than in Figure (4). At an L/G of 2.0, a cooling tower located in Phoenix evaporates nearly 50% more water than the same cooling tower located in Alaska. This only highlights the importance of making sure all equipment is evaluated on the same climate data basis.

It is also important to realize that not all climate data sets are given in the same format. The most detailed data set may provide the average hourly climate on a monthly basis (24 hours x 12 months = 288 data points). Others reduce the number of data points by different averaging methods. Figure (5) shows how these averages trend over the course of a year.

Figure (6) shows that there is very little error introduced in the water consumption calculations by using a simplified climate dataset as shown in Figure (6). The benchmark evaporative cooling tower evaporation was calculated using each of the datasets from Figure (5).

Figure (6) shows that there is very little error introduced in the water consumption calculations by using a simplified climate dataset as long as there are at least 12 data-points (monthly averages).

Figure 5: Weather data for New York/JFK, showing the different averaging cases.

Figure 6: Calculated evaporation, using climate data that is averaged to varying degrees. Design conditions are the same as in Figure (1). L/G assumed to be 1.0.

Also Note: Hybrid systems may require more detailed data sets in order to take advantage of lower nightly or winter temperatures where dry modes can be implemented more frequently to increase water savings.

Field Testing

Two different methods are suggested for testing evaporation in the field. Choosing the appropriate method depends on many factors such as location, basin setup and whether or not the system is once through or closed-cycle. The best method can be determined from the procedures below.

Short Method

The first proposed test method will run in conjunction with an ATC-105 acceptance test, keeping the same protocol on allowable variances of design conditions and parameters of operation. However, with this evaporation test, the balance of water flow and air flow between tower cells is critical. The water flow to each cell must be within ± 5% of the average water flow per cell. The measured fan power must also be within ± 5% of the average fan power for each cell. A balanced tower will allow each cell to be considered identical for the evaporation measurement. During testing, any additional water source interacting with the circulating water loop (make-up water, other water usages, etc.) must be shut off. Since the blowdown will be turned off for the duration of the test, the tower should be pre-bled prior to the test to prevent over-cycling. Check with your water treatment professional on how this should be accomplished.

The tester must have accurate drawings of the cooling tower basin showing any obstructions such as piers, columns or screens present in the basin. The drawing should depict any slopes in the basin walls or bottom. This will allow the tester to choose whether this method is valid, and then select an ideal location to take measurements.

While running near design conditions, an initial and final measurement should be taken over a fixed amount of time. The height differential of the water level, along with area calculated from the basin drawings, will give a change in volume over time. This is the volumetric flow of evaporation.

The length of the test should be sufficient for a large enough change in basin water level. The uncertainty of the test decreases as both the length of the test and water height differential increase. To demonstrate, a test with 9.2 inch basin water level change over 60 minutes has the following uncertainty: Assuming the time is corrected but there is a quarter inch margin of error in the basin water level measurement, the final evaporation measurement would have a 4% uncertainty. This example is shown in Example B.2 in the Appendix B.

The short method will not work for all cooling tower layouts. It cannot be applied to once-through cooling towers as there is no standing basin water level. There should be as-built drawings of the basin. Rough measurements of the tower size could introduce

Note: This is different from estimating the parasitic fan power used by a wet cooling tower. Because of the cube of power requirement for air flow, use of coarse climate data will underestimate the parasitic power needed by an evaporative cooling system. If comparison of both energy and water usage is desired between a hybrid and wet tower, the finest data set available should be used.
error into the final measurement. Depending on the complexity of the basin, the short method may not be accurate enough for evaporation guarantees.

**Long Method**

For cooling towers unable to take advantage of the short method, there is a longer, more complex, method of evaporation testing. The long method is intended to be run during an ATC-150 plume abatement test. Similar to the short method, the balance of water flow and air flow to the cooling tower cells is critical for extrapolating evaporation to the entire tower. Each cell should be within ±5% of the average water flow and fan power measurements. This method allows for normal operation of the tower. Outside water sources may continue to run with the circulating water loop.

The long method uses psychrometric calculations of inlet and exhaust air streams to find a calculated evaporation flow after all the measurements have been performed on a single cell (or two cells) of the cooling tower. Following ATC-150, measurements are taken in the fan exhaust plane with multiple instruments along with the inlet air measurements. It is required to have a minimum of 20 different points of measurements following two perpendicular diameters forming equal annular area segments. Figure (8) demonstrates the instrument layout.

![Fan Hub Diameter](image)

**Figure 8 – Example of 20 instrument locations in fan exhaust plane during ATC-150 test.**

The instruments measure the local air velocity, wet bulb temperature and dry bulb temperature at each location. The measured temperatures combined with barometric pressure can be used to calculate the air properties at each location. Following the method described in ATC-150 5.3.3.3, average air properties are found using a weighted average based on local air velocities. The mass flow of dry air can also be found by using measured air velocity and integrating over the area of the fan exhaust. It is possible to measure negative air flows near the hub of the fan, which should be omitted when finding averages and air flow. Utilizing the mass flow of dry air, inlet and exhaust humidity ratios, it is possible to compute the mass flow of evaporation.

One of the disadvantages of the long method is the complexity in taking measurements, which increases the time of testing as well as the cost to the owner of the equipment. As a result, when this test is required, it is more likely that an already equipped CTI licensed test agency will be involved. It is worth noting that the level of accuracy of propeller or vane anemometers is not as good as the other instrumentation used by CTI Licensed test agencies, such as pitot tubes and Resistance Temperature Detectors (RTDs). This may lead to greater than 5% uncertainty on air flow measurements. An S-type Pitot tube may be advisable.

**Conclusion**

As water, like energy, becomes a critical natural resource, it is necessary not only to develop new water conservation technologies, but also to specify methods for evaluation and field verification. This technical paper introduces two proposals.

1. The first proposal specifies how to compute the amount of water consumed on an annual basis, by using a benchmark wet cooling tower using climate data and a relatively simple method of calculation. The calculation uses simplifying assumptions, but sensitivity analyses show that the margin of error from these assumptions is reasonable. The benchmark water consumption will be used by all potential equipment suppliers. The water usage of any hybrid cooling system on an annual basis will be directly compared to the proposed benchmark to generate a meaningful percentage of water conservation.

2. The second proposal introduces two procedures for measuring the water consumed by an actual cooling system operating in the field. A short procedure, intended to be run during an ATC-105 thermal acceptance test, determines evaporation rate by the evaluation of the water level drop in the cold water basin during a measured amount of time. The long method is intended to be run during an ATC-150 plume abatement test. It measures effluent air temperatures and uses psychrometric equations to compute the average humidity ratio of the exhaust air. From that, the rate of evaporation can be determined.

The authors further propose to use this technical paper as the basis to create two new Cooling Technology Institute standards: one, a bid standard to specify how to calculate proposed hybrid cooling tower water savings; the second, a test standard to evaluate, compare and field-measure water usage. Included in the first standard, would be detailed requirements of what the utility needs to supply to potential bidders by way of climate, altitude, load, et cetera.

**References:**


Appendix A: Details of Benchmark Calculation

This appendix will detail how to calculate the benchmark wet cooling tower evaporation.

Basic Wet Cooling Tower Variables

Figure (A.1) shows the water and air properties of a generic cooling tower.

![Figure A.1 – Overall heat balance for wet tower](image)

L<sub>hw</sub>, T<sub>hw</sub>  G, h<sub>ae</sub>, w<sub>e</sub>

L<sub>cw</sub>, T<sub>cw</sub>  G, h<sub>ai</sub>, w<sub>i</sub>

Basic Wet Cooling Tower Heat Balance

Starting with the concept that the heat entering the system is equal to the heat leaving the system, the following heat balance equation can be derived.

\[
q_{h\text{w}} + q_{c\text{w}} = q_{c\text{w}} + q_{h\text{w}}
\]

\[
q_{h\text{w}} = \text{Heat flow of hot water}, \quad q_{c\text{w}} = \text{Heat flow of cold water} \ (\text{W})
\]

\[
q_{c\text{w}} = \text{Heat flow of inlet air}, \quad q_{h\text{w}} = \text{Heat flow of exhaust air} \ (\text{W})
\]

Equation (A.1) simply states that the heat flow entering the system via the water and air, must equal the heat flow leaving the system via the water and air. Equation (A.1) can then be expanded using the variables defined in Figure (A.1) and known equations for heat flow.

\[
(h_{\text{hw}} \cdot c_{\text{hw}} \cdot T_{\text{hw}}) + (G \cdot h_{\text{ae}}) = (h_{\text{cw}} \cdot c_{\text{cw}} \cdot T_{\text{cw}}) + (G \cdot h_{\text{ai}})
\]

\[
t_{\text{hw}} \cdot c_{\text{hw}} = \text{Specific heat of hot water} \ (\text{J/kg \cdot °C})
\]

\[
t_{\text{cw}} \cdot c_{\text{cw}} = \text{Specific heat of cold water} \ (\text{J/kg \cdot °C})
\]

Reducing Unknowns

To calculate evaporation, Equation (A.3) can be used.

\[
\text{Evaporation (Mass Flow)} = L_{c\text{w}} = G \cdot (w_e - w_i) \ [\text{kg/s}]
\]

However, to implement Equation (A.3), the exhaust air humidity ratio must first be determined. To include this variable, a relationship can be expressed between the mass flows of cold water, hot water and evaporation. This expression can be further expanded using Equation (A.3).

\[
L_{c\text{w}} = [L_{h\text{w}} - L_{c\text{w}}] = [L_{h\text{w}} - G \cdot (w_e - w_i)]
\]

By inserting Equation (A.4) into Equation (A.2), then assuming that the specific heat of water can be expressed using the average water temperature, Equation (A.2) can then be written as:

\[
h_{\text{ae}} = h_{\text{ae}} + h_{\text{ai}} + c_{\text{pw}}(T_{\text{cw}} - T_{\text{ai}}) + c_{\text{pw}}(T_{\text{hw}} - T_{\text{cw}}) \cdot \frac{L_{h\text{w}}}{G}
\]

Equation (A.5) now has 3 unknowns.

- Exhaust air enthalpy and humidity ratio (h<sub>ae</sub>, w<sub>e</sub>)
- Mass flow of dry air (G)

To simplify the benchmark calculation, the mass flow of dry air can be assumed to be equal to the mass flow of hot water. This gives an L/G ratio of 1.0. (Note: the effects of this assumption is detailed in Section 3.1) Thus the equation can be simplified further.

\[
h_{\text{ae}} = h_{\text{ae}} + c_{\text{pw}}(T_{\text{cw}} - T_{\text{ai}}) + c_{\text{pw}}(T_{\text{hw}} - T_{\text{cw}}) \cdot \frac{L_{h\text{w}}}{G}
\]

Equation (A.6)

There are still two unknowns, but assuming the exhaust air is saturated, it is possible to iterate to a solution.

The first step is to approximate the enthalpy of the exhaust air by assuming that there is no loss of water from evaporation. The enthalpy of the exhaust air can be estimated by adding the inlet air enthalpy to the enthalpy removed from the water. From this value, and assuming the exhaust air relative humidity is 100%, the exhaust air humidity ratio can be approximated from psychrometric equations.

The second step is to use Equation (A.6) as intended, since an approximation of the exhaust air humidity ratio is now known. The resulting exhaust air enthalpy will be revised higher than step one, which now compensates for the water lost due to evaporation. (Note: This makes sense when looking at the energy balance Equations (A.1) and (A.2): if there is evaporation, the mass flow of the cold water (L<sub>cw</sub>) will be less, which means the heat in cold...
water will be less, which means the heat in the balancing exhaust air must be greater.)

The second step can then be repeated as needed until the humidity ratio and enthalpy values converge; typically, this only requires one to two iterations for reasonable precision.

Once the exhaust air humidity ratio is known, the evaporation rate can then be calculated. To find the mass flow of evaporation, simply multiply the mass flow of the dry air by the difference in the inlet and exhaust humidity ratio. The volume flow of evaporation will be that value divided by the density of the water at the average water temperature.

\[
\text{Evaporation (Volume Flow)} = Q_e = \frac{I_e}{\rho_{w,avg}} \text{l/s} \quad \text{Eq. (A.7)}
\]

\[
\rho_{w,avg} = \text{Density of Water (At Average Water Temperature) (kg/l)}
\]

Example A.1 (Single Point Analysis)
This example will evaluate the estimated evaporation for a single ambient condition for a wet benchmark cooling tower, assuming the following design conditions:

- Barometric pressure: 101.2445 kPa (29.8975 inHG)
- Inlet air conditions:
  - Wet bulb temperature: 25.55°C (78°F)
  - Relative Humidity: 50%
  - Dry bulb temperature: 34.3°C (93.75°F)
- Water conditions:
  - Hot water temperature \(T_{hw}\): 37.77°C (100°F)
  - Average water temperature \(T_{(w,avg)}\): 33.61°C (92.5°F)
  - Cold water temperature \(T_{cw}\): 29.44°C (85°F)
- Water flow \(Q_{hw}\): 3,785.41 l/s (60,000 GPM)

Inlet Air Properties
By using a psychrometric chart, or corresponding equations, the relevant inlet air properties can be determined.

Note: if using a psychrometric chart, be aware that discrepancies in results can occur from barometric pressure differences. For accurate results, psychrometric equations are recommended. These equations can be found in referenced book [AS1].

- Humidity ratio \(w_i\): 0.01717 (mass moisture/mass dry air)
- Enthalpy \(h_{ai}\): 78.513 kJ/kg (41.433 BTU/lb)

Water Properties
In order to calculate the relevant water properties, the following equations published by Detlev Kröger [Kr1] were used: \(\text{(Note: Equations valid for temperatures from 273.15K to 380K.}\)

\[
\rho_w = 0.001893 \cdot \frac{1}{T^2} - 0.00148 \cdot \frac{1}{T} + 0.000012 \cdot T + 0.999999 \quad \text{Eq. (A.8)}
\]

\[
\rho_w = \text{Water density (kg/m³), } T = \text{Temperature (°C)}
\]

\[
e_{pw} = 0.15599 \cdot T - 2.80627 \cdot 10^{-6} \cdot T^2 + 2.01283 \cdot 10^{-9} \cdot T^3 - 2.17586 \cdot 10^{-13} \cdot T^4
\]

\[
e_{pw} = \text{Water specific heat (J/kg-K), } T = \text{Temperature (°C)}
\]

Also, the mass flow of hot water can be calculated as:

\[
L_{hw} = \frac{Q_{hw} \cdot \rho_{w,hw}}{\rho_{w,hw}} = \frac{Q_{hw}}{\rho_{w,hw}}
\]

\[
L_{hw} = \text{Mass flow of hot water (kg/s)}
\]

\[
Q_{hw} = \text{Volume flow of hot water (l/s)}
\]

\[
\rho_{w,hw} = \text{Water density of hot water (kg/l)}
\]

By using equations (A.8), (A.9) and (A.10), the following water properties can be determined:

- Water density \(\rho_{w,hw}\): 993.156 kg/m³ (62.00 lb/ft³)
- Water density \(\rho_{w,(w,avg)}\): 994.584 kg/m³ (62.09 lb/ft³)
- Specific Heat \(c_{pw}\): 4177.4 J/kg-K (0.9978 BTU/lb-°F)
- Mass flow of hot water \(L_{hw}\):

\[
L_{hw} = 3.78541 \cdot \frac{1}{T_{hw}} \cdot \frac{1}{1000} \cdot \frac{1}{1000} \cdot 497.296 \text{ lb-min}
\]

Exhaust Air Properties – First Iteration
By using Equation (A.6) and assuming no evaporation, a first approximation of the exit air properties can be reached.

- Humidity ratio of exhaust air \(w_e\): \(w_{e,0} = w_i = 0.01717\) (mass moisture/mass dry air)
- Relative humidity of exhaust air: 100%
- Enthalpy of exhaust air \(h_{e,0}\):

\[
h_{e,0}(SI) = 81.325 \text{ kJ/kg}
\]

\[
h_{e,0}(IF) = 41.433 \text{ BTU/lb}
\]

Exhaust Air Properties – Second Iteration
By using a psychrometric chart, or corresponding equations, and knowing the relative humidity of the exhaust air (100%) and enthalpy of the exhaust air (113.325 kJ/kg) or (56.4 BTU/lb), the following properties can be determined:

- Humidity ratio of exhaust air \(w_e\): \(w_{e,1} = 0.03154\) (mass moisture/mass dry air)
- Relative humidity of exhaust air: 100%
- Enthalpy of exhaust air \(h_{e,1}\):

\[
h_{e,1}(SI) = 115.093 \text{ kJ/kg}
\]

\[
h_{e,1}(IF) = 57.62 \text{ BTU/lb}
\]

Exhaust Air Properties – Third Iteration
By using a psychrometric chart, or corresponding equations, and knowing the relative humidity of the exhaust air (100%) and enthalpy of the exhaust air (115.09 kJ/kg) or (57.62 BTU/lb), the following properties can be determined:

- Humidity ratio of exhaust air \(w_e\): \(w_{e,2} = 0.03211\) (mass moisture/mass dry air)
- Relative humidity of exhaust air: 100%
- Enthalpy of exhaust air \(h_{e,2}\):
Since the value of the exhaust air enthalpy has changed by less than 0.1% of the previous iteration, iterating further will provide no practical accuracy improvement.

The humidity ratio of the exhaust air \((w_e)\) after the third iteration is then:
\[
\begin{align*}
\text{w}_{e,3} &= 0.03213 \text{ (mass moisture/mass dry air)}
\end{align*}
\]

**Evaporation Calculation:**
To calculate the evaporation using Equation (A.3), the mass flow of dry air \((G)\) needs to be known. Since the benchmark wet cooling tower assumes an \(L/G\) value of 1, the following is true:
- The mass flow of exhaust air \((G)\): \(= (L_{hw}) = 3,759.51 \text{ kg/s} \) (497,298 lb/min)

Using Equation (A.3), the mass flow of evaporation \((L_E)\) is then:
\[
L_E = \left( 2,759.51 \text{ kg/s} \right) \left( 0.03213 - 0.01717 \right) = 56.29 \text{ kg/s} \approx 744.16 \text{ lb/min}
\]

Using Equation (A.7), the volumetric flow of evaporation \((Q_E)\) is then:
\[
Q_E = \frac{56.29 \text{ kg/s} \times 1000 \text{ l/min}}{994.594 \text{ m}^3} = 56.6 \text{ l/min} = 897 \text{ GPM}
\]

**Example A.2 (Yearly Evaporation Calculation)**
To estimate the benchmark wet cooling tower evaporation, a weather data profile must be provided. Per the weather averaging study done in Section 3.3, the minimal data required is a single monthly average for two of the following variables:
- Inlet Wet bulb
- Inlet Dry bulb
- Inlet Relative Humidity

Taking annual weather data for New York/JFK from [NN1] and averaging values for each month, the following table of temperatures specify the temperature profile for the year.

<table>
<thead>
<tr>
<th>Month</th>
<th>Wet bulb</th>
<th>Dry bulb</th>
<th>Wet bulb</th>
<th>Dry bulb</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>-1.142 °C</td>
<td>1.442 °C</td>
<td>29.945 °F</td>
<td>34.595 °F</td>
</tr>
<tr>
<td>February</td>
<td>-1.543 °C</td>
<td>1.300 °C</td>
<td>29.222 °F</td>
<td>34.340 °F</td>
</tr>
<tr>
<td>March</td>
<td>1.339 °C</td>
<td>4.646 °C</td>
<td>34.410 °F</td>
<td>40.363 °F</td>
</tr>
<tr>
<td>April</td>
<td>6.559 °C</td>
<td>10.667 °C</td>
<td>44.527 °F</td>
<td>51.200 °F</td>
</tr>
<tr>
<td>May</td>
<td>11.312 °C</td>
<td>15.188 °C</td>
<td>52.362 °F</td>
<td>59.338 °F</td>
</tr>
<tr>
<td>June</td>
<td>17.132 °C</td>
<td>20.667 °C</td>
<td>62.837 °F</td>
<td>69.200 °F</td>
</tr>
<tr>
<td>July</td>
<td>19.710 °C</td>
<td>23.850 °C</td>
<td>67.478 °F</td>
<td>74.930 °F</td>
</tr>
<tr>
<td>August</td>
<td>19.367 °C</td>
<td>23.946 °C</td>
<td>66.861 °F</td>
<td>75.103 °F</td>
</tr>
<tr>
<td>September</td>
<td>16.195 °C</td>
<td>20.329 °C</td>
<td>61.152 °F</td>
<td>68.592 °F</td>
</tr>
<tr>
<td>October</td>
<td>10.959 °C</td>
<td>14.392 °C</td>
<td>51.725 °F</td>
<td>57.905 °F</td>
</tr>
<tr>
<td>November</td>
<td>6.438 °C</td>
<td>9.500 °C</td>
<td>43.588 °F</td>
<td>49.100 °F</td>
</tr>
<tr>
<td>December</td>
<td>0.909 °C</td>
<td>3.617 °C</td>
<td>33.637 °F</td>
<td>38.510 °F</td>
</tr>
</tbody>
</table>

Using the weather data from Figure (A.2), and assuming the same barometric pressure and water conditions from Example (A.1), the evaporation rate for each month can be calculated by following the same process as Example (A.1), but varying the inlet wet bulb and dry bulb.

**Note:** The barometric pressure and water conditions are considered by the benchmark cooling tower analysis to be constant for year round operation. This means that the cooling tower will cool the specified water flow from the specified hot water temperature to the specified cold water temperature all year round.

<table>
<thead>
<tr>
<th>Month</th>
<th>(\dot{h}_{ev,3} ) (kJ/kg)</th>
<th>(w_{e,3} )</th>
<th>(L_E ) (kg/s)</th>
<th>(Q_E ) (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>43.312</td>
<td>0.01100</td>
<td>32.318</td>
<td>32.494</td>
</tr>
<tr>
<td>February</td>
<td>42.629</td>
<td>0.01083</td>
<td>32.490</td>
<td>32.666</td>
</tr>
<tr>
<td>March</td>
<td>47.724</td>
<td>0.01214</td>
<td>34.941</td>
<td>35.132</td>
</tr>
<tr>
<td>April</td>
<td>58.645</td>
<td>0.01507</td>
<td>38.951</td>
<td>39.163</td>
</tr>
<tr>
<td>May</td>
<td>68.555</td>
<td>0.01787</td>
<td>41.678</td>
<td>41.905</td>
</tr>
<tr>
<td>June</td>
<td>84.454</td>
<td>0.02256</td>
<td>44.160</td>
<td>44.400</td>
</tr>
<tr>
<td>July</td>
<td>92.735</td>
<td>0.02509</td>
<td>46.351</td>
<td>46.604</td>
</tr>
<tr>
<td>August</td>
<td>91.594</td>
<td>0.02474</td>
<td>46.889</td>
<td>47.144</td>
</tr>
<tr>
<td>September</td>
<td>81.665</td>
<td>0.02173</td>
<td>44.647</td>
<td>44.890</td>
</tr>
<tr>
<td>October</td>
<td>67.680</td>
<td>0.01762</td>
<td>40.787</td>
<td>41.009</td>
</tr>
<tr>
<td>November</td>
<td>57.527</td>
<td>0.01476</td>
<td>37.632</td>
<td>37.837</td>
</tr>
<tr>
<td>December</td>
<td>46.933</td>
<td>0.01193</td>
<td>33.736</td>
<td>33.920</td>
</tr>
</tbody>
</table>

**Figure A.2 – Monthly wet bulb and dry bulb profile for New York/JFK**

**Figure A.3 – Monthly evaporation rate calculation in SI**

**Figure A.4 – Monthly evaporation rate calculation in IP**

Taking the evaporation rates calculated in Figures (A.3) and (A.4) and multiplying by the operation time per month will result in the total monthly evaporation.

**Figure A.5 – Monthly total evaporated water**

<table>
<thead>
<tr>
<th>Month</th>
<th>Days</th>
<th>Hours</th>
<th>Evaporated Liters (In Millions)</th>
<th>Evaporated Gallons (In Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>31</td>
<td>744</td>
<td>87.032</td>
<td>22.991</td>
</tr>
<tr>
<td>February</td>
<td>28</td>
<td>672</td>
<td>79.027</td>
<td>20.877</td>
</tr>
<tr>
<td>March</td>
<td>31</td>
<td>744</td>
<td>94.096</td>
<td>24.858</td>
</tr>
<tr>
<td>April</td>
<td>30</td>
<td>720</td>
<td>101.511</td>
<td>26.816</td>
</tr>
<tr>
<td>May</td>
<td>31</td>
<td>744</td>
<td>112.238</td>
<td>29.650</td>
</tr>
<tr>
<td>June</td>
<td>30</td>
<td>720</td>
<td>115.086</td>
<td>30.402</td>
</tr>
<tr>
<td>July</td>
<td>31</td>
<td>744</td>
<td>124.823</td>
<td>32.975</td>
</tr>
<tr>
<td>August</td>
<td>31</td>
<td>744</td>
<td>126.271</td>
<td>33.357</td>
</tr>
<tr>
<td>September</td>
<td>30</td>
<td>720</td>
<td>116.354</td>
<td>30.737</td>
</tr>
<tr>
<td>October</td>
<td>31</td>
<td>744</td>
<td>109.837</td>
<td>29.016</td>
</tr>
<tr>
<td>November</td>
<td>30</td>
<td>720</td>
<td>98.073</td>
<td>25.908</td>
</tr>
<tr>
<td>December</td>
<td>31</td>
<td>744</td>
<td>90.851</td>
<td>24.000</td>
</tr>
<tr>
<td>Total</td>
<td>365</td>
<td>8760</td>
<td>1255.199</td>
<td>331.589</td>
</tr>
</tbody>
</table>
Appendix B: Field Test Procedures for Evaporation

This appendix will cover the procedures to find an accurate evaporation flow of a cooling tower in operation. Two methods are explained that can be run either in tandem with an ATC-105 acceptance test or an ATC-150 plume abatement test. Additional conditions are applied to the standards for higher accuracy in the evaporation result. The evaporation curves from the manufacturer should be available for planning the test appropriately, and evaporation guarantee evaluation.

Short Method

This method is intended to be run during an ATC-105 acceptance test. In addition to the performance curve and design conditions, an accurate drawing of the basin will be required for volume calculations.

The same variations are allowable on design conditions per ATC-105. For accurate evaporation results, other conditions should be monitored and can affect the validity of the test. The tower must be balanced and each cell water flow should be within ± 5% of the average cell flow. The fans must be running at full speed and be within ± 5% of the average fan power. During the evaporation test time frame, flows such as the make-up and blow-down must be turned off. This includes any other flows that are entering or exiting the circulating water loop.

The tester must have accurate drawings of the cooling tower basin and any obstructions such as piers present in the basin. The drawing should depict all obstructions as well as any gradients in the basin. This will allow the tester to choose an ideal location to take measurements. Measurements should be taken in the spot where the water level is above any slopes for simplicity of volume calculations.

Measuring the evaporation involves taking an initial and final basin water height measurement. The time between the initial and final measurement must be recorded to find the evaporation flow. As an example, an evaporation test could run for 60 minutes. The time-frame selected should take into account the volume of water in the cooling tower, so that issues with a low water level can be avoided. The volume of evaporation per unit time can then be found using:

\[
\text{Q} = \frac{L_{\text{basin}} \times W_{\text{basin}} \times (H_1 - H_2)}{t} \quad \text{Eq. (B.1)}
\]

\[
Q_e = \text{Volumetric flow of evaporation (m}^3/\text{hr)}
\]

\[
L_{\text{basin}} = \text{Basin length, } W_{\text{basin}} = \text{Basin width (m)}
\]

\[
H_1 = \text{Initial height of water, } H_2 = \text{Final height of water (m)}
\]

\[
t = \text{Time of test (hr)}
\]

The short method will not work for all cooling tower set ups. The method cannot be applied to once-through cooling towers as there is no standing basin water level. There should be up-to-date drawings of the basin or rough measurements of the tower size could introduce error into the final measurement. Depending on the complexity of the basin, the short method may not be recommended for evaporation guarantees.

Example B.1 (SI)

A 4 cell cooling tower with 16.5m x 18.3m cells is being tested with a flow of 16,000 m³/h. The basin is an open rectangle with 67.8m x 20.1m. To simplify the calculation, there is no slope to the basin, and the pillar obstruction is insignificant. During a 60 minute evaporation test, the basin water level drops 235mm.

The evaporation flow is 320 m³/h which comes out to 2.00% of the water flow. If there was an error of 4% on the basin water level change (± 7 mm on each individual measurement), the flow would be 320 ± 9.3 m³/h. The evaporation of the total flow would then be 2.00 ± .08 %.

Example B.2 (IP)

There is a 4 cell cooling tower with 54 foot x 60 foot cells cooling 70,000 GPM. The basin is an open rectangle with dimension 222 foot x 66 foot. An evaporation test is run for 60 minutes with a 9.2 inch basin water level change.

\[
Q_e = 222 \text{ ft} \times 66 \text{ ft} \times \frac{\pi \times 222^2}{12} \text{ ft} \times 7.48 \frac{\text{gal}}{\text{ft}^3} \times 60 \text{ min} = 1400 \text{ GPM}
\]

The volumetric flow of evaporation is found to be 1400 GPM which is 2.00% of the tower water flow. If there was an error of 4% on the basin water level change (± ¼ inch on each individual measurement), the flow would be 1400 ± 56 GPM. The evaporation of the total flow would then be 2.00 ± .08 %.

Long Method

The longer and more complex method of testing for evaporation is done in conjunction with an ATC-150 plume abatement test. The design conditions variations allowable by ATC-150 must be followed. The cell must be balanced within ± 5% of the average water flow per cell. The fan power of the each cell must be within ± 5% of the average fan power. There are no restrictions on the entering and exiting flows of the water loop in this test.

Measurements are taken of the effluent air during testing. The test measures the wet bulb temperature, dry bulb temperature and local air velocity of each measuring position. It is required to have 20 measuring stations setup in the exhaust plane of the fan stack. They are aligned in equal area location along two perpendicular diameters. The data is recorded and used to find the humidity ratio of the exhaust air flow. A weighted average based on the local air velocities is used over the 20 stations. The method used can be found in ATC-150 5.3.3.3. The exhaust mass air flow is integrated over the local mass air flow and fan stack area. Negative air flows may be measured near the fan hub and should not be used in finding average conditions or mass air flow.

The mass flow of dry air can be found by integrating the local air velocities over the fan discharge area. The calculated evaporation only applies to the cell that was tested. With the assumption that each cell is identical in operation, the evaporation can be multiplied by the total number of cells for evaporation in the cooling tower.

Evaporation (Mass Flow) = \[
L_e = 6 \times (w_e - w_i) \text{ [kg/s]} \quad \text{Eq. (B.2)}
\]

Evaporation (Volume Flow) = \[
Q_e = \frac{L_e}{\rho_{\text{exh}} \times \gamma} \text{ [l/s]} \quad \text{Eq. (B.3)}
\]

\[
L_e = \text{Mass flow of evaporation (kg/s)} \quad G = \text{Mass flow of dry air (kg/s)}
\]

\[
w_i = \text{Inlet air humidity ratio} \quad w_e = \text{Exhaust air humidity ratio}
\]

\[
Q_e = \text{Volume flow of evaporation (l/s)}
\]

\[
\rho_{\text{exh}} = \text{Density of water (At average water temperature) (kg/l)}
\]
Managing Reliability In Industrial Cooling Systems

This paper discusses the application of a management and tracking system employed to monitor water treatment performance, benchmark, identify opportunities, and improve reliability on critical cooling tower systems at multiple facility locations in the Americas. Benchmarking and the development of key performance indicators, KPIs, are critical to achieving reliability and meeting design service needs. The KPI values should be determined by weighing site and industry requirements as well as cost. The management team ensures system reliability by monitoring the critical KPIs, then reviewing and reconciling exceptions. The individual service representative and local plant owners are responsible for the escalation of critical issues until the specific issue is resolved.

Cooling system reliability in an air separation facility is critical because of the dramatic impact on plant productivity and energy costs. A 1 percent power penalty is generally anticipated for every 5°F gain in heat exchanger approach temperature. In addition to energy penalties these facilities usually have supply agreements with their host sites so unscheduled outages are disastrous.

The primary objectives of a cooling water program, KPIs, and responsibilities are provided in the bullet points that follow.

**Primary Objectives of the Cooling Water Treatment Programs**

- Maintain safe chemical storage, feed, and handling systems at each site.
- Allow the plant to meet regulatory, discharge, safety, and health requirements.
- Minimize microbiological growth within the system to prevent biological fouling, underdeposit corrosion, and propagation of organisms harmful to health, such as Legionella.
- Control corrosion rates at acceptable levels to protect assets and minimize maintenance.
- Maintain clean heat exchangers free from fouling or scale to allow efficient plant operation.
- Operate using the best available chemistry and technology to meet overall performance guidelines and minimize total operational costs.
- Achieve fiscal goals while achieving best-in-class results.

**Key Performance Indicators and Service Standards**

- Corrosion rates are monitored on 60-day intervals.
- Mild steel <3.0 mils per year (mpy) with no pitting with a target of <2.0.
- Copper Alloys <0.3 mpy with no pitting with a target of <0.2.
- Stainless steel <0.1 mpy with no pitting.
- Microbiological Control
  - Aerobic counts <10^4 cfu/mL (colony forming units) tested each visit.
  - SRB (sulfate reducing bacteria) target of 0.0 cfu/mL tested quarterly.
- Approach Temperatures
  - Defined as the gas temperature exiting the cooling minus the supply cooling water temperature. These should be trended with the objective of maintaining the design temperatures. Increases should be jointly investigated by the site water treatment team to maintain plant efficiency.
- Water Usage and Cost Control
  - Meet budgeted water consumption goals by maintaining design cycles of concentration and identifying leaks and overflows on a timely basis.
  - Meet design cost estimates with accurate chemical feed and control systems.
- 100 percent compliance to service visit intervals with a standardized report including KPIs for each scheduled visit.
- Zero chemical run-outs by monitoring and control of chemical inventory.
- Provide the plant personnel with site work instructions and operator training to execute the program and respond to program deviations and potential emergencies.
- Targeted cost savings through productivity and cost improvement projects.
- Cost within contract price.

**Responsibilities**

**Plant Personnel Responsibilities (Includes plant management and operations)**

- Execute the program application manual.
- Contact the service representative if any deviations aren’t covered by the work instructions or cannot be quickly remedied.
- Escalate any performance failures or service lapses.
- Respond to all emergencies following troubleshooting guidelines and notifying service representative as quickly as possible.
Real experts, real results

The Best People
Experienced service engineers who live in your community

Results That Last
Extending asset life while minimizing chemical and water usage

Continuous Innovation
Delivering customized products with a full-service analytical lab and R&D group

Environmental Protection & Safety
Protecting your people, your brand, and the environment with our innovative solutions

Phone number: 804-935-2000
Website: www.chemtreat.com
Water Treatment Consultant Responsibilities

- Create the site work instructions and train the plant personnel.
- Monitor performance trends and provide proactive program consulting.
- Provide a service report with guidance with each service visit.
- Work with the management team to mitigate exceptions and initiate program improvements.
- Escalate any performance issues or maintenance requirements.

Oversight Team Responsibilities (includes vendor and program owner)

- Select and appoint both a technical coordinator and an commercial account manager from both the supplier and customer teams.
- Define KPIs.
- Drill down on exceptions to KPIs across the network.
- Develop action plans with specific and measurable goals for all KPI exceptions.
- Focus on continuous improvement and evaluation of alternate technologies.
- Prepare and execute contingency plans for upset conditions.
- Review and approve program changes.
- Respond to escalation events.
- Develop and implement training plans on an annual basis.
- Quarterly meetings to review all KPIs, KPI exceptions, action plans, productive savings projects, and goal-setting for the upcoming quarter.
- Annual review meetings, review results for entire past four quarters and set goals for the next four quarters.

Impact to System

- Impact varies based on the developed pH and alkalinity. Drops to pH 6.0–8.3 can usually be addressed with additional or supplemental corrosion inhibitors.
- Drops below pH 6.0 need immediate attention and could cause discharge violations.
- Immediate corrosion damage accelerating rapidly below pH 6.0. The system will likely need to be passivated as the protective layers will be stripped.

Corrective Actions

1. Notify representative and program manager of the excursion.
2. Grab a sample for investigation.
3. Increase blowdown for dilution.
4. Attempt to identify and correct the source of contamination. If ammonia and denitrifying bacteria are the cause, an aggressive biocide program will be necessary.
5. Increase the corrosion inhibitor and dispersant to 200 percent of the normal level (if allowed by permit). If the pH drops further, it may be because the additives are acidic.
6. If acid overfeed is isolated as the cause of the excursion, use soda ash (preferred) or dilute caustic (<25 percent) to bring the pH to 6.5–8.2 while continuing increased blowdown. Reducing cycles is critical to prevent significant iron precipitation.
7. Work with the representative or corporate technical support to develop a repassivation plan, typically 2–3 times normal inhibitor package for 2–3 days.

Results

The results of employing this oversight team and focus on key performance indicators have been extremely beneficial to both parties since inception in 2008. The water treatment supplier has enjoyed business expansion within the customer base, and the client has developed a reliable method for benchmarking and performance gap identification, and has effectively increased productivity and reliability in their manufacturing facilities. In addition, both parties have a transparent method of resolving performance gaps, troubleshooting, and driving improvement. Several charts from a recent KPI review and a portion of the cooling tower troubleshooting guide are provided to illustrate the results achieved with this structure.

Cooling Tower Troubleshooting Guide

Low pH Excursions

Potential Causes

- Overfeed of acid or acidic additives.
- CO$_2$ leak.
- Ammonia absorption and microbial oxidation to nitric acids.
- SO2 or H2S adsorption.
Corrosion Coupons
% Mild Steel < 3 mpy

Corrosion Coupons
% 90/10 < 0.3 mpy

2014 Q2 - 82 steel type alloy coupons analyzed
79 coupons within specifications

2014 Q2 - 67 copper alloy coupons analyzed
64 coupons within specifications

Research Cottrell Cooling, Inc.
For All Your Cooling Needs

Research Cottrell Wet Cooling
Keith Silverman
908-333-2049
Keith.Silverman@rc-cooling.com

Jennifer Kellogg
908-333-2004
Jennifer.Kellogg@rc-cooling.com

Research Cottrell Dry Cooling
Neil Dahlberg
908-333-2022
Neil.Dahlberg@rc-cooling.com

With more than 100 years of experience in cooling tower technology, we specialize in custom solutions for the full spectrum of cooling tower applications in many industries, including power generation, petrochemical and chemical.

Our capabilities cover:

- New, design and supply of Air-Cooled Steam Condensers (ACC)
- New, turnkey design and construction of Mechanical and Natural Draft Cooling Towers
- Repairs, repacks, and upgrades to existing Mechanical and Natural Draft Cooling Towers
- Spare parts – including fan stacks, drift eliminators, fill media, distribution systems, and mechanical equipment

A subsidiary of Hamon Corporation
Cooling Towers Certified by CTI Under STD-201

As stated in its opening paragraph, CTI Standard STD-201 "...sets forth a program whereby the Cooling Technology Institute will certify that all models of a line of evaporative heat rejection equipment offered for sale by a specific Manufacturer will perform thermally in accordance with the Manufacturer’s published ratings..."

By the purchase of a CTI Certified model, the Owner/Operator has assurance that the tower will perform as specified.

*Performance as specified when the circulating water temperature is within acceptable limits and the air supply is ample and unobstructed. CTI Certification under STD-201 is limited to thermal operating conditions with entering wet bulb temperatures between 10°C and 32.2°C (50°F to 90°F), a maximum process fluid temperature of 51.7°C (125°F), a cooling range of 2.2°C (4°F) or greater, and a cooling approach of 2.8°C (5°F) or greater. The manufacturer may set more restrictive limits if desired or publish less restrictive limits if the CTI limits are clearly defined and noted in the publication.

For each certified line, all models have undergone a technical review for design consistency and rated performance. One or more representative models of each certified line have been thoroughly tested by a CTI Licensed testing agency for certification and found to perform as claimed by the Manufacturer.

The CTI STD-201 Thermal Performance Certification Program has grown rapidly since its inception in 1983 (see graphs that follow). A total of 41 cooling tower manufacturers are currently active in the program. In addition, 8 of the manufacturers also market products as private brands through other companies.

While in competition with each other, these manufacturers benefit from knowing that they each achieve their published performance capability and distinguish themselves by providing the Owner/Operator’s required thermal performance. The participating manufacturers currently have 103 certified product lines plus 14 product lines marketed as private brands which result in more than 22,500 CTI Certified cooling tower models to select from.

For a complete listing of certified product lines, and listings of all CTI Certified models, please see:

http://www.cti.org/certification.shtml

Those Manufacturers who have not yet chosen to certify their product lines are invited to do so at the earliest opportunity. Contact the CTI Administrator at vmanser@cti.org for more details.
Program Participation
Through May 31, 2015

Number of CTI Certified Product Lines

Number of Participating Manufacturers
Current Program Participants

Program Participants and their certified product lines are listed below. Only the product lines listed here have achieved STD 201 certification. For the most up-to-date information and a complete listing of all CTI Certified models please visit:

http://www.cti.org/certification.shtml

Current Certified Model Lists are available by clicking on the individual line names beneath the Participating Manufacturer name.

Catalog information and product selection data are also available by clicking on the links beneath each listed line.

A

Advance GRP Cooling Towers, Pvt., Ltd.
Advance 2020 Series A Validation No. 07-31-01

Aggreko Cooling Tower Services
AG Line Validation No. 08-34-01

Amcot Cooling Tower Corp.
Series R-LC Validation No. 11-20-05

American Cooling Tower, Inc.
ACF Series Validation No. 10-38-01
ACX Series Validation No. 13-38-02

AONE E&C Corporation, Ltd.
ACT-C Line Validation No. C28B-09R01
ACT-R/ACT-RU Line Validation No. C28A-05R03

B

Baltimore Aircoil Company, Inc.
ACT Line Validation No. 08-11-12
FXT Line Validation No. 92-11-01
FXV Line Validation No. 98-11-09
PCT Line Validation No. 10-11-13
PF2 Series Validation No. C11P-12R01
PT2 Series Validation No. C11L-07R03
Series V Closed VF1 & VFL Validation No. 00-11-10
Series V Open VT0, VT1, VTL & VTL-E Validation No. C11B-92R05
Series 1500 Validation No. C11H-94R09
Series 3000 A,C,D,E & Compass Validation No. C11F-92R16

Bell Cooling Tower Pvt, Ltd.
BCTI Line Validation No. C43A-12R02

C

Cool Water Technologies
RTAi Line Validation No. C52A-13R01
RTi Line Validation No. C52B-13R01

D

Delta Cooling Tower, Inc.
TM Series Validation No. 02-24-01
Decsa
RCC Series Validation No. C42C-14R00

E

Elendoo Technology (Beijing) Co., Ltd.
ELH Line Validation No. 13-50-01
ELOP Line Validation No. C50B-14R00

Evapco, Inc.
AT Series Validation No. C13A-99R16
ATWB Series Validation No. 09-13-06
ESWA & ESWB Series Validation No. 05-13-05
L Series Closed Validation No. 09-13-07
L Series Open Validation No. 05-13-03
PMTQ Line Validation No. 10-13-09
PMWQ Line Validation No. 10-13-08
AXS Line Validation No. C13K-15R00

G

GEA Polacel Cooling Towers, B.V.
CF Series Validation No. 04-25-01
G

GEA Polacel Cooling Towers, B.V.
GEA XF Series Validation No. 13-25-02
GOHL (E.W.Goehl, GmbH)
DTC-ecoTec Line Validation No.C92A-14R01
Guangzhou Laxun Technology Exploit Company, Ltd.
HMK Line Validation No. C45A-12R02
LMB Line Validation No. 12-45-02

H

Hunan Yuanheng Technology Development Company, Ltd.
YHA Line Validation No. C40A-11R03
HVAC/R International, Inc.
Therflow Series TFC Validation No. C28B-09R01
Therflow Series TFW Validation No. C28A-05R03

J

Jaci
KS Line Validation No. 12-46-01

Jiangsu Dayang Cooling Tower Co., Ltd.
HLT Line Validation No. C94A-14R00

Jinan Chin-Tech Thermal Technology Co., Ltd.
CTN Line Validation No. C91A-14R00
CTH Line Validation No. C91B-14R00

K

KIMCO (Kyung In Machinery Company, Ltd.)
CKL Line Validation No. C18B-05R03
Eco-Dyna Cool Line Validation No. C18C-09R01
Endura Cool Line Validation No. C18A-93R07

King Sun Industry Company, Ltd.
HKB Line Validation No. 09-35-01
HKD Line Validation No. 09-35-02
KC Line Validation No. 11-35-03

L

Liang Chi Industry Company, Ltd.
Series C-LC Validation No. C20B-09R01
Series D-LC Validation No. C20F-14R00
Series R-LC Validation No. 11-20-05
Series U-LC Validation No. C20D-10R03
Series V-LC Validation No. 10-20-03

Marley (SPX Cooling Technologies)
Aquatower Series Validation No. 01-14-05
AV Series Validation No. 98-14-04
MCW Series Validation No. 06-14-06
MD Series Validation No. 08-14-11
MHF Series Validation No. C14G-04R07
NC Series Validation No. C14A-92R17
Quadraflow Line Validation No. 92-14-02
NX Series Validation No. C14M-15R00

Mesan Cooling Tower, Ltd.
MCC Series Validation No. C26G-12R02
MXC Series Validation No. 12-26-08
MXL Series Validation No. 12-26-06
MXR-KM Series Validation No.C26C-08R05

Munters Corporation
Oasis PFC Line Validation No. 12-48-01

N

NIBA Su Sogutma Kularleri San, ve Tic, A.S.
HMP-NB Line Validation No. C55A-14R00
Nihon Spindle Manufacturing Company, Ltd.
KG Line Validation No. C33B-12R02

O

OTT Company, Ltd.
OTTC Line Validation No. 12-44-01
OTTX Line Validation No. 12-44-02
OTTC-C Line Validation No. C44C-14R00
OTTX-C Line Validation No. C44D-14R00

P

Paharpur Cooling Tower, Ltd.
CF3 Line Validation No. C51A-13R01
OXF-30K Line Validation No. C51B-14R00
Protec Cooling Towers, Inc.
FRS Series Validation No. 05-27-03
FWS Series Validation No. 04-27-01

R

Reymsa Cooling Towers, Inc.
(Fabrica Mexicana de Torres, SA de CV)
HFC Line Validation No. 10-22-06
HRFG Line Validation No. 04-22-03
LSFG Line Validation No. 09-22-04
RT & RTM Series Validation No. C22G-13R03
SLSFG Line Validation No. 09-22-05

RSD Cooling Towers
RSS Series Validation No. 08-32-01

Ryowo (Holding) Company, Ltd.
FCS Series Validation No. 10-27-04
FDC Series Validation No. 11-27-05
FRS Series Validation No. 05-27-03
FVS Series Validation No. 12-27-06
FWS Series Validation No. 04-27-01
FXS Series Validation No. 05-27-02

S

Shanghai Baofeng Machinery Manufacturing Co., Ltd.
BTC Line Validation No. 12-49-01
Shanghai Liang Chi Cooling Equipment Co., Ltd.
LCM Line Validation No. C82A-14R00
Shanghai Tyacht Cooling System Co., Ltd.
TCT Line Validation No. C83A-15R00
TCC Line Validation No. C93B-14R00
Shanghai Wanxiang Cooling Equipment Company, Ltd.
FBH Line Validation No. 13-54-01
FKH/FKHL Series Validation No. C94A-14R00
Shangyu Dongjie Cooling Tower Co., Ltd.
DMNC Line Validation No. C63A-15R00
DHC Line Validation No. C83B-15R00
Sinro Air-Conditioning (Fogang) Company, Ltd.
CEF-A Line Validation No. C37B-11R02
SC-B Series Validation No. C37C-11R02
SC-H Series Validation No. C37A-10R02

Ta Shin F.R.P. Company, Ltd.
TSS Series Validation No. 08-32-01
Thermal-Cell sdn bhd
TYH Line Validation No. C40A-11R03
Tower Tech, Inc.
TTXL Line Validation No. C17F-08R04
Truwater Cooling Towers, Inc.
EC-S Series Validation No. 12-41-01
EX-S Series Validation No. 12-41-02
VXS Series Validation No. 13-41-03

Wuxi Fangzhou Water Cooling Equipment Co., Ltd.
FKH Line Validation C64A-14R00
FNB Line Validation C64B-15R00

Yantai Ebara Air Conditioning Equipment Company, Ltd.
CDW Line Validation No. C53A-13R01
CXW Line Validation No. C53A-14R00
York (By Johnson Controls)
AT Series Validation No. C13A-99R16
ESWA & ESWB Series Validation No. 05-13-05
LSTE Line Validation No. 05-13-03

Zhejiang Jinling Refrigeration Engineering Company, Ltd.
JNC Series Validation No. C28B-09R01
JNT Series Validation No. C28A-09R03
Zhejiang Wanxiang Science and Technology Company, Ltd.
FBH Line Validation No. 13-54-01

For a complete listing of certified product lines, and listing of all CTI Certified models, please see:

http://www.cti.org/certification.shtml

Always look for the CTI Certified Label
with Validation Number on Your Equipment
SAVE THE DATE

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PRODUCTS MAGAZINE
For nearly thirty years, the Cooling Technology Institute has provided a truly independent, third party, thermal performance testing service to the cooling tower industry. In 1995, the CTI also began providing an independent, third party, drift performance testing service as well. Both these services are administered through the CTI Multi-Agency Tower Performance Test Program and provide comparisons of the actual operating performance of a specific tower installation to the design performance. By providing such information on a specific tower installation, the CTI Multi-Agency Testing Program stands in contrast to the CTI Cooling Tower Certification Program which certifies all models of a specific manufacturer's line of cooling towers perform in accordance with their published thermal ratings.

To be licensed as a CTI Cooling Tower Performance Test Agency, the agency must pass a rigorous screening process and demonstrate a high level of technical expertise. Additionally, it must have a sufficient number of test instruments, all meeting rigid requirements for accuracy and calibration.

Once licensed, the Test Agencies for both thermal and drift testing must operate in full compliance with the provisions of the CTI License Agreements and Testing Manuals which were developed by a panel of testing experts specifically for this program. Included in these requirements are strict guidelines regarding conflict of interest to insure CTI Tests are conducted in a fair, unbiased manner.

Cooling tower owners and manufacturers are strongly encouraged to utilize the services of the licensed CTI Cooling Tower Performance Test Agencies. The currently licensed agencies are listed below.

**Licensed CTI Thermal Testing Agencies**

*License Type A, B*

**Clean Air Engineering**
7936 Conner Rd, Powell, TN 37849
800.208.6162 or 865.938.7555
Fax 865.938.7569
www.cleanair.com / khennon@cleanair.com

*Contact:* Kenneth (Ken) Hennon

**Cooling Tower Technologies Pty Ltd**
PO Box N157, Bexley North, NSW 2207 AUSTRALIA
+61.2.9789.5900 / (F) +61.2.9789.5922
coolingtwrtech@bigpond.com

*Contact:* Ronald Rayner

**Cooling Tower Test Associates, Inc.**
15325 Melrose Dr., Stanley, KS 66221
913.681.0027 / (F) 913.681.0039
www.cttai.com / cttakc@aol.com

*Contact:* Thomas E. (Tom) Weast

**McHale & Associates, Inc.**
4700 Coster Rd, Knoxville, TN 37912
856.588.2654 / (F) 865.934.4779
www.mchale.org / ctitesting@mchale.org

*Contact:* Jared Medlen

*Type A license is for the use of mercury in glass thermometers typically used for smaller towers.
Type B license is for the use of remote data acquisition devices which can accommodate multiple measurement locations required by larger towers.
Cooling Technology Institute

Sound Testing

Cooling towers are used extensively wherever water is used as a cooling medium or process fluid, ranging from HVAC to a natural draft cooling tower on a power plant. Sound emanating from a cooling tower is a factor in the surrounding environment and limits on those sound levels, and quality, are frequently specified and dictated in project specifications. The project specifications are expected to conform to local building codes or safety standards. Consequently, it may be in the interest of the cooling tower purchaser to contract for field sound testing per CTI ATC-128 in order to insure compliance with specification requirements associated with cooling tower sound.

Licensed CTI Sound Testing Agencies

CTI Thermal Certification Agencies

Licensed CTI Thermal Certification Agencies

Agency Name
Clean Air Engineering
7936 Conner Rd, Powell, TN 37849
800.208.6162 or 865.938.7555
Fax 865.938.7569
www.cleanair.com / khennon@cleanair.com
Contact: Kenneth (Ken) Hennon

Cooling Tower Test Associates, Inc.
15325 Melrose Dr., Stanley, KS 66221
913.681.0027 / (F) 913.681.0039
www.cttai.com / cttakc@aol.com
Contact: Thomas E. (Tom) Weast

&

SSA Acoustics
222 Etruria St., Ste 100
206.839.0819
www.ssaacoustic.com / erik@ssaaoustics.com
Contact: Erik Miller-Klein

McHale & Associates, Inc.
4700 Coster Rd, Knoxville, TN 37912
856.588.2654 / (F) 865.934.4779
www.mchale.org / ctitesting@mchale.org
Contact: Jared Medlen

Jointly:

As stated in its opening paragraph, CTI Standard 201... "sets forth a program whereby the Cooling Technology Institute will certify that all models of a line of water cooling towers offered for sale by a specific Manufacturer will perform thermally in accordance with the Manufacturer's published ratings...". By the purchase of a "certified" model, the User has assurance that the tower will perform as specified, provided that its circulating water is no more than acceptably contaminated-and that its air supply is ample and unobstructed. Either that model, or one of its close design family members, will have been thoroughly tested by the single CTI-licensed testing agency for Certification and found to perform as claimed by the Manufacturer.

CTI Certification under STD-201 is limited to thermal operating conditions with entering wet bulb temperatures between 12.8°C and 32.2°C (55°F to 90°F), a maximum process fluid temperature of 51.7°C (125°F), a cooling range of 2.2°C (4°F) or greater, and a cooling approach of 2.8°C (5°F) or greater. The manufacturer may set more restrictive limits if desired or publish less restrictive limits if the CTI limits are clearly defined and noted in the publication.

Those Manufacturers who have not yet chosen to certify their product lines are invited to do so at the earliest opportunity. You can contact Virginia A. Manser, Cooling Technology Institute at 281.583.4087, or vmanser.cti.org or PO Box 681807, Houston, TX 77268 for further information.
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Microsoft Windows® 95/98, 2000, XP, and Windows 7
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