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For Immediate Release
Contact: Chairman, CTI Multi-Agency Testing Committee

Houston, Texas, 3-May-2011

The Cooling Technology Institute announces its annual invitation for interested drift testing agencies to apply for potential Licensing as CTI Drift Testing Agencies. CTI provides an independent third party drift testing program to service the industry. Interested agencies are required to declare their interest by July 1, 2011, at the CTI address listed.

Martin Richard (Marty) Orban passed away on Friday, May 6, 2011 following a lengthy and courageous battle with cancer. Marty retired from his professional career in February, 2009, after nearly 22 years at Mitco, Inc. and working at Calgon for some 12 years prior to that. Over the course of his career, Marty was honored to be active in the Cooling Technology Institute (CTI), the International Water Conference (IWC) where he served as a member of the Advisory Council for many years, and other industry technical groups. Marty was a proud veteran of the United States Air Force, serving in Viet Nam from 1963-67, and a graduate of Point Park College with a degree in Chemical Engineering. Marty will be missed by all his friends and colleagues, but most particularly by his wife, C.J., sons Chad and Tyler Antonides, daughter Melissa (Brandon) Barck, and his grandchild on the way. Marty enjoyed sailing and driving his antique Delorean sports car, as well as travelling. A memorial service was held in Grand Rapids on May 11th to honor this fine man and coworker.
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Swifter
2011 has been an eventful year so far all around the world from the earthquakes and the tsunami resulting in the devastation and nuclear power plant disasters in Japan, to the end of the hunt for Bin Laden, to considerable political unrest in the Middle East causing unstable fuel prices, as well as flooding in the Mississippi river basin that has not been experienced since 1937. You can never be sure what the future may bring.

But in CTI’s future, you can be sure that the one of our most important annual events, the Summer Work Shop, is occurring again this July 17 -20 at the Omni Amelia Island Plantation Resort in Florida. Early indicators are predicting that this summer meeting will be well attended by CTI members and interested individuals from all over globe. This is the time that CTI members and new attendees to the work shop recommend and prepare new standards; as well as update and verify existing standards, codes and guidelines that are so important to our industry. This is the meeting where the work really gets done. Open discussions and an exchange of technical information and expertise results in the excellent and numerous codes and standards that CTI has continuously offered to the industry for 50 plus years. These codes and standards have long been recognized in the USA but are now being readily adapted worldwide as developing nations expand their industrial infrastructure. The various codes and standards that are on the docket this summer for work and review can be accessed and viewed on the CTI web site.

For any of you first time attendees or other attendees, CTI will have a number of experienced members designated as “New-Comer Ambassadors” by their name tag. Their function is to assist you get orientated and directed to those code task groups that you may be interested in attending or participating in their development.

On the business side, CTI is proceeding ahead with our proposed plans to return the management of the Thermal Product Certification process to the CTI staff as well as to expand the CTI certification process to materials and components. A complete business plan was submitted to the Board of Directors at the Winter Meeting in February for their review and consideration. A final decision to proceed is expected to be voted upon by our Board at this meeting in July. If the plan is accepted, then CTI will be adding an administrative / technical individual to our Houston CTI staff. This individual would manage the certification programs with close assistance of the present contracted thermal certification administrator, Tom Weast of CTTA.

To insure adequate capital to fund the start up of this CTI Certification Venture, the proposed business plan called for the solicitation of donations from CTI members. The Board made the recommendation that pre-confirmation by the companies that would donate the money for “start up” would be very beneficial in their final decision. Based on this Board request, the Thermal Certification Continuation Committee and the Product and Material Certification Committee jointly contacted a number of CTI member companies by recent letter, requesting they confirm their interest and financial commitment to this business plan for certification. The response to date has been excellent and our target for committed donations will be in excess of target.

Our recent cooperation agreement with the Eurovent Certification Company (ECC) provides thermal certification, incorporating the CTI STD-201 Standard and process, with the addition of a factory audit program for data of record conformance, for cooling towers sold into European markets. This is proving to be of high interest in Europe. Tower manufacturers in Germany, France, and Turkey as well as global USA-headquartered companies such as BAC, Evapco and SPX-Marley have submitted their lines to be certified in the ECC program.

The sphere of technical influence of CTI codes and standards continues to expand worldwide. Our future business plan will expand this influence into other codes and standards referencing materials and products used in cooling tower manufacturing, installation and operation.

As stated, the Summer Work Shop is when and where the CTI membership goes to work and improves the organization’s codes and standards. It is a lot of dedicated joint-study, stimulating discussions and learning experiences tempered with fun and good fellowship. I look forward to seeing all of our members at Amelia Island as well as meeting new attendees.

Respectfully submitted,

Jess Seawell PE
CTI President 2010/2011
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Greetings to the CTI Journal readers,

Another half year has gone by since the last CTI Journal, again with many significant changes in the world. A sluggish economic picture is continuing, with some jobs and property value recovery, the return of $4/gallon gasoline in the US, and also a shifting world picture with profound events like the Arab Spring and the demise of Osama.

CTI is working to manage itself for the economic times, and adapting to its more global role as an organization. The cooperation agreement with Eurovent Certification Company on thermal certification of cooling towers is well into its first year of operation. CTI is also in the process of developing certification of the performance of certain materials and components for cooling towers to CTI standards. The nature of CTI is shifting toward a need for engagement in administration of these technical and highly important activities.

Activities have been underway for some time to explore plans for the potential future evolution of CTI as an organization to meet these shifting and increasing needs, including the eventual retirement of Tom Weast as CTI Certification Administrator at some point down the road. Participation in the CTI Committee Workshop in July, 2011, and the Annual Meeting in February, 2012, is a very good idea for any who are interested in the future state of CTI.

Jess Seawell, CTI President, has worked hard to engage people to think forward as an organization, and ongoing information can be expected to flow to the organization as the ideas come together.

Your participation and engagement is strongly suggested, as this is an interesting time to be a part of CTI.

Respectfully submitted,

Paul Lindahl, Editor-in-Chief, CTI Journal
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Hypebolic Repack On The Run

JAMES CUCHENS and CHRIS LAZENBY
SOUTHERN COMPANY SERVICES, INC.
JAMES L. BAKER
COMPOSITE COOLING SOLUTIONS, LP

Abstract
The industry’s first hyperbolic repack of its kind was completed last year at the Alabama Power Company’s Miller Steam Plant. At least one of the two units supplied by the tower remained online with water continuously circulating over half the tower throughout the project.

The original fill was severely fouled and deteriorated. It had numerous gaps allowing air bypass, and was falling out of the tower. The Cooling Tower Contractor removed the under-performing fill and replaced it with high performance, anti-fouling fill packs. The new fill was rigidly supported from beneath by a pultruded fiberglass fill support system designed by the Tower Contractor that incorporated aspects of the old “proprietary” hanging system that was part of the tower’s original design. The new bottom-supported system gives owners a new alternative to “traditional” hanging fill methods when replacing fill media.

The project was completed safely, ahead of schedule, and resulted in a tower with improved thermal efficiency testing out at well over 100% of its design.

Introduction
Units 3 and 4 of Alabama Power Company’s Miller Steam Plant were placed into operation in 1989 and 1991 respectively. In an effort to conserve costs, the units were designed to both be served by a common hyperbolic, counterflow cooling tower. To accommodate both units, the tower was designed to handle a flow of 413,200 GPM and cool it from 119.4°F to 89.0°F at a wetbulb temperature of 80°F with a relative humidity of 45%. In order to accommodate the heavy thermal duty, the tower was originally packed with cross-fluted “high efficiency” fill. At the time of the tower’s construction, this was not seen as a detriment since film fills were only beginning to become commonplace and fill fouling was a largely unknown phenomenon. However, as many in the industry learned in subsequent years, such fill often begins to accumulate dirt and/or biological growth – in other words, it fouls up - to the point of causing thermal and structural problems. This began to occur to the fill in the Miller 3 & 4 tower.

To mitigate fill fouling as much as possible, large amounts of chlorine gas were injected into the units’ circulating water system. The chlorine helped control the fouling as much, but could not stop it entirely. Over time the fill slowly accumulated weight due to continual fouling. During a routine inspection in early 2008, significant fouling of the fill was observed. Later in the year, a few fill packs collapsed under the increased loading and fell into the cooling tower basin. While the number of failed packs was relatively small, there was concern that they represented the precursors of much larger problems.

In 1995, load cells were installed in the Miller 3&4 tower to track weight gain in the fill, but by 2008 they had fallen into a state of disrepair. At the recommendation of Southern Company Services personnel, the load cells were repaired and placed back in service. Once in place, the load cells measured an overall weight gain of almost 1,000 lbs per fill pack weighed, which was equivalent to a gain of approximately 5.8 lbs per cubic foot of pack. It was apparent from looking at the historical weight gain trend that though the aggressive chlorination had greatly slowed the rate of fouling in the fill, things were quickly approaching the point where the weight gain could cause catastrophic failure of a significant number of fill packs.

It was apparent to Southern Company and Alabama Power personnel that something needed to be done, but any potential plans were complicated by the fact that due to the operational dispatch of Plant Miller, it was impossible to take Unit 3 and Unit 4 simultaneously off-line for the amount of time needed to replace the fill in the entire tower. One unit at a time could be brought down for an extended outage, but not both, meaning that any repairs or fill replacement that occurred would have to take place while at least half of the tower remained in operation. It became apparent that a unique solution would have to be found to successfully replace the fill while not impacting tower, and thus operating unit, operations. This paper documents the efforts to find a successful solution to this challenge.
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Initial Challenges
Initially a team consisting of Plant Miller personnel, Southern Company Engineering & Construction Services personnel, and Southern Company Research & Environmental Affairs personnel was put together. This team quickly recognized a need to get others from the cooling tower industry involved, as no one on the team had any direct experience with, or had even heard of, a problem similar to that at Plant Miller. It needed to know whether repacking a tower on-line had ever been attempted or executed successfully anywhere, and, if so, how was it accomplished. Unfortunately, an informal survey of different people within the cooling tower industry indicated that no one had any experience with repacking an operating cooling tower. During these discussions, however, many tower contractors indicated an interest in the problem and a belief that with a little bit of planning and flexibility, this might be successfully done. In the spring of 2009, a formal Inquiry Package was issued asking selected tower contractors to propose ideas, work plans, and costs for performing an on-line repack of the Miller 3 & 4 cooling tower with vertically-fluted, anti-fouling fill.

In addition to the practical aspects of repacking an on-line tower, the Inquiry asked the contractors to guarantee the thermal performance of the tower. This was important to Plant Miller in order to ensure continued operational efficiency of the two units. Obviously, replacing a cross-fluted, high-efficiency type fill with an anti-fouling fill would normally result in a loss of tower performance. However, at this point the fill in the Miller 3 & 4 tower had degraded to the point that the tower had suffered a capability loss of 25% versus its original tested performance. As such, it was thought that even with an anti-fouling fill as a replacement, it would be possible to recover a large portion of the lost performance. While not able to get back to the original design point, the thought was that the tower performance after the repack would still be significantly improved.

Upon receiving the proposals from the contractors, it appeared that both efforts – repacking the tower on-line and recovering a large portion of the lost thermal performance – might be possible. After review and discussion by the Southern Company team, Composite Cooling Solutions (CCS) was selected to partner with Southern Company in what was by all accounts a groundbreaking endeavor. Contracts were signed, work plans and unit outage schedules were put in place, and in October of 2009, CCS personnel showed up at the Plant Miller site accompanied by construction equipment and palette after palette of vertically-fluted PVC fill.

The plan proposed by CCS included repairing some of the tower’s gate valves, isolating sections of the tower risers, and simultaneously partitioning off and draining sections of the cold water basin. Once dry underneath, CCS personnel would remove the existing fill and replace it with the anti-fouling fill. Rather than having stainless tubes passing through the actual fill packs and suspending the tubes from the tower structure, as had been done with the original fill, CCS devised a system whereby the new fill packs would be supported by fiberglass box beams, which were then hung off of the existing hangers. Once all of the fill in the isolated section had been replaced, that section of the tower would be placed back in service and a different section isolated. In this manner, CCS planned to systematically work through the entire tower while maintaining enough flow to keep one unit – first Unit 4 and then Unit 3 – in operation throughout the duration of the project. The project was supposed to begin in October, 2009, when Unit 3 was scheduled to come off-line, continue through December, 2009, when Unit 3 would be returned to service and Unit 4 taken off-line, and conclude by the end of January, 2010, when Unit 4 would be placed back in operation. Failure to complete the project by the scheduled date would result in significant lost generation to Alabama Power, since it would be impossible to operate both Units at full power if the entire tower were not in service.

If at First You Don’t Succeed...
CCS personnel arrived on-site in early October and began to receive replacement fill packs and construct bottom supported hanging modules for installation in the tower.

Once Unit 3 came off-line in late October, the CCS crew began working inside the tower. On October 30, CCS personnel began installing an inflatable bladder to segregate the tower basin into two halves and allow for draining of half of the tower basin.

Unfortunately, right during the crew’s break for lunch, a pump, most likely the tower makeup pump, engaged. The unforeseen flow exerted too much pressure and floated the bladder, tearing it in multiple places. Repairs were attempted, but the bladder had failed totally and could no longer be used to segregate and seal the basin. Faced with this unforeseen problem, CCS was forced to either quickly come up with an alternate means of segregating the basin or watch the project schedule unravel before their eyes.

Maintaining Flexibility
Showing great ingenuity, CCS quickly developed plans for constructing a double wall across the entire basin using their patented double wall fiberglass casing combined with 7” plywood and PVC...
lining. Unlike the bladder, however, this wall could not be installed with even half of the tower in operation. Alabama Power personnel were consulted and it was determined that it might be possible to shut down Unit 4 while keeping Unit 3 off-line for a very brief period to facilitate the installation of the wall. On Saturday, November 7, Miller Unit 4 began powering down. Working together, Alabama Power and CCS personnel were able to power down the unit, drain the entire cooling tower basin, install the wall, refill half of the basin, and bring the unit back on-line in just twelve hours from start to finish, an extraordinary feat.

With the wall in place and working properly to keep half of the basin isolated, the CCS crew began replacing the fill on the isolated half of the tower.

The fill replacement process started with removal of a section of the existing drift eliminators followed by a crew cutting the wires holding the existing fill packs and letting them drop into the dry portion of the basin. Track-hoes were used to remove the fill from the basin and place it in dump trucks, which then took the fill to an on-site landfill for disposal. Ultimately a third shift was employed to handle the bulk of the clean-up and disposal work at night, allowing the maximum amount of daylight hours for the installation of the new fill. The new fill modules were placed into the tower beginning in the center and working outward toward the tower shell. The packs around the tower perimeter were field cut to ensure a tight fit with the shell. Once the section had been repacked, new drift eliminators were installed and the crew moved to the next section and began the process again.

Work continued in this manner through November and into December of 2009. In the middle of the month, Miller Unit 4 came down for its scheduled outage, allowing for a brief work period with the entire tower out of operation. During this period, work on the Unit 3 half of the tower was completed on December 18, and work commenced on the Unit 4 half later the same day. Shortly thereafter, the Unit 3 half of the basin was refilled and that half of the tower placed back into operation.

The Unit 4 installation work was performed in a slightly different manner than Unit 3. During the Unit 3 installation, the CCS crew noticed that when all of the existing fill was removed prior to installation of any new fill packs, extreme cross winds were created by virtue of half of the tower being left entirely open. These winds created a potentially hazardous work environment for the crews. To remedy this situation, CCS began immediately installing new fill modules as soon as individual existing packs had been removed, leaving minimal open space in the tower plenum. This method not only cut down on the cross winds, but also proved to be slightly quicker than the original method employed on the Unit 3 half of the tower. Work continued in this manner until CCS completely repacked the Unit 4 half of the tower and installed new drift eliminators. Due to the efforts of the CCS crews, the entire job was completed on January 7, 2010, nine days ahead of schedule.

**Proof in the pudding**

Despite the remarkable task of removing and installing over 735,000 cubic feet of fill safely and ahead of schedule, the project could not be considered a success yet. It still remained to be seen whether CCS had accurately predicted the thermal performance of the repacked tower, a fact that could not be verified until the tower was tested in accordance with CTI ATC-105. As previously discussed, the change from cross-corrugated to vertically fluted fill caused a slight change in the thermal design of the tower. The repacked tower was rated by CCS to cool 425,000 gpm of water from 122.5°F to 91.5°F at a wet-bulb temperature of 80.0°F with a relative humidity of 54%. Southern Company performed a test the week of June 21, 2010, and when the results came in the repacked tower tested out at more than 110% of CCS’ guaranteed design. More importantly, the repacked tower performed such that even though repacked with vertically fluted, anti-fouling fill in place of its original high-efficiency, cross-corrugated fill, there was no overall detriment to the units’ thermal performance, and Plant Miller Units 3 & 4 were able to successfully operate during the heat of an Alabama summer.

**Conclusion**

Like many “first of its kind” projects, the Miller 3 & 4 fill replacement presented many unique challenges, and it would still be fair to say that trying to repack a hyperbolic cooling tower while keeping a portion of it in operation should be avoided if at all possible. However, this project proved that by planning for what you know, having back-up plans for what you do not, and maintaining open communication and a good working relationship, even things that appear extremely difficult on the surface can be accomplished. The expertise, teamwork, and flexibility maintained by Alabama Power and CCS personnel throughout the project resulted in a truly remarkable, first of its kind achievement.
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Abstract
Evaporative cooling systems emit a visible plume a significant portion of the time. Even though a cooling tower plume contains mostly pure water and hardly any pollutants, it is often seen as a nuisance. This paper describes the psychrometry of the plume under typical operating conditions and reviews how to specify no visible plume. Several technologies exist to reduce or abate the visible plume and these techniques will be shown. A new technology will be introduced which has the capability of saving water while inherently reducing the plume. Based on this new technology, an additional technology is proposed to abate the plume under more severe operating conditions.

Scope
Throughout this paper, we will ask ourselves several basic questions about plume abatement and we will try to answer them as clearly as possible. The paper will lead us to show how the new Dual Coil Closed Circuit Cooling Tower in water efficient mode of operation can reduce the visibility of the plume.

We will ask:
• What is a plume?
• When is it visible or not visible?
• When is a visible plume a nuisance?
• How to specify no visible plume?
• What are the psychrometrics of the plume?
• How do you abate the plume?
• How does the new Dual Coil Closed Circuit Cooling Tower reduce the plume?
• What is a plume?

A plume is a column of moisture rising in the atmosphere. It is a cloud of microscopic droplets of water.

In wet cooling systems the plume is produced by the condensation of water vapor from the heat transfer media.

Figure 1 is a 4-cell mechanical draft tower with one cell in operation in a chiller plant in the Midwest region of the United States.

When is a plume visible? Not visible?

Wet or evaporative cooling systems combine heat and mass transfer. In evaporative cooling, the liquid to be cooled is generally put in contact with cold, ambient air. The hot liquid in contact with the cold air evaporates while at the same time the air gains moisture in the form of water vapor. The vapor is normally invisible. The evaporation of the liquid gives away latent heat, so the liquid cools down while the air warms up; this is the heat transfer part. The vapor transferred to the air raises its moisture content; this is the mass transfer part.

When the moisture contained in the air mass reaches a critical value - generally called “saturation” – the vapor condenses, forming tiny droplets of liquid. The microscopic droplets of liquid refract the sun light, all at different angles, and they appear like white, visible clouds.

In Figure 3, the plumes from the hyperbolic towers, the plume from the smokestacks - where wet scrubbers are used – and the clouds in the sky all look the same because of the tiny droplets of water they contain.
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When is a visible plume considered a nuisance?

The plume may appear as a cloud of pollution, even though it is made of pure water droplets. When the plume stays near the ground, the tiny water droplets in the plume produce fog, low visibility and potential safety hazard to ground traffic and air traffic. In freezing weather, a low plume near ground level produces ice on roadways, another potential hazard to road traffic. If it is dense enough, a plume may affect radar transmissions and interfere with air traffic control.

The following figures illustrate various examples of plumes from cooling towers. A wind tunnel scale model of city buildings is shown in Figure 4. The wind tunnel tests provide visualization of how a plume from a cooling tower may affect neighboring buildings.

How to specify no visible plume?

Typically the specifying engineer will use a fogging frequency chart describing the weather conditions at a given site. The fogging frequency chart plots statistical data of the weather at the site from a weather data base. One or several cooling tower fogging frequency curves will be superimposed to the weather data to determine the severity of the plume problem.

This fogging frequency chart has the air dry bulb temperature along the x-axis and the air relative humidity along the y-axis.

The example fogging frequency chart shown in Figure 8 contains weather data points for Fresno, California. Weather data can be obtained for all regions of the United States and the International community through resources such as the National Climactic Data Center (NCDC). Seasonal data points are provided and each data point has a certain time of occurrence attached to it.
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Over the weather chart, the cooling tower manufacturer will draw a set of curves delimiting the areas on the chart of visible and not visible plume (Figure 9). The orange curve is for a conventional wet cooling tower operating in evaporative mode. Under any combination of air temperature and relative humidity to the right and below the orange line, the tower produces no visible plume. But to the left and above the orange curve, the tower produces a visible plume.

A set of heat exchangers can be incorporated to the cooling tower so it no longer produces a visible plume, even under more severe conditions. For example, the green curve shows the limit between the area of no visible plume below and to the right, and visible plume above and to the left.

By dividing the amount of time of the data points above the green line by the total amount of time of all the data points on the graph, you get a number or percentage of time the plume from the cooling tower is visible.

The question again is: How to specify no visible plume?

From the fogging frequency chart, the engineer can specify “no visible plume for x% of the time”. A number like 5% of the time is considered severe because it will lead to a fairly expensive tower with large, plume abatement heat exchangers. A number such as 15 to 20% of the time is more economical thus more typical, but may not be satisfactory to the end user.

Instead of looking at all the weather data for the location, one can distinguish between day-time and night-time temperatures, and associate plume visibility to one rather than the other. For example plume visibility at night-time may be less of a concern than plume visibility during day-time.

Once a “no visible plume” condition has been specified, the engineer makes sure that a cooling tower (open or closed circuit) can be designed to meet such criteria within a reasonable budget. It may be advisable, particularly in the case of field-erected towers, to have the tower tested according to CTI test code ATC-150 to verify the plume guarantee when the cooling tower has been commissioned.

Where there is limited sensitivity to plume in the near field, it can be acceptable to have a light, wispy visible plume located above the fan exhaust area, extending around 15 m – 50 ft. In such a case, the design of the plume-abated cooling tower is called “limited visible plume”.

When a limited visible plume is not acceptable, meaning that at the design point NO visible plume may occur, even just above the fan stack area, then the design of the plume-abated tower is called “zero visible plume”.

In the pending revision of CTI test code ATC-150 this nomenclature has been changed to Level 1 and Level 2 plume, level 1 being “limited visible” and level 2, “zero visible”. In other words, level 2 is more stringent than level 1. To get a level 2 plume, usually air mixers must be installed to thoroughly mix the stream of hot saturated air with the stream of dry air.

Here is a photo of a cooling tower fan stack exhaust with some “wispy” plume. This would be considered a Level 1 plume.
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What are the Psychrometrics of the Plume?

Psychrometrics or psychrometry is an engineering field which studies the physical and thermodynamic properties of gas-vapor mixtures.

In general the psychrometric properties of a mixture of air-water vapor can be plotted on a chart usually called the Psychrometric Chart or the Mollier Diagram.

This complex chart shows air temperatures (dry bulb, wet bulb, and dew point), humidity ratio, enthalpy, air relative humidity, etc., all drawn at a given barometric pressure, normally sea level.

Changes between one condition of a mixture and another can be shown on this chart to assist the engineer in modeling the physical and thermodynamic process.

The psychrometric chart is complex and difficult to read so for the purpose of this paper, we’ll use a simplified version of the chart as shown below.

The humidity ratio is by definition the ratio of the mass of water vapor to the mass of dry air in a given sample of air. The relative humidity is the ratio of the fraction of water vapor in a given sample of moist air to the fraction in an air sample saturated at the same temperature and pressure.

On the saturation line, there is equilibrium between the water vapor and the liquid. This is where condensation starts to occur and the plume becomes visible.

We will demonstrate some typical examples of evaporative cooling of gas-vapor mixtures in the following pages. We will look at a wet cooling tower or wet cooler, air IN and air OUT conditions.

We will see on the chart the effect a change of heat load, airflow or ambient air temperature and relative humidity have on these conditions, as well as how the probability of a visible plume increases under certain conditions. The “mixing” or “dilution” of two streams of moist air is a process that we have represented in the examples below by a simple line joining two points. In reality the mixing process is more complex. Therefore, some conservatism should be applied to compensate for this simplification.

Examples

In the case of a wet cooling tower or a wet cooler, cooling from 35 °C (95 °F) hot water temperature (HWT) to 29.4 °C (85 °F) cold water temperature (CWT), the air goes in at 25.6 °C (78 °F) wet bulb temperature, 34.4 °C (94 °F) dry bulb temperature and 50% relative humidity: this is the blue diamond on the chart in Figure 13.

In a typical wet cooling mode, the air-water vapor mixture would come out the fan stack at 33.2 °C (91.7 °F) WBT, 33.5 °C (92.3 °F) DBT, 98% relative humidity. This is the red diamond on the chart. When the air at the fan exhaust mixes with the ambient air, the mixture lies on the line that joins both points. It does not cross the saturation line so normally no visible plume in such conditions.

In the same tower as before but under 150% heat load (in the form of 50% more temperature range), the air comes out the fan stack at a much higher temperature and closer to saturation, 36.7 °C (98 °F) DBT and 99% relative humidity. This is the orange triangle on the chart. When the exhaust air mixes with the ambient air, the
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mixture lies on the mixing line which doesn’t cross the saturation line – no plume expected.

Under the same conditions as before, with 100% heat load but the airflow cut in half by slowing down the fan drives to half speed, the exhaust air would come out the fan at 38.9°C (102 °F) DBT and 100% RH. This is the green dot on the chart in Figure 14. The mixing line touches the saturation curve; therefore minimal plume will be visible.

In the winter: see the grey dots on the bottom left of the chart: -11.4°C (11.5 °F) DBT, 90% RH going IN and 7.2°C (44.9 °F) DBT, 100% RH coming OUT. The mixing line between the two winter points crosses the saturation line: the plume is clearly visible and dense.

**How do you abate the plume?**

- There are several different ways to eliminate or abate the visible plume from an evaporative cooling tower.
- The Parallel Path Wet-Dry “PPWD” with water-to-air heat exchangers.
- The Parallel Path Wet-Dry with air-to-air heat exchangers.
- The Series Path Wet-Dry “SPWD”.
- The Dual Coil Closed Circuit Cooling Tower

**PPWD= Parallel Path Wet Dry**

Here is a schematic of a PPWD counterflow tower.

In the summer: see the blue and red diamonds on the chart: 34.4°C (94 °F) DBT, 50% RH going IN and 33.5°C (92.3 °F) DBT, 98% RH coming OUT: no visible plume

In the spring: see the blue and purple triangles on the chart: 8°C (46.3 °F) DBT, 70% RH going IN and 18.7°C (65.7 °F) DBT, 100% RH coming OUT: therefore minimal plume will be visible. The higher entering air relative humidity increases the probability of a visible plume.

The wet, evaporative section is at the bottom in blue. The plenum is extended upward to leave room for fin tube, heating coils to be installed vertically along the sides of the tower.

Hot water from the process goes into the heating coils first then into the wet section. Sometimes the water flow going to the heating coils is a fraction of the overall water flow rate.

Air dampers are often installed in front of the heating coils. In the summer mode of operation, the air dampers are closed so most of the cooling air goes through the wet section, but due to damper leakage some air bypasses the wet section resulting in additional energy usage. In the no-plume mode of operation, the air dampers are open and some cooling air goes through the wet section while some cooling air goes in parallel through the dry section.

The air coming from the wet section is warm and saturated with moisture, while the air going through the dry section is hot and dry. When both flows of air mix in the plenum, the overall relative humidity of the exhaust air is less and the plume remains invisible. Let’s see how this is shown in the psychrometric chart.
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The cold ambient air is represented by point A on the bottom left of Figure 17. As the air goes through the wet evaporative section, it warms up and gains moisture. The air from the wet section comes out as shown by point C on the top right of the chart.

In parallel, a mass of cold ambient air A goes through the dry section. The blue point on the bottom left A is the same as before but as the air goes through the dry section it heats up without gaining any moisture so it is represented by a horizontal line in the chart. The air from the heating coils comes out as point B at the bottom of the chart.

In the tower plenum, the dry air from the heating coils mixes with the moist air from the evaporative section; the mixture happens along the line that joins B and C.

Point D represents the mixture of the wet and dry air at the fan exhaust. As that mixture D enters in contact with the cold ambient air A above the fan stack, the new mixture is described by the line between these two points A and D.

As long as the mixing line D-A does not cross the saturation curve, we can say that there is no visible plume at the fan exhaust under these conditions.

PPWD is a good technology, particularly adapted to large field erected towers. Usually it has a very high first cost.

The water-to-air heat exchangers are typically metallic fin tube bundles consisting of 10-12 fins per inch and designed in accordance with standard API 661. This technology requires higher than usual plenum heights for the water-to-air heat exchanger installation. The resultant high structural loads, due to additional weight and a higher center of gravity, become critical under seismic and wind load requirements.

Baffles can be installed in the tower plenum to enhance the mixing between the hot dry air and the saturated air and provide level 2 plume abatement. A vacuum system is also added to remove the non-condensable gases trapped at the top of the tube bundles while at the same time providing a siphon that lowers considerably the operational pumping head.

Another PPWD technology uses air-to-air heat exchangers made of patented plastic packs in the tower plenum designed to de-saturate the leaving air by sensible heat transfer with ambient air.

**SPWD-Series Path Wet-Dry**

Another way to abate the plume, more typically utilized in packaged cooling towers, is by heating the exhaust air with heating coils in the plenum above the drift eliminators or over the fan. The psychrometric chart will show that the amount of heat required to heat the exhaust air enough to abate the plume is much greater than in the case of a PPWD system. Typically very hot water or preferably steam is used to heat the air and the heating coils have only one or two rows of tubes.
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large. In addition, the added static pressure incurred year-round from the fin coil makes the application of this technology in induced draft cooling towers often impractical, and adds to the overall fan energy.

**The Dual Coil Closed Circuit Cooling Tower**

The dual coil closed circuit cooling tower is based on a new fin coil technology that has been developed to provide water conservation and plume abatement for factory assembled and field erected cooling towers. In contrast to the PPWD and SPWD arrangements discussed previously, the dual coil closed circuit cooling tower is comprised of two separate spiral fin coils and two independent spray water systems. The fin coils serve a dual purpose of providing both sensible and latent heat transfer, depending on the ambient conditions.

Although fin coils have been used extensively for dry cooling, there have also been limited applications in evaporative closed circuit cooling equipment to improve winter operation dry capacity and limited free cooling. Typical fin coils, utilized in these coolers, are comprised of round tube coils with spiral fins spaced at 4-5 fins per inch. These coils tend to be constructed of spiral fins on round tubes with welded return bends. However, the cost of the dry cooling capacity for these round tube fin coils is a large increase in the air-side pressure drop which in turn negatively impacts the tower thermal capability in the design summertime evaporative cooling mode.

The new spiral fin coil technology utilizes elliptical tubes with an extended surface fin tension wound around the tube. The elliptical tube design allows for closer tube spacing, resulting in greater surface area per plan area than round tube coil designs and without the air side pressure drop increase. Because of this, the thermal capacity is greatly increased compared to bare tube elliptical coils.

The elliptical tube fin coil was developed following extensive testing to optimize the fin height, fin spacing, and tube spacing.

Many manufacturing obstacles were successfully overcome. These included: developing a process for “finning” an elliptical tube, producing a continuous serpentine circuit, and achieving a robust connection between the fin and tube.

The result is an elliptical spiral fin technology which develops increased heat transfer and reduced air side pressure drop as compared to round tube fin coils. This reduced air-side pressure drop allows for less fan energy with increases in heat transfer efficiency.
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The dual coil closed circuit cooling tower offers a combination of sensible and evaporative heat transfer to significantly reduce any plume that may occur with evaporative cooling equipment. A standard control panel can be provided to control the mode of operation and assure that the plume reduction or water savings are maximized. During the coldest times of the year, when the potential for visible plume is greatest, the dual coil closed circuit cooling tower operates 100% dry, completely eliminating plume and using no water.

This new arrangement can operate with the entire unit spray system on, or one half of the spray system on and half dry, or in completely dry operation.

When the dual coil tower operates with one coil wet and the other dry, the visibility of the plume is reduced. The process fluid to be cooled flows in series from the first coil to the second. The dry coil is the first coil, with the warmest process fluid.

Warm dry air then exits into the fan plenum from the first dry coil while warm moist air exits from the second wet coil. These two air streams join and mix at the fan as shown in Figure 25. Although the arrangement is completely different from a traditional PPWD design, the psychrometrics for plume abatement are similar.

In Figure 24, cold, ambient air enters the cooler as shown by point H on the left side. The air that flows through the wetted section of the coils comes out hot and saturated as shown by the top right point J.

On the dry side of the unit, the cold, ambient air again depicted by point H enters the unit, heats up without gaining moisture and follows the horizontal line H-K to the bottom right point K.

Both masses of air J and K meet and mix in the plenum above the coils; the mixing is represented by line J-K. After mixing, the air at the fan lies on line J-K. Point M represents the mixture of the wet and dry air at the fan exhaust.

In Figure 25, the schematic of the dual coil closed circuit cooler shows how the hot saturated air from the sprayed section mixes in the plenum with the hot dry air before being discharged through the fan exhaust.

As the air at the fan exhaust comes in contact with the cold, ambient air, both streams of air mix. Their mixing is represented by line M-H. Line M-H does not cross the saturation curve so after mixing there is only minimal visible plume from the dual coil tower in this mode of operation.

If necessary, air mixers can be installed in the plenum section to provide more thorough mixing of the hot saturated air and the hot dry air before discharging to the atmosphere to completely eliminate visible plume for most or all conditions. Under severe cold weather conditions, the dual coil closed circuit cooling tower can be operated in 100% dry mode, again completely eliminating the plume at the most difficult conditions.

It is also possible to apply the dual coil (or multi-coil) technology for larger field erected applications, however, the need for two coils is replaced by multiple coils. For these applications, both water savings and plume abatement can be achieved without adding to the tower height or fan power requirements.

For both factory assembled and field erected applications, the change to a closed system must be anticipated in the design stage since the heat exchanger is no longer needed and piping will change. In addition, substituting a closed circuit cooler instead of an open cooling tower allows for smaller evaporative water inventory and less water treatment chemical requirements in the warmer seasons, while allowing for no water or water treatment chemicals at all during cold months.
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Conclusions
What conclusions can we draw from our review of plume abatement?

- We have asked ourselves several basic questions about cooling tower plume.
- We have seen that a visible plume can be a nuisance.
- Under certain circumstances such as visual perception, aesthetics, safety, etc. plume abatement is important!
- Let us not forget that plume abatement systems save water too!

- There are several possible technologies to abate the plume from wet cooling towers.
- The new dual coil closed circuit cooler technology can reduce or eliminate plume and save water without adding height and at minimal cost add.
- The new dual coil closed circuit cooler technology saves energy when compared to typical closed circuit cooler designs.

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New Methods for Drift Eliminators
Performance Evaluation

Jan Cizek and Ludmila Novakova
CTU IN PRAGUE

1. Abstract
The subject of the paper is aimed for methodology for the evaluation of cooling tower drift eliminator performance. Two independent methods for the evaluation of eliminator performance were used. The former method is based on the numerical determination of particle trajectories in the area of drift eliminators. The latter approach applied the method commercially known as IPI (Interferometric Particle Imaging). This method seems to be the most suitable for such purposes. It is a non-invasive method based on optical interference beam passed through the transparent particles and the beam reflected by such particles. The performance of drift eliminators was evaluated by comparison of the droplet size distribution below and over them.

**Keywords:** Drift Eliminator, Drift Reduction, IPI

**Nomenclature:**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>( A_p )</td>
<td>particle cross-sectional area</td>
<td>(m²)</td>
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<tr>
<td>( C_D )</td>
<td>drag coefficient of a spherical particle</td>
<td>(-)</td>
</tr>
<tr>
<td>( D )</td>
<td>droplet diameter</td>
<td>(m)</td>
</tr>
<tr>
<td>( g )</td>
<td>gravitational acceleration</td>
<td>(m/s²)</td>
</tr>
<tr>
<td>( N_C )</td>
<td>total number of particles under the eliminator</td>
<td>(-)</td>
</tr>
<tr>
<td>( N_N )</td>
<td>total number of particles over the eliminator</td>
<td>(-)</td>
</tr>
<tr>
<td>( n )</td>
<td>refractive index of droplets</td>
<td>(-)</td>
</tr>
<tr>
<td>( R )</td>
<td>particle radius</td>
<td>(m)</td>
</tr>
<tr>
<td>( V_A )</td>
<td>fluid movement velocity</td>
<td>(m/s)</td>
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<tr>
<td>( V_P )</td>
<td>particle movement velocity</td>
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<td>( \lambda )</td>
<td>wavelength of light</td>
<td>(m)</td>
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<td>( \rho_A )</td>
<td>air density</td>
<td>(kg/m³)</td>
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<td>( \rho_P )</td>
<td>particle density</td>
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<td>( \Theta I )</td>
<td>camera viewing angle</td>
<td>(°)</td>
</tr>
<tr>
<td>( \Delta \theta )</td>
<td>angular distance between interference stripes</td>
<td>(-)</td>
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</table>

2. Review
Methods for determining water loss due to droplet drift can essentially be divided into two groups, based on the variables measured. The first group of methods employs chemically sensitive materials. The distribution of droplet sizes in the areas below and above eliminators is measured by means of probes inserted in the air stream containing the water droplets. Knowing the drift velocity, the total amount of water loss over a unit of time can be determined. The variable measured by the other group of methods is the direct mass quantity of water carried by the air flow. These methods make use of the isokinetic extraction of samples. An overview of methods employed for measuring droplet drift, as well as a brief characterisation of them and their areas of application, is given in [2] and [4]. Fig.1 shows a classification of these methods.

Methods using sensitive materials and isokinetic extraction were elaborated very well in the 1970s and are being used to this day. A great advancement has been made in optical methods of measuring particle size, based on diffusion of light, interference and laser-induced fluorescence.

Generally speaking, large differences exist in the sensitivity and accuracy of the methods used for various ranges of droplet sizes. The methods for measuring particle sizes are more reliable for smaller sizes of the droplets studied (< 200 μm in diameter); methods for measuring the total mass flow show a higher accuracy for flows containing larger droplets (> 200 μm in diameter) [5]. A disadvantage of certain methods, chiefly those designed for measuring droplet size, is that they do not allow in their analysis for the separation of droplets generated by condensing from drift droplets. The results then contain an error concerning the definition of droplet sizes, in the approximate range 0 – 20 μm.

Several different approaches applied in eliminator efficiency calculations can be found in available literature. A comprehensive review of methods that were applied in efficiency determination during the period of intensive eliminator research (1960-1980) is found in [4]. Methods for theoretical efficiency determination are based on determining either the trajectory of a droplet when passing through an eliminator, or the point of its impact on a wall. The droplet trajectory is calculated based on the equilibrium of forces affecting the particle in the flow field; the interaction of the flowing air and the liquid phase is thus not taken into consideration. The correct calculation of the droplet trajectories is conditioned by knowledge of the flow field in the eliminator area. Since available literature only encompasses older studies, it often describes cases where substantially simplified mathematical models were applied in flow calculations [1], [3], [10].
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3. Eliminator efficiency calculation

3.1. Assumptions for particle trajectory calculations

Based on the velocity field measured using the PIV method, the trajectory of the particles – water droplets – borne in the air stream was calculated. The trajectory calculation was made under the following assumptions:

1. The velocity field is not affected by the presence and movement of the particles.
2. Given the low density of the particles, their interactions are disregarded.
3. The velocity field of the fluid (air) in which the particle is borne is two-dimensional and attains the values measured by the PIV method.
4. The probability of the presence of a particle of a given diameter is constant along the entire inlet.
5. The diameter of a particle of the given diameter.
6. The diameter of a monitored particle is constant, i.e., no evaporation takes place inside the eliminator.
7. The effect of the film of water on the walls is neglected. A particle is deemed intercepted if it touches the wall; particle reflection and splashing, and the tearing off of parts of the film of water by the flowing air are disregarded.

In each case, the velocity of the air flowing through the eliminators was measured using the PIV method. The velocity field was measured along the entire cross-section of the eliminator. The assumption of two-dimensional flow was confirmed by a test measurement. The optical accessibility of the measurement area did not permit a detailed and correct measurement of the areas in the immediate vicinity of the walls. For the trajectory calculation, the velocity profile in the area was approximated based on the last measured value, down to zero velocity by the wall.

The approximation significantly reduced the numbers of wrongly-determined trajectories, but erroneous calculations could not be entirely eliminated for small particles. This is because particles up to a certain size copy the air movement sufficiently reliably near the walls and do not hit the walls. However, these particles were identified in the calculation as separated due to the inaccurate shape of the velocity profile near the walls. For small particles (ωD < 20 – 30 μm), the eliminator efficiency was therefore assessed to be greater than it actually was.

3.2. Velocity field measurement

The PIV method was chosen for measuring the 2D velocity field of the air stream. The PIV method principle allows non-invasive measurement of velocities in the entire channel cross-section defined by the eliminator walls. The method is based on monitoring the movement of seeding particles in the flow field. The fluid therefore has to contain appropriate seeding particles, which copy the fluid movement with adequate accuracy. The measurement plane is illuminated with laser sheet two times in a row. Nowadays, the Nd:YAG laser is most commonly used for illuminating the measurement area. The light reflected from the seeding particles is recorded with a specialised CCD camera capable of recording two images within 1 μs. In this way, pairs of images (image pairs) are taken with a defined time interval Δt. Subsequently, the images are analysed by means of their correlation. For a detailed description of the method as well as details on the measurement and image processing methods, refer to [8], [9], [6].

An experimental track was designed in order to measure the velocity fields using the PIV method. The measurement area comprises an exhaust space on a square floor plan with a 300 x 300 mm edge. The air flow velocity can be adjusted smoothly throughout the necessary range (approx. 1.5 – 3.6 m/s). When designing the track, the chief requirements concerned the quality of optical access to the measurement area.

3.3. Particle trajectories and efficiency determination

The particle movement trajectory was calculated based on solving the motion equation. Given the nature of the motion and the fluid properties, the following forces affecting a particle of radius R moving in the fluid stream were taken into consideration:

Drag Force: \[ \bar{F}_D = \frac{1}{2} C_D A_p \rho_A (\bar{v}_A - \bar{v}_p) \] (1)
Gravity Force: \[ \bar{F}_G = \frac{4}{3} \pi R^3 \rho_p \bar{g} \] (2)
Lifting Force: \[ \bar{F}_L = \frac{4}{3} \pi R^3 \rho_A \bar{g} \] (3)

In this case, the equation characterising the particle motion is as follows:

\[ m_p \frac{d\bar{v}_p}{dt} = \frac{1}{2} C_D A_p \rho_A (\bar{v}_A - \bar{v}_p)^2 + \frac{4}{3} \pi R^3 (\rho_p - \rho_A) g \] (4)
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For a spherical water droplet of constant radius $R$ and density $\rho_P$, Equation (4) is:

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(5)

Equation (5) is a non-linear differential equation. The fourth-order Runge-Kutta method with a fixed pace was applied in the numerical solution. For each calculation point, the air flow acceleration rate was obtained by interpolation from the velocity field measured by the PIV method.

The drift velocity of the particles was entered as a boundary condition for the vertical velocity of particles entering the eliminator. The horizontal component of the particle velocity at the eliminator inlet was assumed to be zero.

For each studied size, trajectories of particles entering the eliminator at a constant density in its entire cross-section were determined. The number of trajectories ranged between 22 and 38, depending on the eliminator type. Fig. 3 shows the particle trajectories for the Type 1 eliminator; the results are quoted for 20, 40 and 70 microns. Trajectories of particles assessed as separated are plotted in blue; trajectories of non-separated particles, in red.

4. Measuring eliminator efficiency using IPI

4.1. The IPI method

The interferometric method for measuring the sizes of transparent spherical particles was chosen for the eliminator efficiency measurement from among the available methods. It is referred to in the literature as IPI, and sometimes as ILIDS (Interferometric Laser Imaging for Droplet Sizing). It is a non-invasive optical method producing not only information on sizes of individual particles below and above an eliminator, but also information on the position of each particle, its velocity, etc. The results can then include the integral value of the entire drift from a cooling tower as well as the eliminator efficiency according to particle size, the correlation between particle size and velocity, etc. What is more, the minimum measurable sizes are nearly an order of magnitude smaller compared to standard methods.

The IPI method was authored by G. König et al. in [6] in 1986. The method principle is schematised in Fig. 4.

When using the IPI method for real-world measurements, one of the cardinal issues is the method for interpreting the data obtained. The greatest difficulty is finding the individual interferograms in the recorded image. A classic illustration of measured data is shown in Fig. 5.

With respect to interpreting the obtained data, detecting the position of an interferogram in a measured image requires the correct determination of either the spatial frequency of interference stripes (accepting the simplifying assumption that the obtained signal corresponds to the laws of geometrical optics), or the actual particle size (by comparison with a signal obtained using the full Lorenz-Mie theory).

Choosing to solve the formation of the interference based on geometrical optics, one has to start from the passage of light through the particle. The following case is of importance to application in cooling towers where a droplet of water is present in the air, i.e., where $n_1 < n_2$. The resulting formula for the particle size is then:

$$D = \frac{2}{\cos(\Theta/2) + \frac{n\sin(\Theta/2)}{\sqrt{1 + n^2 - 2n\cos(\Theta/2)}}} \frac{\lambda}{\Delta \theta}$$

(6)
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The correct derivation (full Lorenz-Mie theory) of the spatial distribution of light based on solving the system of Maxwell’s equations is rather lengthy and is therefore not shown herein. It can be seen in [26], for instance. A comparison of both methods for a particle sized 10 μm is shown in Fig. 7.

Figure 8 shows an example histogram for particles under the eliminator (blue) and over the eliminator (black). The red curves represent the approximated dependency according to the Weibull distribution. The distribution shown was measured for a Type 1 eliminator in velocity mode 1. For this mode, 4,103 and 980 particles were found under and over the eliminator, respectively.

5. Experimental set-up

The measurement of particle sizes over and under the eliminator made use of the same cooling tower model as the PIV measurement. In this case, it was fitted with a water nozzle, generating droplets sized up to 300 µm. The flow rate of water in the nozzle was set at 0.3 l/min. No film of water formed on the eliminator walls during the measurement at this flow rate. The air flow velocity was set in modes identical to those in the velocity measurements: 1.5, 2.6 and 3.5 m/s.

The results of eliminator efficiency measurements in the little cooling tower model and efficiencies determined by calculations were verified with a measurement in a big cooling tower model (Fig. 9). This device creates conditions very similar to real-world operation. The cooling tower model includes a water nozzle of the same type commonly used in cooling systems; the cooling air passes through standard cooling fills. Moreover, the tower dimensions permit the elimination of the possible effect of walls in the central section. Another advantage of the device is that a nearly real-world environment can be simulated in forced convection towers. The cooling water flow rate is several times that of the little cooling tower. The experimental work included the measurement of efficiency for the Type 1 eliminator as well as two types of cellular eliminators. The measurement was conducted as a verification in order to rule out the adverse effects of the small scale of the little model, including the lower water flow rate, etc.

6. Results

The resulting data were processed into histograms for particles, over and under eliminators and between 20 and 400 micrometres, segmented by 10 micrometres. The two-parameter Weibull distribution was used to describe the size distribution, which is convenient for describing size distributions for particle sets. In connection with these applications, the distribution is often referred to as the Rosin-Rammler distribution. The function for the probability density of the Weibull distribution is defined as

\[
f(x) = \begin{cases} 
cd^c x^{c-1} \exp \left( \frac{x}{d} \right)^c & \text{for } x > 0 \\
cd^c x^{c-1} & \text{for } x \leq 0,
\end{cases}
\]

where \(c\) and \(d\) are the distribution parameters. The resulting eliminator efficiency is represented by the below quotient for each particle size class:

\[
\eta_i = \frac{N_p - N_k}{N_p},
\]

where \(N_p\) is the number of particles under the eliminator, \(N_k\) is the number of particles over the eliminator, and the index \(i\) denotes the \(i\)-th particle size class.
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The eliminator efficiency was always determined for several selected water droplet sizes. These data were then used to find the coefficients $a$ and $b$ for

$$F(D) = 1 - e^{-aD^b} \quad (9)$$

Function $F$ corresponds to the expected dependence of eliminator efficiency on droplet diameter. The function formula is the result of the quotient of two particle presence distributions (below and above the eliminator).

The measurement results in curves that characterise the dependence of eliminator efficiency on droplet size. Figure 10 shows a comparison of the two measurements for the little and big cooling tower models, along with the result obtained in the particle trajectory calculation.

7. Conclusion

Velocity fields in the area of three types of blade eliminators were measured by means of the PIV method. To calculate the trajectories of particles, a numeric model was assembled, using the data from the measurement by means of the PIV method. The trajectories of particles were calculated in the area of all three monitored types of eliminators, and the relation of the eliminator efficiency to the size of precipitated droplets was assessed. The resulting relations were verified experimentally using the modified IPI method. Measurement of the three types of blade eliminators (Type 1, 2 and 3) was carried out in a small-size model cooling tower. Due to the parameters of the small model, in which the operating conditions of cooling towers cannot be simulated, a verification measurement for one type of eliminator (Type 1) was also carried out in a large-size model tower. Very good agreement was demonstrated between the calculated and experimentally verified values. The difference between the experimental values and the calculated ones did not exceed 5% in the whole interval (Fig. 10). Therefore, it can be stated that both the experimental methods yield comparable results throughout the whole monitored range of air stream velocities and precipitated droplets sizes.

The IPI method of particle size measurement proved to be a suitable tool for the measurement of particle sizes in the area of the eliminators. To achieve high-quality data, a fully automatic evaluation of measured data can be used. Due to the fact that this method is non-invasive, the achieved results are not influenced by the presence of other elements, and so this method does not require calibration in this respect. With ever-improving parameters of reading and lighting technology, it is also possible to expect significant improvements in the method’s measuring range and in the extent of its use. One substantive option seems to be its use under the conditions of real cooling towers. Here, the method could be used, for example, to check measurements of the correct functioning of eliminators during operation.

This paper summarises the outcomes of a research project conducted as part of the industrial research and development project “Energy and Environmental Optimisation of Cooling Towers” (PERMANENT PROSPERITY Programme), implemented in cooperation between FANS, a.s., and the Czech Technical University in Prague, Faculty of Mechanical Engineering, in 2006-2009.

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ABSTRACT
Optimizing the cost performance of treatments in cooling systems requires the use of models that calculate the minimum effective dosage of scale and/or corrosion inhibitors and blends. This paper describes the theory, development, and applications of performance models to optimizing and comparing treatments in open recirculating cooling systems. The impact of blending inhibitors on dosage is described. Treatment and model limitations are also discussed.

INTRODUCTION
The control and prediction of scale formation in cooling water systems is increasingly of economic significance, and is of special interest as chemists push the envelope of operation and control through water reuse, the utilization of less than desirable waters for makeup (including high TDS sources, high silica waters, and those with high levels of barium and strontium), and through concentrating the recirculating water to the mechanical limits of an open recirculating cooling system. Thermodynamic indices have been used traditionally to predict scale in these and other industrial water systems where mineral scale formation can be a costly problem. Dosage models for minimizing treatment dosages are derived from these thermodynamic indices. An understanding of the basis for the driving forces used for developing scale inhibitor dosage optimization models is essential for understanding their use in the dosage requirement kinetic models and in developing as universal a model as possible. Dosage models can only be as accurate and reproducible as the thermodynamic driving force indices used to develop them. Thermodynamics and kinetics answer several critical questions concerning projected water related problems and their solution:

WILL SCALE FORM? Thermodynamics only based indices tell only one part of the scale formation and control story. Indices such as ion association model free ion saturation ratios (degree of supersaturation) \(^{1,2,3,4,5}\) and less rigorous methods such as the simple indices (Langelier Saturation Index \(^6\), Ryznar Stability Index \(^7\), Practical Scaling Index \(^8\), and other indices based upon total analytical values) indicate whether or not scale is likely to form. And the seasoned professional can interpret them to reach a usually reliable prediction of whether or not scale will form, how bad a problem it will cause, and whether or not inhibitors can control it.

HOW MUCH WILL DEPOSIT? Other thermodynamic derived indicators, such as free ion momentary excess \(^9\) describe the instantaneous precipitation (or dissolution) required to bring a water to equilibrium. They are frequently used to estimate the quantity of scale that might form, as are their less rigorous counterparts such as the CCPP (calcium carbonate precipitation potential) \(^10\) used in municipal water treatment.

WHEN WILL IT HAPPEN? WILL IT HAPPEN IN MY LIFETIME? Kinetic models add the element of time. Thermodynamic models tell you what will happen if a water is allowed to rest unperturbed for an infinite period of time. Kinetic models portray what will happen within the time constraints of your particular system, be it a twenty four (24) hour half life cooling tower, a six (6) second residence time utility once through condenser cooling system, or a three (3) week turnover fire water system in a nuclear power plant. Kinetic models add the parameters of induction time and growth rate. When inhibitors are added to the equation, their impact on induction time is critical to practical dosage calculation.\(^11,12,13,14\)

A thorough evaluation would include all of these factors:
- the Thermodynamic Driving Force,
- the Quantity of Scale Forming,
- the Time before scale will form,
- the rate it will precipitate and form on surfaces,
- the inhibitor level required to safely get the water through the system, and
- the limit beyond which scale inhibitors will not be able to prevent scale at any dosage.

This paper summarizes the impact of both thermodynamic and kinetic considerations upon scale formation and control in cooling systems, and other industrial water processes. Where available, calculation methods are described. The relevance of the kinetic considerations is also emphasized where appropriate.

A similar approach is discussed for optimizing corrosion inhibitor dosages, including those where inhibitor solubility is the limiting factor for dosage.

THERMODYNAMIC: DRIVING FORCE INDICES
Thermodynamics tells us what to expect if a water sits unperturbed for an infinite period of time. In the case of predicting mineral scale formation, thermodynamic indices indicate whether or not a scale forming specie will tend to precipitate and whether or not the scale former will cause growth on existing deposits. All of the indices in use today, including the simplest and the most sophisticated, are derived from the basic relationship which defines the solubility product. For calcium carbonate this equates to:

\[
{\text{Ca}}{\text{C}}{{\text{O}}_3} = K_{sp}
\]

where

- \(\{\text{Ca}\}\) is the calcium activity in the water at the current conditions
- \(\{\text{CO}_3\}\) the carbonate activity at current conditions
- \(K_{sp}\) is the solubility product at the current conditions of temperature, ionic strength, and pressure.
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The “free” ion activities for \{Ca\} and \{CO_3\} are used in ion association models to improve accuracy and account for phenomena such as common ion effects.\(^1,2,3,9,14\) The activity of the individual ions can be estimated using simple techniques such as the Debye-Huckel equation or extensions of it, or using more rigorous, but less generalized, methods such as those derived by Pitzer\(^1,2,11,15\) and others.

A simple arrangement of Equation 1 relates “what we have” to “what we can ultimately have”:

\[
\text{Equation 2 Saturation Ratio} = \frac{\{Ca\} \{CO_3\}}{K_{sp}} \quad \text{what we have}
\]

where \(K_{sp}\) is the solubility product for the scale forming specie under the conditions being evaluated.

Table 1 summarizes the Saturation Ratio relationship for common (and some not so common) mineral scales that might be expected in cooling water and other industrial aqueous systems.

Some water treatment chemists and engineers express the Saturation Ratio in the base ten logarithm form, and call it a Saturation Index:

\[
\text{Equation 4 Saturation Index} = \log_{10}(\text{Saturation Ratio})
\]

Simple indices, such as the Langelier Saturation Index, Ryznar Stability Index, and Practical Scaling Index are expressed in this manner. In fact, it can be shown that the Langelier Saturation Index is the base ten log of calcite saturation ratio calculated with some simplifications and assumptions:

**Langelier Saturation Index Assumptions:**

1) Total analytical values for Ca and CO\(_3\) are used rather than free ion concentrations

2) CO\(_3\) is estimated from “M” alkalinity with the assumption that all titrated alkalinity is in the HCO\(_3\) form. Although Langelier recommends correcting “M” alkalinity for non-carbonic acid system alkalinity, most users ignore the noncarbonate alkalinity correction when calculating the index. Example non-carbonate contributions include phosphates, silicates, borates, sulfides and cyanides.

3) A simplified activity coefficient is calculated using the basic Debye-Huckel correlation.

As a result, the usefulness of the Langelier Saturation Index, and similar simple indices, is limited to neutral pH waters of low ionic strength, such as many potable waters.

Simple indices such as the Langelier Saturation Index should not be confused with more rigorous indices that express their results as the base ten logarithm. More sophisticated evaluations will also sometimes express the driving force as the base ten log.\(^1,14\)

**Interpreting Saturation Ratios and Indices**

Table 2 provides simple guidelines for interpreting indices derived from the solubility product relationship.

---

**Ion Association Reduces Available Ion Concentration**

Simple indices assume that all ions are free. This can lead to an overstatement of scale potential by the use of higher than available values for the reactants (e.g. Analytical Values of Ca and CO\(_3\), rather than free ion concentrations). Ions in solution are not all present as the free species. For example, calcium in water is not all present as free Ca.\(^2\) Barium and strontium in a water are also not present totally as free ions. Anions such as sulfate also become associated with other ions and are present as “bound” rather than “free” ions. Other species form which are not available as driving forces for scale formation. Examples include the soluble calcium sulfate species, hydroxide species, and bicarbonate - carbonates. Table 3 outlines example species that can be present in a typical water.

Speciation of a water is time prohibitive without the use of a computer for the iterative number crunching required. The process is iterative and involves:

1) Checking the water for electroneutrality via a cation-anion balance, and balancing with an appropriate ion (e.g sodium or potassium for cation deficient waters, sulfate, chloride, or nitrate for anion deficient waters).

2) Estimating ionic strength, calculating and correcting activity coefficients and dissociation constants for temperature, correcting alkalinity for non-carbonate alkalinity.

3) Iteratively calculating the distribution of species in the water from dissociation constants (a partial listing is outlined in Table 3).

4) Checking the water for balance and adjusting ion concentrations to agree with analytical values.

5) Repeating the process until corrections are insignificant.

6) Calculating saturation ratios based upon the free concentrations of ions estimated using the ion association model (ion pairing).

The use of ion pairing to estimate the free concentrations of reactants overcomes several of the major shortcomings of traditional indices. Indices such as the LSI correct activity coefficients for ionic strength based upon the total dissolved solids. They do not account for “common ion” effects.\(^1,6\) Common ion effects increase the apparent solubility of a compound by reducing the concentration of reactants available. A common example is sulfate reducing the available calcium in a water and increasing the apparent solubility of calcium carbonate. The use of indices which do not account for ion pairing can be misleading when comparing waters where the TDS is composed of ions which pair with the reactants versus ions which have less interaction with them. The indices will also not be transportable between waters of varying quality. For example, a high sulfate water will have lower free calcium concentrations than a water with the same ionic strength but derived from chloride. Both waters will have the same ionic strength. Both will have the same “simple” index.

The “No Ion Pairing Correction” lines in Figure 1 depict the Langelier Index based upon total analytical values. Note that the calculated index, and therefore predicted scale potential, are almost identical for the high sulfate and high chloride cases. The ion pairing lines plot the base ten log of saturation ratio when corrected for ion pairing, and using free ion concentrations.
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Ion association model saturation ratios are used routinely in oil field, reverse osmosis, and mining applications for the prediction of barium and strontium based scales. This would be expected because barium and strontium derived scales are typically encountered in high TDS brackish water and brines.

**THERMODYNAMIC: QUANTITY OF SCALE PREDICTION**

Momentary Excess has been used to indicate the quantity of scale that might precipitate. This index describes the quantity of scalant which would have to precipitate (or dissolve) instantaneously to bring a water to equilibrium.

Precipitation to equilibrium assumes that one (1) mole of calcium will precipitate for every mole of carbonate that precipitates. On this basis, we can estimate a quantity X, the precipitation required to restore a water to equilibrium, as follows:

Equation 5  \[ [Ca - X][CO_3 - X] = K_{sp} \]

X is a quantitative indicator of precipitation reserve for a water. X will be a small value when either calcium is high and carbonate low, or when carbonate is high and calcium low. It will increase to a maximum when equal parts of calcium and carbonate are present. As a result, this index (Precipitation to Equilibrium) will provide vastly different values for waters with the same saturation ratio. Momentary Excess can also be used to estimate the maximum precipitation expected for other scale forming species.

In the case of sulfate, momentary excess is calculated by solving for “X” in the relationship:

Equation 6  \[ [Ca - X][SO_4 - X] = K_{sp} \]

The solution becomes more complex for tricalcium phosphate:

Equation 7  \[ [Ca - 3X][PO_4 - 2X]^2 = K_{sp} \]

The index provides a quantitative indicator of scale potential and has been used to correlate scale formation in a kinetic model.\(^{12}\) The index does not account for two critical factors. The pH will change in some cases as precipitate forms by the precipitation of alkalinity contributors such as carbonate or phosphate. Secondly, the index does not account for changes in driving force as the reactant levels decrease due to precipitation. A rigorous model would decrease the reactants by a minute amount, and recalculate the driving force after each minute precipitation, until equilibrium was reached.

Momentary Excess does not represent a quantitative assessment of the amount of a fouling which will precipitate. It is an indicator of the capacity of a water to scale, and can be compared to the buffer capacity of a water. The calculation method is covered in more detail in the literature.\(^{10,12}\)

Estimates of actual precipitation involve an iterative process, primarily due to the change in pH that occurs as some scales, including CaCO\(_3\), Mg(OH)\(_2\), Ca\(_2\)(PO\(_4\))\(_2\), precipitate.

**A POWER INDEX**

Saturation Ratio provides a measure of the driving force for scale formation. It is a potential for scale formation analogous to voltage in electrical calculations. Momentary Excess provides a measure of how much scale might be moved by the Saturation Ratio driving force, much like amperage being a measure of the number of electrons being moved by the voltage driving force.

The author is investigating the use of a Scale Power Index to normalize some of the confusing aspects of scale index calculations. For example, higher order scale such as tricalcium phosphates can have very high Saturation ratios (> 100,000) but very low Momentary Excess (<0.01 mg/L).

The Power Index is calculated from two other indices as outlined in Equation 8.

Equation 8:  \[ PI = \text{Saturation Ratio} \times \text{Momentary Excess} \]

This factor is seen in many kinetic models for crystallization and growth on existing substrates and has been found useful in developing models for some scale inhibitors.

**KINETICS: INDUCTION TIME**

Thermodynamics tells you if a scale is likely to form. Thermo can also indicate how much scale is likely to form through indicators such as “free ion” momentary excess, which describes the instantaneous precipitation (or dissolution) required to bring a water to equilibrium. Kinetics can tell you when the scale is likely to form, and the rate at which it will form. As outlined in this section, the thermodynamic and kinetic models are intimately related.

Saturation ratio calculations, and even simple indices, indicate whether or not scale is likely to form, or dissolve, if left undisturbed for an infinite period of time. Residence times in cooling systems are significantly less than infinity. The thermodynamics based indices, such as ion association model saturation ratios, tell you whether or not scale is likely to form. Kinetics tell you when it is likely to form, and if it will form before the water passes through the cooling system and is safely discharged. A criticism of thermodynamic based indices is that they only tell you what will happen at time equals infinity. This section discusses induction time, its relationship to thermodynamic based saturation ratios, and the relevance of thermodynamic indices under actual cooling water chemistry, temperature, and residence times.

**Induction Time:** When reactants are mixed, a solution is heated, cooled, undergoes a pressure change or is otherwise perturbed, the impact of the environmental changes is not immediate. A finite time passes before the perturbation affects any susceptible reaction. In the case of scale formation, induction time can be defined as the time before a measurable phase change (precipitation or growth) occurs after perturbation. In a pure system, with only the reactants present such as calcium and carbonate, or barium and sulfate, scale formation might proceed as follows:

1) Aqueous calcium carbonate molecules congregate, and form larger and larger clusters.
2) The clusters grow to a critical size and overcome the “activation energy” needed for the change from the “aqueous” to “solid” phase to occur.
3) The phase change is then observed. In the case of CaCO\(_3\), pH drops as the salt changes phase, and the induction time can be defined.
4) Crystals will then grow.

Induction time has been studied extensively for industrial processes. In the case of sucrose crystallization, the objective is to minimize induction time and maximize crystallization. In the case of scale control, the objective is to extend the induction time until a water has safely passed through the cooling system, or other process adversely affected by scale. The induction time, in the absence of scale control, the objective is to extend the induction time until a water has safely passed through the cooling system, or other process adversely affected by scale. The induction time, in the absence of scale...
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inhibitors, has been modeled for common scales, including barite (BaSO₄) and calcite (CaCO₃). Figures 2 and 3 are derived from this, and related works, by Mason Tomson, his staff and graduate students at Rice University.

Figure 2 profiles the untreated induction time for calcite in the practical operational range for calcite of 0 to 140x saturation. This range was chosen because it is the effective range for most scale inhibitors. The 140x saturation ratio limit is a commonly accepted upper limit for operation with common inhibitors such as phosphates and polymers. Figure 3 profiles the saturation ratio range for barite, 0 to 80x saturation.

It should be noted that the induction times for both calcite and barite are several orders of magnitude below the typical residence time in an open recirculating cooling tower system. As a result, the use of the thermodynamic saturation ratios for predicting scale is accurate and an acceptable practice in typical cooling tower operating ranges. Actual induction times in cooling systems will typically be lower than those of a pure system. Existing “seed” crystals and deposits provide a substrate for crystal growth without the necessity for achieving the “activation energy” for the initial phase change. In other words, it is easier to keep a clean system clean than to keep a dirty system from getting dirtier. Other factors can also decrease induction time.

Although beyond the scope of this paper, it should be noted that scale formation in cooling tower systems is typically “second order” for bulk water precipitation. Once through systems, such as utility condenser cooling systems, tend to be closer to “first order” for growth on an existing substrate.

**KINETICS: INDUCTION TIME EXTENSION BY INHIBITORS**

Scale inhibitors do not prevent scale formation forever. They typically only delay the inevitable. Most threshold effect scale inhibitors function by interfering with the kinetics of crystal formation and growth, extending the induction time until the water has passed through the system without forming crystals or causing growth on existing substrates. Dosage models have been used successfully to prevent scale in cooling systems, reverse osmosis, oil field and mining applications. The impact of common scale inhibitors on induction time can be modeled by adding an inhibitor term to a classic model for induction time:

\[ \text{Time} = \frac{[\text{inhibitor}]^M}{k \cdot [\text{SR} - 1]^{P-1}} \]

where

- **Time** is the induction time
- **inhibitor** is the scale inhibitor molar concentration
- **k** is a temperature dependent rate constant
- **P** is the number of molecules in a critical sized cluster

Other, more empirical models, are also in use for calculating induction time extension by inhibitors. (Tomson ref)

It must be noted that there is a maximum saturation ratio beyond which inhibitors will not prevent scale by this mechanism at any dosage. This is typically 140x saturation for calcite and 80x saturation for barite, as outlined in Table 4.

**Degree of Supersaturation:** An ion association model saturation ratio is the driving force for the model outlined in this paper, although other similar driving forces have been used. Calculation of driving force requires a complete water analysis, and the temperature at which the driving force should be calculated.

Figure 4 depicts the impact of saturation ratio increases on the dosage required at constant temperature and residence time at less than the critical saturation ratio. This profile represents the dosage required to prevent growth on an existing substrate.

Figure 5 depicts the impact of saturation ratio increases on the dosage required at constant temperature and residence time when the critical saturation ratio is achieved and spontaneous nucleation and crystal growth occurs. This profile represents the dosage required to prevent growth in a typical cooling system.

Figure 6 depicts the impact of dosage increases upon induction time at constant calcite saturation ratio and temperature.

**Temperature** Temperature affects the rate constant for the induction time relationship. As in any kinetic formula, the temperature has a great impact upon the collision frequency of the reactants. A common concept in basic chemistry is that reaction rates increase with temperature. The rule-of-thumb frequently referenced is that rates approximately double for every ten degrees centigrade increase in temperature. The temperature constant k in equation 9 and similar models was found to correlate well with the Arrhenius relationship, as outlined in formula 10.

\[ K = A e^{Ea/RT} \]

Where:

- **k** is a temperature dependent constant;
- **Ea** is activation energy;
- **R** is the Gas Constant;
- **T** is absolute temperature.

This temperature effect is independent of the effect of temperature upon saturation ratio calculations. Figure 7 depicts the impact of temperature on dosage requirements, all other parameters being constant.

**pH** pH affects the saturation ratio calculations, but it also may affect the dissociation state and stereochemistry of the inhibitors. Inhibitor effectiveness can be a function of pH due to its impact upon the charge and shape of an inhibitor molecule. This effect may not always be significant in the pH range of interest (e.g. 6.5 to 9.5 for cooling water).

**Active sites:** It is easier to keep a clean system clean than to keep a dirty system from getting dirtier. This rule of thumb may well be related to the number of active sites for growth in a system. When active sites are available, scale forming species can skip the crystal formation stage and proceed directly to crystal growth. Other factors can impact dosage such as suspended solids in the water. Suspended solids can act as sources of active sites, and can reduce the effective inhibitor concentration in a water by adsorption of the inhibitor.

It can be seen that the models follow what would be expected based upon common sense and experience. Dosage increases with increasing supersaturation. Induction time increases as dosage increases. Models of this type have been developed for common scales and most commercial inhibitors. Application of the models to operating...
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inhibitors may have a particular operating range where they are most effective. A blend of the common scale control agents ATMP and HEDP demonstrates this effect. In this case, a blend of complementary inhibitors might seem to be synergistic. In actuality, the dosage for one of the inhibitors in a blend will have an optimum dosage lower than the dosage requirement for the blend. For example:

a) HEDP (1-hydroxy ethylidene-1,1-diphosphonic acid) is typically most cost effective at lower temperatures and lower saturation ratios.

b) ATMP (aminotris(methyleneephosphonic acid)) is typically most cost effective at higher temperatures and higher saturation ratios.

c) An HEDP/ATMP blend provides a smoothing effect over a broad application range of saturation ratio and temperature.

Table 6 summarizes dosage requirements for each phosphonate, and for a one-to-one blend, versus scale stress. Figure 7 presents the same data graphically.

HEDP dosages are lower at lower temperatures and saturation ratios. ATMP dosages gain an advantage under conditions of increasing temperature and saturation ratio stress.

**APPLICATION NICHES**

Inhibitors and their blends have specific application niches where they tend to be used.

As seen in Table 6 and Figure 8, application niches for the phosphonates compared can be identified based upon performance and mg/L dosage as follows:

HEDP tends to provide the lowest dosages at lower saturation ratios and lower temperatures.

ATMP tends to control scale at lower dosages at intermediate saturation ratios and temperatures.

Of the three (3) phosphonates compared, PBTC (2-phosphonobutane-1,2,4-tricarboxylic acid) tends to provide the lowest dosage and highest upper limit at high saturation ratios.

Cost performance may vary based upon the actual cost per pound of the inhibitors (or blends).

For purposes of this paper three treatment niches will be defined:

**The “Comfort Zone”**

The “Comfort Zone” is defined as a region where achieving scale and corrosion control is a relatively stress free operation. Calcium carbonate scale potential is well below the accepted limits for common phosphonates (Calcite x saturation 30 to 80, versus a limit of 135 to 140 x saturation). Temperatures are below 120 °F. HEDP tends to be used with polymers and copolymers in the “comfort zone.” Other treatments may be used due to treatment program constraints such as all polymer treatments where phosphate discharge is restrictive.

**The “Stressed CaCO₃ Zone”**

The “Stressed CaCO₃ Zone” is defined as a region where achieving scale and corrosion control is difficult and requires excellent control. Calcium carbonate scale potential is approaching or above the accepted limits for common phosphonates (Calcite x saturation 120 to 200 versus a standard treatment limit of 135 to 140 x saturation). Stressed inhibitors such as PBTC and blends of PBTC with PMA (polymaleic anhydride) are required. Blends of HEDP and PMA are sometimes used. Skin temperatures are typically above 120 °F.

**The “Stressed Phosphate Zone”**

The “Stressed Phosphate Zone” is defined as a region where corrosion control is achieved by super-saturating the water with a solubility limited inhibitor such as orthophosphate, pyrophosphate, or zinc (in which case a purist would define the niche as a “Stressed Zinc Zone”). Calcium carbonate scale potential is typically controlled well below the accepted limits for common phosphonates. The solubility limited corrosion inhibitor is fed at a rate to assure the maximum presence of inhibitor without creating an inhibitor-based fouling problem.

Typical saturation ratio and solubility based control ranges for the inhibitors are outlined in Table 7. Maximum solubilities shown are calculated using a computerized ion association model as follows. The limiting factor for an ion’s solubility is determined (e.g. Ca₃(PO₄)₂, Zn₃(PO₄)₂). The concentrations of other species for this ion are back calculated from the limiting factor. The maximum solubility is calculated as the sum as all bound forms of the ion under study, plus the free ion concentration. Analytically, the maximum soluble zinc equates to the maximum filtered zinc in a water having a difference between the measured “total” (unfiltered) and “soluble” (filtered) values. The impact of zinc, orthophosphate, and pyrophosphate on each other’s solubility is iteratively determined in the actual simulation model used. Figure 9 profiles the maximum solubility of a four to one (4:1) blend of orthophosphate and zinc, which parallels the maximum recommended dosage, beyond which fouling would be expected from precipitating inhibitor.

**KINETICS: RATE**

Studies on operational surface condensers in the 1980’s demonstrated that calcium carbonate build-up on condenser tubes could be modeled as a function of thermodynamic driving forces such as saturation ratios and momentary excess, when combined with the elements of temperature and time.

At saturation ratios below the critical point, growth on an existing scale was found to correlate with a model in the format:

\[
\text{Equation 11} \quad \text{deposit buildup} = \text{crystal growth} = K \left[ \text{driving force} \right]^n t
\]

where deposit buildup is the measured increase in deposit.

K is a temperature dependent rate constant or relating well with the Arrhenius relationship.

driving force is momentary excess at lower saturation ratios and saturation ratio at higher
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saturation ratios. The “power” index combination of saturation ratio and momentary excess has also been used successfully.

**PUTTING IT ALL TOGETHER: COST PERFORMANCE**

Several values are required to calculate and compare cost performance:

1) raw material/product cost.
2) models to calculate optimum dosage.
3) target operating concentration ratio and related values required for blowdown-leak-drift loss calculations.

Cost performance in its simplest form is based upon cost per million pounds of blowdown, or simply:

Equation 12: \[ \text{cost/mm pounds blowdown} = \text{treatment dosage (ppm)} \times \text{treatment cost/pound} \]

Comparisons based upon cost per million pounds of blowdown are valid only when comparing treatment costs at the same target concentration ratio. When comparing treatments under different operating conditions, the total treatment costs must be compared at the target concentration ratio for the treatment. For example, a treatment based upon the combination of PBTC and PMA (upper limit 225 x Calcite saturation) might operate at a target concentration ratio higher than a treatment based upon HEDP (upper limit 140 x Calcite saturation).

In the past five years, raw material costs for scale and corrosion inhibitors have increased rapidly and disparately; necessitating a frequent review of treatment cost performance, and even reformulation.

**SUMMARY**

Simple Indices and rigorous Ion Association Model Saturation Ratios have been used to predict scale and estimate its severity in cooling water systems. A criticism of their use is that they are thermodynamic based and represent what will be expected at \( t = \infty \), and as result, that indices might not be representative of what will happen in a finite residence time cooling system or other aqueous industrial process. Induction time modeling validates the application of thermodynamic based indices to systems such as open recirculating cooling towers where the induction time for scale formation (or growth) from an untreated water is significantly shorter than the residence time of water in the system. The addition of inhibitor impact upon induction time provides a kinetic basis for scale inhibitor dosage models.

The same concept of induction time modeling can be used to determine inhibitor dosage required to extend the induction time for a given scale forming specie until a water has passed through the system. Models have been developed and used successfully using this method for over thirty years in cooling water systems ranging from low residence time utility once through condenser cooling systems, to long holding time index cooling towers.

It can be seen from the models developed that there is an intimate relationship between thermodynamic “indices” and kinetic aspects of the scale formation process and its inhibition.

The same thermodynamic solubility models can be used to calculate the maximum dosage for “solubility limited” corrosion inhibitors such as orthophosphate, polyphosphate, and zinc. Dosages are based upon maximum soluble inhibitor concentrations, and the concept that treatment levels above the maximum inhibitor solubility will not improve corrosion control and may result in the feed of another deposit control agent to prevent the solubility limited inhibitor from becoming a foulant.

Cost performance comparisons provide a useful tool for minimizing treatment costs and dosage. Computerized models allow optimization of formulations for target waters and operating ranges. This approach also provides a means for formulating replacement treatment programs for a given water should raw material shortages or rapidly rising costs force a change in treatment approach. This treatment limits and optimum dosage approach also provides a product management tool for improving the consistency of treatment programs recommended and run by different field personnel.

Computer modeling provides a useful tool for predicting scale formation, estimating the water chemistry impact on scale formation and corrosion, and optimizing inhibitor dosages and overall treatment costs. Like all computer modeling tools, the results should be used as a tool for the water treatment professional, and not as a substitute for experience and judgment.

**REFERENCES**

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TABLE 1 - SATURATION RATIO FORMULAS

<table>
<thead>
<tr>
<th>Compound</th>
<th>Saturation Ratio</th>
</tr>
</thead>
</table>
| Calcium carbonate      | \[
\frac{(\text{Ca})(\text{CO}_3)}{K_{sp, \text{CaCO}_3}}
\] |
| Barium carbonate       | \[
\frac{(\text{Ba})(\text{CO}_3)}{K_{sp, \text{BaCO}_3}}
\] |
| Strontium carbonate    | \[
\frac{(\text{Sr})(\text{CO}_3)}{K_{sp, \text{SrCO}_3}}
\] |
| Calcium sulfate        | \[
\frac{(\text{Ca})(\text{SO}_4)}{K_{sp, \text{CaSO}_4}}
\] |
| Barium sulfate         | \[
\frac{(\text{Ba})(\text{SO}_4)}{K_{sp, \text{BaSO}_4}}
\] |
| Strontium sulfate      | \[
\frac{(\text{Sr})(\text{SO}_4)}{K_{sp, \text{SrSO}_4}}
\] |
| Tricalcium phosphate   | \[
\frac{(\text{Ca})^3(\text{PO}_4)^2}{K_{sp, \text{Ca}_3\text{PO}_4}}
\] |
| Amorphous silica       | \[
\frac{\text{H}_4\text{SiO}_4}{(\text{H}_2\text{O})^2 \cdot K_{sp, \text{SiO}_2}}
\] |
| Calcium fluoride       | \[
\frac{(\text{Ca})(\text{F})}{K_{sp, \text{CaF}_2}}
\] |
| Magnesium hydroxide    | \[
\frac{(\text{Mg})(\text{OH})^2}{K_{sp, \text{Mg(OH)}_2}}
\] |
| Trizinc phosphate      | \[
\frac{(\text{Zn})^3(\text{PO}_4)^2}{K_{sp, \text{Zn}_3\text{PO}_4}}
\] |
| Zinc hydroxide         | \[
\frac{(\text{Zn})(\text{OH})^2}{K_{sp, \text{Zn(OH)}_2}}
\] |
| Calcium pyrophosphate  | \[
\frac{(\text{Ca})(\text{P}_2\text{O}_7)}{K_{sp, \text{CaP}_2\text{O}_7}}
\] |

Table 2: Interpreting Saturation Ratios and Log Indices

<table>
<thead>
<tr>
<th>Log_{10} Indices</th>
<th>Saturation State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under saturated:</td>
<td>Scale will not tend to form.</td>
</tr>
<tr>
<td>\left[\text{IAP}\right] &lt; K_{sp}</td>
<td>\text{Log}_{10} \frac{(\text{Ca})(\text{CO}<em>3)}{K</em>{sp, \text{CaCO}_3}} &lt; 1.0</td>
</tr>
<tr>
<td>\left[\text{IAP}\right] = K_{sp}</td>
<td>\text{Log}_{10} \frac{(\text{Ca})(\text{CO}<em>3)}{K</em>{sp, \text{CaCO}_3}} = 1.0</td>
</tr>
<tr>
<td>\left[\text{IAP}\right] &gt; K_{sp}</td>
<td>\text{Log}_{10} \frac{(\text{Ca})(\text{CO}<em>3)}{K</em>{sp, \text{CaCO}_3}} &gt; 1.0</td>
</tr>
</tbody>
</table>

Note: Log_{10} Indices refers to those that express the Saturation Ratio in Log_{10} form. Interpretation of Byrnar and Practical indices differs. See the references for specifics.
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ABSTRACT
There are a total of 15 hyperbolic and 30 mechanical draft cooling towers on the AEP system. These towers utilize a cross-flow or counter-flow thermal transfer design, and almost all of the cross-flow towers are treated wood structures.

AEP replaced four cross-flow mechanical draft towers during the period of 2008 through May 2010, and a counter-flow mechanical draft tower was built for a new unit in 2009. All five of these new towers used polyester fiberglass structure from the same pultruder and were designed and constructed by a single cooling tower company. These five towers are the first fiberglass structure cooling towers on the AEP system which have been placed in-service.

Failed or cracked fiberglass columns were found in four towers and surface blisters were noticed in two of the new towers after 2 to 18 months of operation. This paper will summarize where the failures, cracks and blisters occurred, along with steps AEP is following up on to minimize cracks and blisters in future fiberglass cooling towers.

BACKGROUND
AEP is one of the largest electric utilities in the United States, delivering electricity to more than 5 million customers in 11 states. AEP ranks among the nation’s largest generators of electricity, owning more than 38,000 megawatts (MW) of generating capacity in the U.S., with individual unit ratings ranging from 25 MW to 1300 MW.

AEP merged with Central South West Corporation in 2000, and the system is geographically designated as an eastern and western generating fleet. The eastern fleet currently has generating units in Indiana, Kentucky, Michigan, Ohio, Virginia and West Virginia, while the western fleet’s generating units are located in Arkansas, Louisiana, Oklahoma and Texas.

FAILED FIBERGLASS COLUMNS AND BEARING PADS
Cross-Flow Cooling Tower No. 1
A new 14 cell, fiberglass structure, cross-flow, mechanical draft tower was completed in May 2008. Figure 1 represents the cross-flow structure for the tower and shows the ~ 40 ft columns (supplied in a single length with no splices) which support the 60” to 30” hot water distribution pipe on top of the hot water deck. There are six transverse bays in each cell with the transverse bents spaced every 6 ft, longitudinal bents spaced every 6 ft, and vertical elevations of 6 ft. The 3½” pipe columns rest on elevated concrete piers which are at eye level. All of the fiberglass columns were originally designed to sit on a fiberglass/neoprene bearing pad.

This unit had an outage in December 2009 and the cold water basin was drained so the new tower could be inspected. During the outage, approximately 90% of the fiberglass bearing pads had failed under the 3½” pipe columns, and a total of 55 pipe columns (out of 168) had cracked at the bearing pads. Photo 1 represents the worse case failure found in the tower, while Photo 2 represents several of the typical failure modes found after 18 months of operation. Almost 60% of the failures were under the 60” hot water pipe in Cells 1 through 5, while the other 40% were spread out under the smaller pipes in Cells 6 through 14. The fiberglass bearing pads were replaced by the cooling tower contractor with 304 stainless pads under the high load columns. Below is a summary of how much was cut-off the 55 pipe columns above the bearing pads to remove the cracks in December 2009:

- 2 columns had 6 ft cut-off and a new 6 ft column section spliced in
- 1 column had 4 ft cut-off and a new 4 ft column section spliced in
- 14 columns had 3 ft cut-off and a new 3 ft column section spliced in
- 12 columns had 2 ft cut-off and a new 2 ft column section spliced in
- 26 columns had 1 ft cut-off and a new 1 ft column section spliced in
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There was not enough time during the December 2009 outage to chase out all of the cracks, so 11 pipe columns were left in-place with internal cracks at “horseshoe” reinforcement folds as shown in Photo 3.

This unit had another outage in September/October 2010 and the cold water basin was drained. A total of 35 pipe columns (not found with cracks in Dec. 2009) were now found with cracks or faces starting to shear, and 12 of these columns had 1.5” to 10” cut-off and a stainless steel shim or pedestal installed. A total of 29 of the previous 55 splice repaired pipe columns had the splice removed and a stainless pedestal installed. As a result, 90 (or 54%) of the 168 pipe columns exhibit damage at the bearing pad after 28 months of operation. Below is a summary of what was found and repaired in the fall of 2010:

- 23 columns (not exhibiting problems in Dec. 2009) had small cracks or were starting to mushroom at the stainless pads. These were left as-is and will be monitored.
- 11 columns (not exhibiting problems in Dec. 2009) had 1.5” cut-off and a stainless block (or shim) installed
- 1 column (not exhibiting problems in Dec. 2009) had 10” cut-off and a stainless pedestal installed
- 26 columns (repaired with a splice in Dec. 2009) had 1 ft stainless pedestals installed
- 3 columns (repaired with a splice in Dec. 2009) had 3 ft stainless pedestals installed

Cross-Flow Cooling Tower No. 2

Another new 12 cell, fiberglass structure, cross-flow, mechanical draft tower was completed in May 2008. Figure 2 represents the cross-flow structure for the tower and shows the ~ 48 ft columns (supplied in a single length with no splices) which support the 66” to 30” hot water distribution pipe on top of the hot water deck. There are six transverse bays in each cell with the transverse bents spaced every 6 ft, longitudinal bents spaced every 6 ft, and vertical elevations of 6 ft. The 4” and 3½” pipe columns rest on the cold water basin floor. All of the fiberglass columns were originally designed to sit on a fiberglass/neoprene bearing pad.

During a several day outage in March 2010, approximately 75%+ of the fiberglass bearing pads had failed under the pipe columns and a total of 35 highly loaded columns (out of 164) had cracked at the bearing pads and were repaired. A total of twelve 4” columns failed while twenty-three of the 3½” columns failed. Photo 5 represents the worse case failure found in the tower after 22 months of operation. Roughly 35% of the failures were in Cells 1 through 4 under the 66” or 60” hot water pipe, while the other 65% were spread out under the smaller pipes in Cells 5 through 12. The fiberglass bearing pads were replaced by the cooling tower contractor with 304 stainless pads under the high load columns. Below is a summary of how much was cut-off the 35 highly loaded columns (e.g. pipe, motor or gearbox) to remove the cracks in March 2010:

- 10 columns had 17” cut off the bottom and stainless steel pedestals installed
- 25 columns had 1” to 3” cut off and stainless steel blocks (or shim) installed

This unit had another outage in October/November 2010 and the cold water basin was drained. A total of 53 columns (not repaired in March 2010) were found with damage at the stainless steel bearing pad (e.g. cracks, mushrooming or faces starting to shear [Photo 4]), and 19 of these columns had 1” to 17” cut-off and a stainless steel shim or pedestal installed. As a result, 88 (or 54%) of the 164 highly loaded columns have cracked after 28 months of operation. Below is a summary of what was found and repaired in November 2010:

- 34 columns (not repaired in March 2010) had small cracks or were starting to mushroom at the stainless pads. These were left as-is and will be monitored.
- 11 columns (not repaired in March 2010) had 1” to 2” cut-off and a stainless block (or shim) installed
- 8 columns (not repaired in March 2010) had 6” to 17” cut-off and a stainless pedestal installed
- 6 columns (previously repaired in March 2010) had additional column material cut-off and a higher stainless steel pedestal or additional shim plates installed.

Photo 4 – Pipe column starting to shear along face
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Cross-Flow Cooling Tower No. 3

A new 14 cell, fiberglass structure, cross-flow, mechanical draft tower was completed in May 2009. Figure 1 represents the cross-flow structure for the tower and shows the ~ 40 ft columns (supplied in a single length with no splices) which support the 60” to 30” hot water distribution pipe on top of the hot water deck. There are six transverse bays in each cell with the transverse bents spaced every 6 ft, longitudinal bents spaced every 6 ft, and vertical elevations of 6 ft. The 3½” pipe columns rest on elevated concrete piers which are at eye level. All of the fiberglass columns were originally designed to sit on a fiberglass/neoprene bearing pad.

During an outage in February/March 2010, approximately 90% of the fiberglass bearing pads had failed under the pipe columns and a total of 39 pipe columns (out of 168) had cracked at the bearing pads. Photos 6 and 7 represent the typical failure found in the tower after just 8 months of operation. Roughly 35% of the failures were under the 60” hot water pipe in Cells 1 through 5, while the other 65% were spread out under the smaller pipes in Cells 6 through 14. The fiberglass bearing pads were replaced by the cooling tower contractor with 304 stainless pads under the high load columns. Below is a summary of how much was cut-off the 39 pipe columns to remove the cracks in February/March 2010:

- 11 pipe columns had 18” cut of the bottom and stainless steel pedestals installed
- 28 pipe columns had 2” to 3” cut off the bottom and grout pads installed

Counter-Flow Cooling Tower

A new 10 cell, back-to-back, fiberglass structure, counter-flow, mechanical draft tower was constructed in 2009 and commissioned in early 2010. The columns are constructed of three separate pieces with two levels of splice blocks (designated by the red arrows in Photo 8). The four-bolt splice connections are comprised of a positioning tube inside of the column ends and flat plate on opposite sides. There are eight transverse bays in each cell with the transverse bents spaced every 6 ft, longitudinal bents spaced every 6 ft, and vertical elevations of 6 ft. The 3” and 4” columns rest on the cold water basin. All of the fiberglass columns were originally designed to sit on a fiberglass/neoprene bearing pad. Two 30” hot water distribution pipes enter each of the west side cells to supply water to the east and west back-to-back cells.

During a short March 2010 start-up outage the fiberglass bearing pads were replaced by the cooling tower contractor with 304 stainless pads under the high load columns (3,000 lbs or higher). During this outage a total of 10 highly loaded 3” columns were found cracked where they rest on the bearing pads. It is reported that none of the removed fiberglass plates exhibited any damage or cracks. Three of the 18 ft high 3” columns were replaced, while the other seven had 1” or 2” cut off the bottom and 304 stainless steel blocks installed under the columns. Photo 9 shows several cracks in a 3” column where it rests on the bearing pad.
• 8 columns had cracks where the column sits on the bearing plate and were cut short by 1” or 2” and stainless steel blocks installed under the columns.

This unit had another outage in November 2010 and the cold water basin was drained. A total of two 3” columns (not exhibiting cracks in May 2010) now had cracks at the stainless steel bearing pad and both columns had roughly 2” cut-off and a stainless steel shim installed. Two additional 3” columns (not inspected in May 2010) were found with cracks at the lower splice joint, and both of those lower columns were replaced in November 2010.

• A handful of failed fiberglass bearing pads were found during construction and replaced on the cross-flow tower Nos. 1 and 2. It was originally thought debris had been trapped under the bearing pad, or the pedestal surface was not smooth and caused a stress concentration. In hindsight, those bearing pad failures during construction were a warning as to what would happen after the towers were placed in-service.

Below is a summary of the possible failure mechanisms which are causing the cracks in the fiberglass columns.

• The shear capacity of fiberglass is 4,500 psi, so in order to maintain a 3 to 1 safety margin then the highest shear load should be 1,500 psi or less. The calculated applied compressive stress along the seating surface of a 4” x ½” column (loaded to 13,043 lbs) and a 3½” x ¼” column (loaded to 11,416 lbs) is 3,478 psi and 3,512 psi, respectively.

• Failed column and bearing pad assemblies indicate the column cut into the fiberglass bearing pad (like a cookie cutter), which then caused the bearing pad to become inserted into the column and impose an internal force which overstressed the corners (Reference Photos 11 and 12). The FRP/neoprene bearing pads have been replaced under the high load columns in all the towers with 304 stainless/neoprene bearing pads.

• Several bolts on the stainless steel anchor clips were over tightened which drew in the bolted surface of the column. Cracks due to over tightening would occur on the interior surface and not be visible during construction inspections.

• If a bolt can not be inserted through all the drilled bolt holes by hand, then construction personnel may pound the bolt through the holes versus threading it through. Bolts pounded through the bolt hole (on the back surface of the column) can fail the surface surrounding the bolt hole by tearing out a chunk. This would typically be covered over.

Summary of Failed Columns

From a collection of failed column sections pulled from the structures, 80% of the cracks originated from the exterior surface while 20% originated on the interior surface. It was also observed that 70% of the cracks were located on the corners and roughly 30% of the cracks occurred on the face of the column. The failed pipe columns occur throughout the entire length of the tower, with about half of the failures occurring under columns supporting 66” or 60” pipes and the other half of the failures occurring under columns supporting 54” to 30” pipes, motors or fan gearboxes.
which ranged from 7 to 8 pH. Laboratory analysis of the liquid found in November 2009 and a honey colored liquid with an acetone odor was collected from tower Nos. 2 and 4 during the summer months to control algae. Buckman Bellacide 325 several times each week (in 5 gallon doses) and shock feeds 12.5% concentrated bleach hypochlorite once or twice daily (up to 50 minutes per event) to control biological growth. The make-up water sources for the cross-flow towers Nos. 1, 2, 3 and 4 are fresh water lakes or rivers. AEP feeds 93% concentrated sulfuric acid continuously into the make-up water to control pH, and shock feeds 12.5% concentrated bleach hypochlorite once or twice daily (up to 50 minutes per event) to control biological growth. Buckman Bulab 7126 (1 ppm) or Bulab 7045 (5 ppm) is fed continuously into the make-up water to control pH, fluoride (3.75 mg/L), phosphate (22.8 mg/L), chloride (84 mg/L), nitrate (121 mg/L), and sulfate (215 mg/L). An IC chromatogram found two peaks of organic acids, two peaks of potentially phosphonated or sulfonated compounds and five other peaks which could not be identified. The pultruder nor the cooling tower contractor have performed a forensic examination of the blistered columns or pipe saddle side plates.

For the period of May 2008 through November 2009, AEP collected all available temperatures, pH and chemistry data for the circulating water systems on cross-flow towers Nos. 1 and 2. AEP’s analysis of the above data indicates both towers were operated within the parameters of the specified water condition limits (i.e. less than 125°F, pH range of 6.5 to 9.0, free available chlorine of less than 1.1 ppm or chlorides of less than 450 ppm).

AEP also sent a mass e-mail in early 2010 to approximately 100 individuals associated with utility sized cooling towers asking whether anyone had experienced blisters on pultruded polyester fiberglass shapes. One instance was reported in isolated cells of a cooling tower at a refinery in 2005/06 which was attributed to water chemistry upsets, but specifics were not available. Responses were obtained from 25 individuals and, except for the above instance, no one had experienced blisters. Many utilities stated they were treating the circulating water systems similar to AEP’s treatment procedure. Several people offered an opinion that the blisters were due to fabrication problems versus a water chemistry induced issue.

No definitive conclusions have been reached on the blister situation or whether the blisters will affect the long term structural integrity of the pultrusions. AEP is in the process of monitoring the blisters, collecting more samples for analysis, and has set-up a laboratory experiment at AEP’s Dolan Lab (near Columbus, Ohio).

AEP FREEZE/THAW TESTS ON PULTRUDED FIBERGLASS

At AEP’s Dolan Lab in mid 2009, a total of 16 small sections (3/8” x 1”) were obtained from 3” x ½” flat strips, 3” x ¼” flat strips and ¼” thick tube (column). Eight of the samples exhibited internal porosity while the other eight samples did not exhibit any visual defects. All the samples were measured and photographed with an electron microscope prior to any testing and after testing. It was determined that soaking each sample in – 70°F water for a half hour provided a saturated sample. The weight difference between

SURFACE BLISTERS

Surface blisters were found on two of the cross-flow towers after 18 months of operation. Approximately 20% of the columns in the cross-flow tower No. 2 had dime-size surface blisters which were usually on one face and linear as shown in Photo 13. Roughly 15% of the columns in the cross-flow tower No. 1 had pea-size surface blisters which were on multiple faces and located randomly. These blisters are located throughout the entire length of the towers and from the submerged cold water basin up to the fan deck. Almost all of the pipe saddle side plates (3/4” thick pultruded fiberglass) exhibited thumb-size surface blisters along the submerged area of the hot water deck as shown in Photo 14.

The make-up water sources for the cross-flow towers Nos. 1, 2, 3 and 4 are fresh water lakes or rivers. AEP feeds 93% concentrated sulfuric acid continuously into the make-up water to control pH, and shock feeds 12.5% concentrated bleach hypochlorite once or twice daily (up to 50 minutes per event) to control biological growth. Buckman Bulab 7126 (1 ppm) or Bulab 7045 (5 ppm) is fed continuously into the make-up water to control pH, fluoride (3.75 mg/L), phosphate (22.8 mg/L), chloride (84 mg/L), nitrate (121 mg/L), and sulfate (215 mg/L). An IC chromatogram found two peaks of organic acids, two peaks of potentially phosphonated or sulfonated compounds and five other peaks which could not be identified. The pultruder nor the cooling tower contractor have performed a forensic examination of the blistered columns or pipe saddle side plates.

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the dry and saturated samples was roughly 1% to 2%.

Two groups of the saturated samples were frozen and then either fan dried or placed in an oven maintained at 115°F until all moisture was driven out of the samples. The other two groups of saturated samples were not frozen, but were either fan dried or oven dried at 115°F. The process for all four conditions was repeated eight times before each sample was again viewed and documented via an electron microscope.

A total of 83 defects were documented in the 16 samples, but not all defects were measured. The defects increased in size under all four of the conditions, but it appears more changes occurred when all defects were measured. The defects increased in size under all design operating temperature of the cross-flow cooling towers.

It was observed that changes in the length or width of the cracks or voids occurred after the first cycle. It was also observed that two column sections (with no visual defects prior to testing) developed cracks after the soak/freeze/air dry cycling. The electron microscope does not have the capability of providing light or measuring depth into the photograph.

This data raises concerns about the expected life of saturated FRP components subjected to freezing and/or 115°F conditions, and whether exposed ends (from cutting, drilling, etc.) need to be coated.

**AEP LESSONS LEARNED**

Based upon the above pultruded fiberglass structural failures, surface blisters, testing and recent lessons learned on five new fiberglass cooling towers, below is AEP’s current design philosophy for new fiberglass structure cooling towers.

New fiberglass towers shall comply with CTI STD-137 “Fiberglass Pultruded Structural Products for Use in Cooling Towers”, and CTI STD-152 “Structural Design of FRP Components”. All exceptions to these standards must be detailed in writing at the time of bid. Minimum design stresses, water immersion correction factor and temperature correction factor, etc. are to comply with CTI STD-137. The structure’s design basis is to incorporate the cooling tower contractor’s published construction tolerances (i.e. column plumbness, cut end squareness, cross-sectional thickness, enlarged bolt holes, drilling tolerances, etc.). As a result, the reduction of a structural member’s load carrying capacity due to the contractor’s published construction tolerances shall not be covered by (or included in) the CTI service factors.

Any visually cracked structural member shall be replaced (at the expense of the cooling tower contractor) during construction and throughout the entire length of the warranty period. Any closed structural members (columns) which exhibit the surfaces being drawn together because of over tightened bolts shall be replaced (at the expense of the cooling tower contractor) even if no visual cracks are on the external surface. Contractor shall provide construction details to preclude over-tightening of bolts (e.g. use of torque wrenches, helical washers, lock nuts, etc.).

All fiberglass structural components are to be pultruded reinforced fiberglass with thermosetting resin and UV inhibitors throughout the cross-section. All fiberglass components are to be delivered to the plant site in a finished condition, so that no field applied resins are required.

A minimum of a 0.010 inch thick veil is required on the surfaces of all structural components (i.e. columns, diagonals, girts, handrails, etc.), and the veil is to incorporate proper UV inhibitors for long term exposure to ambient conditions. CTI STD-137 (09) states a 0.007 inch thick veil is standard.

All glass products shall be boron free. The glass products shall be Type E or Type E-CR (corrosion resistant).

Fiberglass bearing pads are unacceptable. All columns are to have full bearing contact to the cold water basin (with no gaps between the column and concrete) prior to tower completion. All column splice joints are to have full bearing contact between column ends.

The cooling tower company is responsible to provide all shop and field quality control and quality assurance requirements on all material, and set aside material not meeting this specification. Owner’s engineer will spot audit the material and reject all material not meeting this specification (even if it has been installed). The following visual acceptance criteria will be used during construction and the entire warranty period. The visual acceptance criteria for all fiberglass pultruded products shall comply with ASTM D-4385-08, Visual Acceptance Level III, except for the columns which will have stricter requirements as noted below:

- Presence of any defects in excess of the following definitions shall be cause for rejection. Repairs will not be considered for these defects.
- Blisters – Accept to Level I requirements, which does not allow blisters.
- Folded reinforcement – Folded near-surface reinforcement is not permitted along the straight edges if it exceeds 20% of the cross sectional thickness.
- Insufficient cure – Accept to Level II requirements, which does not allow insufficient cure. This will be tested in the shop and field via a Barcol hardness tester, and all values must exceed 45.
- Internal porosity – Accept to Level II requirements.
- Internal shrinkage cracks – No more than two (2) internal shrinkage cracks on each face of a cut end. All internal shrinkage cracks are defined as oriented perpendicular to the internal ply or reinforcement. If an internal shrinkage crack penetrates any internal ply or reinforcement, then it is defined as a crack and the piece is rejected. Any cracks oriented parallel to the internal ply or reinforcement will be defined as a delamination and rejected.
- Resin-rich areas – Accept if material reduction thickness is not over 10% and the area width is 1/8" or less. May be continuous in length, but not more than one area on a face. Resin-rich areas on opposing surfaces are not permitted. Must satisfy dimensional requirements.

The stated thickness of the pultruded shapes shall not deviate by more than 10% of the nominal thickness.

All holes are to be drilled and shall not exhibit “splinters” or “gouges” on the backside. No punched holes are acceptable.

The fiberglass pipe joints shall comply with CTI STD-154 for “Cooling Tower Filament Wound Fiberglass Piping Systems”. Specifically, all joint wraps shall have a minimum thickness equal to the pipe thickness, and the overall wrap length shall be 26 times the pipe wall thickness and tapered at both ends to provide a smooth transition. In addition, all wrapped joints are to be performed by a qualified and certified technician.

**CONCLUSIONS**

The cooling tower contractor has been responsive in performing warranty repairs to these cooling towers, and we are continuing to work with the cooling tower contractor to identify all of the failure mechanisms.

There are no current national standards which completely covers the design, fabrication and construction of fiberglass cooling towers.
The individual owner/buyer needs to become extremely knowledgeable about pultruded fiberglass before the specification is submitted for bidding so the final product is acceptable to the owner for a 30 year operating life. AEP has offered several clarifications in this paper in relation to current CTI Standards with the expectation that a better pultruded product can be specified, provided and constructed.

It appears that all the failure mechanisms for pultruded products are not completely understood, and the pultruders, cooling tower contractors and tower owners will need to work together to comprehend why column bottoms are cracking/failing and what can cause surface blisters.

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APPENDICES

Figure 1 – Transverse Cross Section of a Cross-Flow Cooling Tower, 3½” Pipe Column Sits on Elevated Concrete Pier

Figure 2 – Transverse Cross Section of a Cross-Flow Cooling Tower, 4” & 3½” Pipe Columns Sit on Cold Water Basin Floor
The Progression of Automation and Process Control For The Management of Open Cooling Water Systems

Kevin Milici
Gary E. Geiger
GE Water & Process Technologies

ABSTRACT
Enhancement opportunities for cooling water systems can be placed into three major categories. The first is optimizing the dosing of specialty and adjunct commodity chemicals used for corrosion, scale/deposit, and microbiological control. Making sure the right dosage of the right chemistry at the right time avoids “overfeeding” for worst case situations. Once optimized, minimizing the variation greatly reduces the potential for failures that result in unscheduled shutdowns or impaired operations. Secondly, confidence from effective measurement and control enables the optimized use of increasingly scarce water supplies, and/or the ability to utilize lower quality, alternative water sources. Lastly, the productivity of personnel charged with operating cooling systems can be greatly enhanced.

In recent years, much focus has been placed on online instrumentation and control. These advances are and will continue to be welcome contributions to the management of open evaporative cooling water systems. Now, direct measurement of the multiple core chemistries for effective cooling water treatment to control steel corrosion, deposition, and microbiological activity is realized in a single instrument platform. This paper discusses the advent and merits of new online monitoring and control technology using case studies and practical scenarios as illustrations of the impact for users.

Keywords: Automation, deposit control, corrosion control, biological control, orthophosphate, free chlorine, polymer, phosphate, cooling water, cooling tower, direct measurement, and stressed water condition.

MULTIPLE DIMENSIONS OF COOLING WATER MANAGEMENT

Obtaining optimal results from open, evaporative cooling systems requires careful management of the three interrelated dimensions of corrosion, deposition, and microbiological activity (Figure 1). For several decades, this concept has been widely understood and practiced by knowledgeable providers of water management services and operators of cooling systems themselves.

Poorly controlled steel corrosion results in the formation and accumulation of corrosion products. As they accumulate on heat exchange surfaces, these products can impede heat transfer, restrict cooling flow, constrain production, and increase energy consumption. As a result, production processes can be economically disadvantaged and the life span of capital assets becomes threatened. The application of inorganic phosphates for steel corrosion control requires the use of polymeric dispersants for the control of calcium phosphate or iron phosphate deposits. While polymers vary in their tolerance characteristics, their efficacy can be compromised by the release of soluble iron from an active corrosion site.

Deposits, regardless of whether they are the result of corrosion and/or mineral scales, facilitate microbiological fouling. Non-biological deposition provides sites that enhance the potential for colonization and growth of microorganisms. In turn, microbiological growth entraps more suspended solids or particulate matter, thereby accelerating the cycle of deposition. Microorganisms can cause microbiologically influenced corrosion (MIC) associated with biofilms and the proliferation of anaerobic bacteria that prosper in the environments created under deposits. Organisms within biofilm can deplete oxygen, block corrosion inhibitors from reaching fouled surfaces and concentrate corrosive products through metabolism. The result can be severe localized corrosion, as well as the premature loss of capital equipment. Deposits can lead to under-deposit or crevice corrosion, resulting in pitting-type corrosion.
CORE COOLING WATER CONTROL CHEMISTRIES

As background to the advancements, a brief review of three common elements of cooling water treatment programs is in order:

Steel Corrosion Control With Inorganic Phosphates

For more than three decades, the dominant inhibitors for steel corrosion in cooling waters have been the inorganic phosphates. The primary form of inorganic phosphate used is orthophosphate. Suppression of both anodic and cathodic half-cell reactions can be achieved with orthophosphate.

At near-neutral pH modes of operation, typically a pH of 6.8 to 7.8, and the use of high concentrations of orthophosphate (12 to 20 mg/L PO₄), the formation of a tenacious protective oxide film is promoted, suppressing the overall corrosion reaction. Treatment programs designed to operate in the alkaline mode employ significantly lower orthophosphate concentrations (3 to 10 mg/L PO₄), with system pH typically in the range of 7.8 to 9.0, as these waters are inherently of lower corrosivity. In alkaline modes, orthophosphate primarily functions to stifle the cathodic half-cell reaction with a meta-stable calcium phosphate barrier film that limits electron transfer. Film formation is driven by localized high pH at the cathode. Polyphosphates (pyrophosphate or hexametaphosphate) and/or zinc are common supplements to an orthophosphate-based corrosion control. Their addition fortifies cathodic protection.

Calcium Phosphate Deposit Control With Polymeric Dispersants

The moderate to high concentrations of orthophosphate required in recirculating cooling water for effective steel corrosion control would not be possible without the use of a calcium phosphate precipitation inhibitor to maintain phosphate solubility in the bulk cooling water and prevent deposition at heat transfer surfaces. Effective polymeric inhibitors/dispersants for calcium phosphate were first developed in the late 1970’s. Since that time, a wide variety of copolymers and terpolymers have been introduced and have expanded the role from calcium phosphate inhibition to particulate fouling control. However, the primary role of the polymeric dispersant in an inorganic phosphate-based program is to prevent calcium phosphate deposition or scaling. Calcium phosphate demonstrates inverse solubility with respect to both pH and temperature. If scaling is to be avoided, at any given concentration of calcium hardness and phosphate, the required concentration of the dispersant is dictated by the waterside temperature of the hottest process equipment and the operating pH range. With neutral pH, high orthophosphate regimes, precise pH control is required to minimize high pH swings and to avoid exceeding the control capabilities of the inhibitor.

Microbiological Control with Halogen

The control of microbiological populations in industrial water systems is essential to prevent biofouling. Biofouling of heat exchange equipment and tower fill reduces heat transfer efficiency and can force unscheduled shutdowns and extended turnarounds leading to lost production. Biofouling can also damage equipment through microbiologically influenced corrosion (MIC), an established inter-relationship.

Modern-day technology for effective microbiological control in recirculating cooling water commonly entails the use of a halogen(s) as oxidizing biocides, frequently paired with non-oxidizing biocides. Biocide application is often enhanced through the use of “biocide enhancers.” While generally non-toxic to target microbes, these enhancers significantly improve the level of microbiological control normally achieved by disinfectants such as chlorine, bromine or non-oxidizers.

Chlorine, in the form of gas or sodium hypochlorite (10 to 12.5 percent by weight as NaOCl) is the backbone of most cooling water microbiological control programs. Sodium hypochlorite is clearly favored from a safety perspective. Being able to measure and control free halogen, hypochlorous acid (HOCl) and hypochlorite ion (OCl⁻), is fundamental to the general microbiological cleanliness and control of any cooling system. As awareness of risks associated with proliferation of Legionella bacteria has grown, along with best practices for minimizing this organism and its associated health risk, the application of halogen has become more focused. For example the Cooling Technology Institute recommends a continuous halogen residual as the preferred program.²

DELTA PHOSPHATE FOR POLYMER MANAGEMENT

As previously discussed, polymeric dispersants enable the use of orthophosphate as an effective steel corrosion control agent. These materials prevent the formation of detrimental calcium phosphate or iron phosphate deposits, as well as ensuring that the corrosion inhibition program remains intact. Considering the performance characteristics of a given polymer, the concentration required for controlling bulk water precipitation and deposition of calcium phosphate depends on multiple factors. These include water chemistry, polymer, temperature, water velocity, and system half-life.

The late 1970’s marked the introduction of the industry’s first effective polymeric dispersant for the inhibition of calcium phosphate in high orthophosphate, neutral pH corrosion control programs. Through the balance of that decade, and into the 1980’s, various field techniques and parameters were evolved to assess whether or not sufficient polymer was present, under changing systems conditions, to prevent calcium phosphate deposition and the loss of effective corrosion inhibition. Experience ultimately yielded a rigorous definition of truly “soluble” orthophosphate as that which is measured after passing through a 0.22 µm filter. Comparing that value to the total (unfiltered) orthophosphate was the basis of the control parameter of “delta orthophosphate” or simply “delta phosphate.” Hence, delta phosphate is defined by the simple equation:

Delta Orthophosphate = Total Orthophosphate – Soluble Orthophosphate

Routine monitoring of the delta phosphate, along with other system parameters, became an effective indication of potential problems. High delta orthophosphate may be the result of high pH excursions, low polymer dosages, excessive orthophosphate, over-cycling (blocked blowdown), and/or the presence of system contamination. The delta orthophosphate is a good safeguard against feeding too much phosphate to achieve a filtered target residual. The ill-advised overfeeding of phosphate in an attempt to achieve a desired filtered orthophosphate concentration is prevented with an upper control limit for the delta orthophosphate. If the delta orthophosphate is at or above a threshold value, corrective action is generally neces-
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sary to avoid calcium phosphate deposition. The acceptable delta orthophosphate threshold concentration typically ranges from 1.5 to 3.0 mg/L PO₄, depending upon whether the cooling water chemistry is managed in an alkaline or neutral pH mode. If the delta orthophosphate reaches a set upper control limit, it is not an absolute indication that a problem is occurring. However, experience shows that it is a strong basis to investigate the reason for the high value.

TECHNOLOGY EVOLUTION

Generation 1
The year 2008 marked the commercial introduction of a new technology platform for the direct colorimetric measurement of proprietary water-soluble polymers used for deposit control in cooling water treatment programs. Innovative reagent chemistry was the cornerstone of the technology, and overcame the variance and inaccuracies experienced with the preceding turbidimetric methods. The unique attributes of the reagent chemistry were twofold. First, it was both highly specific in its interaction with the functional groups and structure of the target polymer. Secondly, high sensitivity permitted detection down to low concentrations. Combined with robust electronics and fluids management, the platform delivered an on-line measurement system that was well suited for the industrial environment, enabled deployment in multiple configurations, and provided for ease of use.

Evolution Goals
In planning for the development of the subsequent generation of the technology, several key goals were set, namely:

- As the platform was chosen because of its potential to expand the number of control analytes that could be measured, incorporate analytes into the measurement system in order to continue to progress the management of the inter-relationships of corrosion, deposition, and microbiological activity.
- Incorporate the ability to measure orthophosphate on-line in cooling water.
- Distinguish between and measure both total orthophosphate, as well as soluble orthophosphate, using the rigorous definition previously described.
- Fully utilize the body of experience and best practice of using the metric of delta phosphate, to ensure sufficient polymer is always present, even under the most stressful of conditions and circumstances that can drive enhance phosphate formation and the loss of corrosion inhibition.
- Incorporate the measurement of the most commonly used halogen, chlorine, to complete a core staple of chemistries for effective cooling water management.
- Maximize the simplicity of the system, from the perspectives of deployment to both operational reliability and ease of use.
- Lastly, accomplish all of the above using the single measurement platform, translating to a cost of deployment that is practical for a wide segment of cooling tower owners and operators.

As a result of an extensive development effort, the next generation of the platform has been achieved. An overview of the advancement is described in the following section.

System Overview
An overview of the components of the measurement is described in three broad categories, including on-board filtration, detection, and electronics.

Filtration First
Whether due to the entrainment of suspended solids and/or in situ biological growth, fouling of the “wet” components has always been the Achilles heel of the simplest and most advanced on-line instruments. Operational reliability is compromised, maintenance and troubleshooting time and effort escalates, and ultimately, unsatisfactory control is the result. The initial generation of the technology had a unique self-backwashing filtration system that performed extremely well in the vast majority of waters. However, there was a clear opportunity to build upon the initial success. As a result, an on-board filtration design evolved that was capable of handling the toughest of water qualities, while providing greatly extended filtration runs, and an absolute minimization of manual intervention. Due to varying and demanding cooling water properties, the raw water is initially filtered through a 30 μm main element. This serves to remove large-sized particulate matter from progressing to the downstream fluidics. The advanced design inherently minimizes filter cake build-up on the element. It also is equipped with an automated back-flushing capability that periodically pushes any filter cake off of the main filter element, extending filter runs to extraordinary lengths. The 30 μm filtered water is routed downstream to a staging vessel that reduces the water pressure to atmospheric for subsequent measurement of the target analytes.

Measurement
Rugged solenoid pumps move the 30 μm filtered water through the first of two detector cells, dedicated to the measurement of the target polymer and free chlorine. The detector cell comprises of a clear detector tube, LED (light emitting diode) emitters, and photodiode detectors. For this detector cell, the active LED’s are red and green for polymer, and blue for free chlorine. A zero measurement or blank of the sample is first made to compensate for any natural color or fine particulate suspended solids in the water. A single reagent, engineered for measurement of both the target polymer and free chlorine, is added to the sample stream in a pre-determined ratio. The mixture then passes through the detector cell. The LED’s are activated to obtain an absorbance. The absorbance is then converted to a concentration for polymer and free chlorine. The same process is then repeated for total orthophosphate, except that the sample is re-routed to a second detector cell with an active UV LED. Once the polymer, free chlorine, and total (or consider unfiltered in lieu of total) orthophosphate have been measured, the sample staging vessel is filled again and automatically filtered through a 0.22 μm membrane filter. Measurement of orthophosphate occurs again in the phosphate detector cell; however, this time it yields a 0.22 μm filtered, or soluble, concentration for orthophosphate. After the measurement of filtered orthophosphate is made, the 0.22 μm membrane is back-flushed, and any particulates that are trapped on the membrane surface are discarded.

Electronics
The measurement device’s core functions are managed by an instrument-specific set of electronics. This includes on-board filtration, fluids management, and signal processing from the optical
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measurement of polymer, orthophosphate (total and soluble), and free chlorine. Temperature compensation, identification of spurious measurements, and self-zeroing between readings to remove the effects of sample variation is incorporated. A state-of-the-art touch screen human interface enables easy navigation through simple structure menus for current value display; historical values retrieval (including on-board time-series charting), calibration, diagnostics and alarms.

After all of the analytes have been measured, values are transmitted via an analog signal to a paired control center. Here, proprietary algorithms drive the actions needed to manage cooling water chemistry based on varying system conditions. The measurement device and paired control module are available in a pre-configured, complete plug-and-play systems, including a complimentary array of measurements (pH, ORP, conductivity, corrosion rates) and capabilities.

**FIELD STUDIES**

The measurement device and control system demonstrated its performance in industrial cooling systems in a series of initial field trials. Following summarizes of highlights from two of those cases:

**Field Study I**

**Background.**

This cooling system uses surface water as make-up. Cooling tower blow down is not controlled per se, but the maximum conductivity target is 1,200 μS/cm. Operating in an alkaline mode, with a pH range of 7.5 to 8.8, an inorganic phosphate-based treatment was used for carbon steel corrosion control. The target control range for total orthophosphate was 8 to 10 mg/L PO₄. A separate product, containing polymer for calcium phosphate deposit control and a calcium carbonate inhibitor had the primary role of protection against calcium phosphate and calcium carbonate scale respectively. Both the phosphate and deposit inhibitor products were fed proportional to metered make-up water flow.

Control of total orthophosphate in the system was achieved with periodic adjustments to the chemical feed rates based on the results of off-line wet analytical testing for total orthophosphate by plant personnel twice per week, as well as weekly by water management services personnel. The pH of the recirculating cooling water was also managed with the same controller, feeding acid as necessary. Liquid sodium hypochlorite (NaOCl) was the source of chlorine for primary biological control. In the base case, sodium hypochlorite was shot-fed based on periodic off-line testing for free chlorine against a target control range of 0.1 to 0.5 mg/L Cl₂. In the new control mode, sodium hypochlorite feed was controlled automatically based on an ORP probe with ORP measurements correlated to the desired free chlorine residual.

**Base Case**

Figure 2 is a representative data set over a 40-day period of the off-line test results for total orthophosphate from three sources. These included the semi-weekly results of plant operating personnel (Testing 1), as well as weekly confirmatory results from the water treatment services team (Testing 2). In addition, grab samples were collected two to three times per week for off-site laboratory analysis. The off-site laboratory utilized state of the art analytical instruments, including automated discrete colorimetric analyzers, with strict method quality control protocols being applied in order to ensure all analytical systems are under control and accuracy is validated. While the multiple sources showed reasonable agreement, the total orthophosphate concentration was often below the lower control limit, and which presented an opportunity for improved control. Figure 3 shows the laboratory results for total, soluble and delta orthophosphates over the same period. Delta orthophosphate ranged from 1 to 3 mg/L PO₄.

**New Technology Impact**

The new control system was deployed in the cooling system, with the primary goal of demonstrating improved control over orthophosphate feed for corrosion control, as well as polymer for the management of deposition. A control target of 6 to 8 mg/L PO₄ soluble orthophosphate was set for optimum control of carbon steel corrosion. The phosphate-containing product was automatically controlled to maintain the desired soluble orthophosphate concentration, recognizing that some portion of the total phosphate applied would not remain soluble. Figure 4 presents a detailed view over an eight-day period of the measurement and control of soluble orthophosphate with the new technology. The system effectively drove the soluble orthophosphates levels to within the target range, “hugging” the lower control limit. The off-line laboratory testing continued, clearly and consistently validating the accuracy of the on-line device’s measurements. Figure 5 shows the trend in the system’s measurement of total orthophosphate over the same period, also consistently validated by laboratory analysis. Figure 6 reveals the corresponding trend in delta orthophosphate, against an upper control limit of 2 mg/L PO₄. Delta orthophosphate levels were consistently below 2 mg/L PO₄, and below 1 mg/L PO₄ about 75 percent of the time. This indicates sufficient polymer present for calcium phosphate deposit control. The control system has the added dimension of further refining polymer dosing, should the delta orthophosphate exceed its upper control limit, quickly bringing the delta phosphate back within the prescribed range.

Figure 7 summarizes all of the on-line measurements of orthophosphate by the new technology for the recirculating cooling water, during the period. The two peaks for delta phosphate correspond to points in time were the pH values, as well as the total orthophosphate concentration, were at their highest. The impact and sensitivity of just a few tenths of the pH unit on increasing the gap between total and soluble orthophosphate is apparent. Figure 8 presents the system’s measured threshold polymer concentration, which is available and functional to do the work of deposit control. The polymer concentration is tightly controlled to a goal of 11 +/- 1 mg/L. However, there are two increases in polymer concentration corresponding to the aforementioned peaks in delta threshold, by temporarily increasing polymer dosing until the delta orthophosphate falls below that threshold. Finally, the addition of sodium hypochlorite to the system for microbiological control was based on conventional oxidation-reduction potential (ORP) technology. Figure 9 presents the system’s measure of free chlorine over this same period, as well as the ORP measurements. The two measurements track well, and periodic grab sampling and testing for free chlorine confirmed the accuracy of the device.

**Field Study II**

A chemical plant’s recirculating cooling system uses filtered surface water as make-up, operating at 8 to 10 cycles of concentration, in
a near-neutral pH mode within a pH range of 6.7 to 7.7. Cycles of concentration are automatically controlled based on conductivity. The pH of the recirculating water is controlled via a pH probe tied to a caustic (NaOH) pump so as to avoid pH depressions. Due to the nature of the production process served by the cooling tower system, total residual chlorine is the basis of halogen control, with is performed with regular manual testing and adjustments.

Figures 10 through 13 highlight the performance of the new technology in a control mode. Figure 10 shows consistent control of total orthophosphate over a two-week period, well within the historical control limits of 7.5 to 12.5 mg/L PO₄. Again, periodic grab samples were taken for off-site confirmatory laboratory analysis and compared to the new on-line device’s results. Laboratory values consistently matched that of the on-line measurements. Figure 11 shows the systems measurement of soluble orthophosphate, consistently controlled to the new control target of 11 mg/L PO₄, and again confirmed by off-line laboratory results. Figure 12 is the calculated delta orthophosphate over the same period, showing consistently low values, well under 1.0 mg/L PO₄, indicative of good phosphate management and adequate polymer in the system for the prevention of calcium phosphate. Finally, the new technology’s measurement and consistent control of threshold polymer levels (Figure 13) is shown over the same period.

In this application, a pre-existing commercially available instrument for the measurement of total orthophosphate was in place. The pre-existing instrument is of high quality and reputation. Figure 14 shows the measurements from this existing technology as well as from the new multi-parameter technology platform over a 30 day period. The data clearly shows the congruence of the two measurements. Simplification through consolidating the measurement of multiple parameters onto a single on-line platform and avoiding the acquisition and ongoing costs and complexities of multiple instruments is an obvious benefit.

CONCLUSIONS & SUMMARY

- Lowering total cost of operation for cooling water systems uses levers that fall into three broad categories of chemicals usage, minimization of fresh water consumption, and improving the productivity of personnel associated with various tasks for monitoring and control.
- All three dimensions, and their interrelationships … corrosion, deposition, and microbiological activity must be managed for successful cooling water performance.
- Technology innovation has advanced, with the ability to directly measure the primary components of orthophosphate for steel corrosion control, polymers for calcium phosphate deposit control, and free chlorine for microbiological control, all on a single on-line measurement platform.
- The technology has demonstrated its ability to accurately measure these analytes in industrial systems, validated by high quality laboratory techniques.
- Improved control can enable lower dosages to be applied, consistent with what is actually required at a given time, as opposed to always treating for an episodic worst-case condition.
- Minimizing variation provides confidence for the ability to operate consistently at target concentrations, which can change over time with a system’s water quality, contaminants, etc.
- Simplicity and cost-effectiveness have been achieved by consolidating the measurement of multiple parameters onto a single on-line platform and avoiding the acquisition and ongoing costs and complexities of multiple instruments creates a cost-effective means to implement the technology on a wide segment of recirculating cooling systems.

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Figure 2: Off-line measurements of total orthophosphate during base case mode period.
Figure 3: Off-line measurement of all measures of orthophosphate during base case.

Figure 4: On-line measurement of soluble orthophosphate during new control mode period.

Figure 5: On-line measurement of total orthophosphate during new control mode period.

Figure 6: On-line delta orthophosphate measurement during new control mode period.

Figure 7: All on-line measures of orthophosphate concentration and pH during new control mode period.

Figure 8: On-line measure of threshold polymer concentration during new control mode period.

Figure 9: Free chlorine.

Figure 10: On-line measurement total orthophosphate during new control mode period.
Figure 11: On-line measurement soluble orthophosphate during new control mode period.

Figure 12: On-line measurement of delta phosphate during new control mode period.

Figure 13: On-line measurement threshold polymer concentration during new control mode period.

Figure 14: On-line measurements of total orthophosphate from multiple instruments.
Efficacy Of Non-Chemical Devices In Controlling Legionella: Results From A Model Cooling System

ABSTRACT:
Five (5) non-chemical devices (NCD) were evaluated for control of planktonic and sessile Legionella and heterotrophic plate count (HPC) bacteria populations within a pilot-scale cooling tower system. The devices included magnetic, pulsed electric field, electrostatic, ultrasonic, and hydrodynamic cavitation. Two model cooling towers were designed and operated to simulate field conditions (e.g., heat load, residence time, liquid loading rate, evaporative cooling, blowdown and make-up system). One tower served as the untreated control (T1) while the NCD was installed on the second tower (T2). Each device trial was conducted over a minimum of 4-weeks. Legionella and heterotrophic plate counts (HPC) were monitored in both planktonic and biofilm phases. Physicochemical monitoring included temperature, conductivity, pH, alkalinity, hardness, total dissolved solids (TDS), ORP, and chloride. Make-up water for each system was dechlorinated city tap water. This report presents the results of Legionella testing that was performed during, but was independent of, the ASHRAE-sponsored study RP-1361 that investigated the effect of these devices to control heterotrophic plate count bacteria.

INTRODUCTION
Control of microbial growth in cooling systems is typically achieved with the use of chemical biocides1-3. Non-chemical water treatment methods have been used as a “Green Chemistry” alternative to chemical water treatment for control of scale and microbial growth. Unfortunately, few controlled studies have been performed to verify the efficacy of these devices in controlling Legionella and other microbial growth in cooling towers. The objective of this investigation was to assess the ability of several classes of non-chemical treatment devices (NCDs) to control the growth of Legionella in a model cooling system. In addition, water samples from full-size cooling towers treated with NCD’s were also tested.

NON-CHEMICAL WATER TREATMENT DEVICES

MAGNETIC TREATMENT
Manufacturers of magnetic water conditioners generally do not make claims of microbial control. Water passes through a fixed magnetic field, which alters the water chemistry to prevent the formation of “hard” scales on cooling surfaces. Magnetic water conditioners have been applied to reduce scaling and corrosion in industrial systems for several decades4,5,6.

PULSED POWER AND ELECTROSTATIC TREATMENT
Pulsed electric field (PEF) treatment or electro-pulse treatment involves the application of water with pulses of electromagnetic energy. These pulses may inactivate microorganisms present in the water7. However, the purported mechanism by which this process occurs has not been definitively established8.

ELECTROSTATIC
Electrostatic treatment systems are essentially identical to those involved in the operation of pulsed-power treatment systems9. Electrostatic systems apply a static electric field rather than pulses of energy. The manufacturers do make claims for scaling, corrosion, and microbial control.

ULTRASONIC CAVITATION
Ultrasonic energy is used to inactivate microorganisms through a cavitation process known as sonication10,11. It has been suggested that the collapse of cavitation bubbles is responsible for bacterial inactivation.

HYDRODYNAMIC CAVITATION
Sudden high pressure changes can form very small vapor bubbles within the fluid in a process known as cavitation. Bubbles are said to quickly collapse, leading to extremely high local temperatures, pressures, and fluid velocities12. Inactivation of surrounding organisms is said to occur from implosion of these small bubbles of fluid vapor within a liquid13.

MATERIALS AND METHODS

Cooling Tower System Description
Two pilot-scale model cooling tower systems were used to evaluate the performance of each device. The two model cooling towers used in this study were designed to be identical. A schematic outlining the cooling system setup for each tower is shown in Figure 1.

In each pilot-scale system, water is stored in a 60 gal (227 L) holding tank prior to being pumped at a rate of 7 gpm (26.5 L/min) by a 2 hp (1.5 kW) centrifugal pump into a stainless steel heating bath. Immediately prior to entering the heating bath, the flow of water is split and each flow path continues into one of two 1 in. (12.7 mm) OD copper coils wrap around a 15 kW (14.2 BTU/s) immersion heater, and the entire heating apparatus is surrounded by a stainless
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steel box containing dechlorinated water. The box is sealed by a lid made of 0.127 mm plexiglass in order to minimize evaporative losses. The immersion heater is controlled by a thermostat, which was adjusted throughout the experimental trials to maintain a water bath temperature of approximately 120°F (49°C). This heating bath temperature provides enough thermal energy to elevate the temperature of the system water to 95-100°F (35-38°C)

Once the system water passes through the two copper coils, the flow paths are combined. The flow is then diverted through a sampling rack containing a series of biofilm sampling coupons. The sampling coupons were 5.61 cm2 (0.87 in.2) stainless steel washers which were scrubbed and autoclaved at 121°F (49°C) prior to installation in the experimental towers. These coupons were installed at the beginning of each device trial, and they were used to quantify biofilm growth within each of the cooling tower systems. Coupons were installed parallel to the direction of flow.

Upon exiting the sampling rack, the system flow passes through a number of sensors for data collection, including a pH probe, an ORP probe, a conductivity probe, and a thermometer which records the water temperature prior to tower entrance. Each of these probes is connected to an automated data collection system which records data values at 1-hour intervals. The flow then passes through a flow meter to ensure that a system flow rate of 7 gpm (26.5 L/min) is maintained. Immediately before tower entrance, the flow travels past an additional conductivity meter. This conductivity meter is connected to a blowdown control system which uses conductivity readings to control when the tower goes through blowdown based on a user-defined setpoint. The setpoint is chosen based on the make-up water conductivity, and it was selected to produce 4-5 cycles of concentration in the cooling tower system.

Flow enters each of the cooling towers by way of a 110° full cone square spray nozzle. This allows the flow to be distributed evenly over the surface of the CF1200 packing installed in each tower. The height of the packing in each tower is adjusted so that the spray from the nozzle contacts the packing at its uppermost edge, diverting flow through the interior of the packing rather than down the side wall of the tower. A total of three units of packing (1 ft3; 0.028 m3 each) were installed vertically in each tower system, for a total packing height of 3 ft (0.91 m).

Once the water travelled through the packing, it is deposited into a 20 gal (76 L) sump. In order to minimize water losses from splashing, screening is placed around the perimeter of each tower’s support legs. Upon entering the sump, the water temperature is 85-90°F (29-32°C), thereby maintaining a temperature differential across the packing of approximately 10°F (6°C). This cooling is accomplished by a variable frequency axial fan placed at the top of the tower, above the water entrance. The rate of airflow generated by this fan is controlled by a potentiometer to produce the desired 10°F (6°C) temperature differential. The 20 gal (76 L) sump is connected to the 60 gal (227 L) holding tank via a 2 in. (51 mm) diameter PVC pipe, and as water travels through the system it is pulled from the sump back into the holding tank, completing the cooling water cycle.

Make-up water used for all experiments in this study was dechlorinated City of Pittsburgh tap water. Dechlorination was accomplished by passing the water through a fixed-bed activated carbon adsorber [Loret et al., 2005]. The cylindrical activated carbon adsorber had a height of 6 ft (1.8 m) and a diameter of 12 in. (0.3 m). The column contained 8.7 gal (33 L) of activated carbon (coconut shell based, 8 x 30 mesh size, Activity = 1000), and the flow rate through the column during make-up water generation was maintained at or below 3 gpm (11 L/min) in order to ensure a minimum contact time of 3 min. Make-up water for each cooling tower was stored in four 125 gal (473 L) polyethylene tanks to provide enough water for two days of tower operation (approximate tank residence time = 48 hrs). In between device trials, the carbon column was flushed by running water through it at twice the flow rate necessary for chlorine removal (> 6 gpm; > 23 L/min) for a minimum of 1 hr.

Device Trial Protocol

For each device trial, a control tower and a test tower were utilized. The control tower (T1) received no treatment during the testing process, while the device tower (T2) received treatment from the device being evaluated. The device was activated at the beginning of the study, and it was not turned off until the investigation had been completed. For the remainder of this report, the control tower in each device trial will be referred to as T1 (Control), and the device tower will be referred to as T2 (Device). Lights in both the shower room containing the two test towers and the locker room containing the make-up water storage tanks were kept on throughout the duration of each device trial. No algal growth was observed in either of the towers or the make-up water storage tanks during any of the device trials or chlorination tests.

A total of five (5) non-chemical water treatment devices were tested over the course of this investigation (Table 1). Before the beginning of each device trial, several measures were taken to ensure consistent starting conditions. Each tower received 4 gal (15 L) of dilute acetic acid and 8.5 oz (250 mL) of 5.25% sodium hypochlorite solution, and the towers were allowed to operate for several hours in order to eliminate any residual microorganisms present in the system and to remove scale formed during the previous trial. Both towers and their corresponding sumps and holding tanks were scrubbed with 5% acetic acid to remove as much scale as possible. Each system was drained completely using a shop vacuum and refilled with fresh make-up water. The draining and refilling process was repeated a minimum of 2 times for each tower prior to the beginning of a new device trial. Additionally, the plastic packing in each of the towers was replaced prior to the initialization of a new test. The new packing was installed after the tower had been drained and rinsed to reduce the amount of residual solid material which it collected.

In order to maximize the cooling potential of the packing, each tower underwent a “seasoning” process prior to trial onset. This process was in accordance with the packing manufacturer’s specifications. To season the packing, each tower was allowed to operate with a heat load for approximately 1 hr. Following this period of operation, each tower system was shut off, allowing heated water deposited on the packing surface to evaporate, leaving a thin layer of deposited minerals on the packing surface. This process was repeated a minimum of two times prior to the beginning of each device trial, and the entire process occurred over approximately 3 days. Each tower system was drained and replenished following the final seasoning of the packing. Make-up water storage tanks were also drained and refilled prior to the beginning of a new device trial. Device trials began less than 24 hours after the final refilling of both the tower systems and the make-up water storage tanks.
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BIOLOGICAL MONITORING

Bulk water samples were collected twice weekly using sterilized sampling bottles. Biofilm samples were collected weekly by swabbing the biofilm coupon surface and resuspending the material into 10.0 mL of sterile deionized water. All biological samples were kept chilled during transport to the laboratory. Upon arrival, samples were shaken thoroughly and subject to a series of dilutions.

A series of three dilutions was plated for HPC testing of each bulk water and biofilm sample. The range of dilutions used for make-up water analysis was $10^{-2} - 10^{-4}$ for this investigation, while the bulk water tower dilution range was $10^{-3} - 10^{-5}$ and the biofilm sample dilution range was $10^{-4} - 10^{-6}$. Legionella testing was performed using a modified method based upon the International Standards Organization (ISO) Standards 11731-1:1998 and 11731-2:2004. The minimum/maximum concentration limits were >6000 CFU/mL. Heterotrophic plate count bacteria test dilutions were plated according to Standard Method 9215 pour plate protocol. The minimum/maximum concentration limits were 1.0 CFU/mL />300,000 CFU/mL.

NON-CHEMICAL DEVICE DESCRIPTIONS

Magnetic Device (MD)
The magnetic device had a 13” flow-through cylinder which exposed water to 4 alternating magnetic poles. According to the manufacturer, the device operates by keeping mineral ions such as calcium and magnesium in suspension, preventing them from forming scale on cooling surfaces. The magnetic device was installed in the cooling tower system used in this study according to the manufacturer’s specifications. The device was placed along the water flow path immediately before entrance into the top of the cooling tower.

Pulsed Electric Field Device (PEFD)
The pulsed electric field non-chemical treatment device is composed of two primary components: a signal generator and a treatment module. The signal generator is housed in a stainless steel box, and it contains all of the system’s replaceable parts. The treatment module, which consists of a 1” diameter PVC cylindrical flow-through reactor, is connected to the signal generator via an umbilical cable. According to the manufacturer, the device is capable of controlling scale formation, equipment corrosion, microbial populations, and algal growth in a cooling water system.

The treatment module was placed directly after the centrifugal pump and immediately before the heat bath. The treatment module may also be placed directly after the heat exchanger but before the entrance of water into the cooling tower. The PEFD was installed in the cooling tower system according to the manufacturer’s specifications.

Electrostatic Device (ED)
The ED device was composed of a 1” flow-through reactor vessel. While the PEFD bombards the water with pulses of electromagnetic energy, the ED exposes the water in the reactor chamber to a steady electrostatic field. The ED was installed according to the manufacturer’s specifications at the same location as the PEFD, directly after the centrifugal pump but immediately before the water flow entrance into the heat exchanger.

Ultrasound Device (UD)
The ultrasonic device was installed according to the manufacturer’s specifications, and a representative from the manufacturer approved the final installation. A sidestream was constructed for the application of this device, with the sidestream intake positioned near the outlet end of the 60 gallon storage tank and the outflow positioned near the storage tank’s inlet.

The UD diverts water from the cooling system sump or holding tank through a venturi and into an ultrasonic treatment cell. Once through the venturi, air is introduced into the water stream. According to the manufacturer, the vacuum pressure generated by the venturi during normal operation should be between 0.4 and 0.75 bar below atmospheric pressure. The water/air mixture then enters an ultrasonic treatment chamber containing 6 ceramic transducers. Upon exiting the treatment cell, the water passes through a basket filter prior to discharge back into the cooling system sump.

Hydrodynamic Cavitation Device (HCD)
Water is diverted from the cooling system sump or holding tank into the HCD device, and the water is returned to the sump from which it was initially withdrawn. Water drawn from the system sump enters a pressure-equalization chamber. The flow of water is then split into two separate streams and each of these streams enters a vortex nozzle.

CONTROL TOWER (T-1) CONDITIONS

The make-up water quality and performance of T1 (Control) throughout the course of the entire investigation were monitored in order to ensure similar conditions of operation for each individual device trial.
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**T1 (CONTROL) SYSTEM OPERATION**

Average values observed in the control tower (T-1) for all of the combined data runs are shown in Table 2. The target temperature differential throughout the investigation was 10 °F. During all other device trials, a temperature differential of approximately 9-13 °F was maintained.

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<thead>
<tr>
<th>T1 (Control)</th>
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<tr>
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<td><strong>Daily Make-up Water Consumption (gal)</strong></td>
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<td><strong>Daily Blowdown (gal)</strong></td>
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<td><strong>Conductivity (μS/cm)</strong></td>
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<tr>
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<tr>
<td><strong>Magnesium Hardness (mg/L as CaCO₃)</strong></td>
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<td><strong>Total Hardness (mg/L as CaCO₃)</strong></td>
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<td><strong>TDS (mg/L)</strong></td>
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<td><strong>Planktonic HPC (CFU/mL)</strong></td>
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<td><strong>Sessile HPC (CFU/cm²)</strong></td>
<td>2.57E+06</td>
<td>3.66E+06</td>
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**Table 2 – Average values for T1 (Control)**

**BIOLOGICAL PARAMETERS**

The average log heterotrophic plate count for the make-up water over the course of the investigation was 4.4 log CFU/mL. Throughout each device trial, a planktonic population of between 105 – 106 CFU/mL was maintained in the control tower (Figure 2).

**FIELD SURVEY**

Water treatment professionals were asked to submit water samples for Legionella and HPC testing from cooling towers that were treated with non-chemical devices. They were asked to complete a survey form that indicated the type of device being used and whether chemical biocides were also in use. They were requested to submit a sample from a chemically treated tower in the same vicinity for comparison.

**RESULTS AND DISCUSSION**

**CHEMICAL AND OPERATIONAL DATA**

Detailed analysis of the chemical and operational data collected during the investigation of the five (5) non-chemical devices can be obtained from our report submitted to the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) report RP-1361. 3

**Legionella RESULTS**

Legionella species were isolated from both the bulk water and biofilm samples during each device trial (Tables 3 and 4). When detected, the concentration in the bulk water ranged from 20 - >6000 colony forming units (CFU) per milliliter. Legionella species isolated included L. pneumophila serogroups 1, 5 and 6 and non-pneumophila species. There was no significant difference in recovery between the control tower and device towers with respect to Legionella or heterotrophic plate count bacteria during any of the device trials.

**HPC RESULTS**

Analysis of the HPC data collected during the evaluation of all of the non-chemical devices indicated no significant difference in planktonic or sessile (biofilm) populations between the control tower (T1) and the device tower (T2). Based on the results of statistical analysis (the paired t-test), there was no significant difference in planktonic heterotrophic plate counts between T1 (Control) and T2 (Device) for any of the trials. These results are presented in detail in the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) report RP-1361. 3

**Figure 2 – T1 (Control) average planktonic microbial populations for each device trial**

An average sessile heterotrophic plate count of 2.6 x 106 CFU/cm² was observed for T1 (Control) for the entire investigation.

**Table 3. Planktonic (Bulk Water) Legionella Culture Results (CFU/mL)**

**Table 4. Sessile (Biofilm) Legionella Culture Results (CFU/mL)**
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DEVICE TRIALS

**Magnetic Device**

The magnetic device did not control or prevent Legionella colonization of the model tower. The first device tested was the magnetic device (MD) and the trial was conducted between 3-13-09 and 4-20-09. Make-up water was tested after 7 days and was negative for Legionella. Legionella pneumophila serogroup 5 was first detected in the device tower biofilm sample after 14 days. Both the bulk water sample and biofilm samples from the device tower were positive at 28 days, whereas the control tower samples were negative for Legionella until day 28. The control tower and the device tower were positive for Legionella at 38 days – both planktonic and biofilm samples were positive.

**Pulsed Electric Field Device**

The pulsed power device did not control or prevent Legionella colonization of the model tower.

The pulsed electric field device was tested between 5-2-09 and 7-10-09 in two trial runs. Legionella pneumophila serogroup 5 was first detected in the Device tower biofilm sample after 11 days. Both the bulk water sample and biofilm samples from the device tower and control tower were positive at 21 days and reached a maximum concentration of >6000 CFU/mL at 25 days. The control tower bulk water sample was first positive for Legionella pneumophila serogroup 5 at day 18. The control tower and the device tower were positive for Legionella until the end of trial 1 – both planktonic and biofilm samples were positive. Trial 2 showed that the device tower and the control tower colonized with Legionella pneumophila serogroup 5 at the same rate. Both towers were positive within 7 days of the start of the trial. Make-up water was tested after 8 days and was negative for Legionella.

**Electrostatic Device**

The electrostatic device did not control or prevent Legionella colonization of the model tower.

The electrostatic device was tested between 7-18-09 and 8-21-09. Legionella pneumophila serogroup 5 was first detected in both the Device and Control tower bulk water after 4 days. The Device tower biofilm sample was also positive after 4 days. The Control tower and the Device tower were positive for Legionella until the end of trial 1 – both planktonic and biofilm samples were positive. Both the Device tower and Control tower reached a maximum concentration of >6000 CFU/mL at 12 days.

**Ultrasonic Device**

The ultrasonic device was tested between 9-2-09 and 10-4-09. Legionella pneumophila serogroup 5 was first detected in both the Device and Control tower bulk water after 3 days. The Control and Device tower biofilm samples were also positive after 8 days. Legionella pneumophila serogroups 1, 5 and 6 were detected in the Device tower after day 3, both the Control and Device towers were positive for each serogroup throughout the experiment. Both the Device tower and Control tower reached a maximum concentration of >6000 CFU/mL at 15 days.

**Hydrodynamic Cavitation Device**

The hydrodynamic cavitation device did not control or prevent Legionella colonization of the model tower. The hydrodynamic cavitation device was tested between 10-27-09 and 11-24-09. Legionella pneumophila serogroups 5 and 6 were first detected in both the Device and Control tower bulk water at a concentration of 20 and 60 CFU/mL respectively at the start of the experiment. The Control and Device tower biofilm samples were also positive after 16 days. Legionella pneumophila serogroups 1, 5 and 6 were detected in the Control or Device towers throughout the experiment. Both the Device tower and Control tower reached a maximum concentration of >6000 CFU/mL in both the bulk water and biofilm samples at 16 days.

FIELD SURVEY

Twenty-four (24) samples from cooling towers treated with the following non-chemical devices were received for testing and included: pulsed electric field (6), hydrodynamic cavitation (11), electrostatic device (3), copper-silver (2), and UV oxidation (2). These samples were submitted from ten (10) sources; one source was a non-chemical device manufacturer that submitted 10 samples on a single day. Six samples were submitted from chemically treated towers. Excluding the samples submitted by the non-chemical device manufacturer, Legionella pneumophila (serogroups 1 and 4) was isolated from 64% (9/14) of the non-chemical device treated towers vs. 17% (1/6) from the chemically treated tower samples. Mean Legionella concentration from the non-chemical device treated towers was 258 CFU/mL. Legionella was not detected in any of the 10 samples submitted from the non-chemical device manufacturer. If these samples are included in the tabulation, Legionella pneumophila (serogroups 1 and 4) was isolated from 38% (9/24) of the non-chemical device treated towers.

The mean HPC count for the 10 samples submitted from the non-chemical device manufacturer was 8 CFU/mL. Excluding the 10 samples submitted by the non-chemical device manufacturer, the mean HPC count from the non-chemical device treated towers was 198,285 CFU/mL (range 17,000 - >300,000) vs. 175,333 CFU/mL (range 44,000 - >300,000) for the chemically-treated towers.

CONCLUSIONS

This report presents the results of Legionella testing that was performed during, but was independent of, the ASHRAE-sponsored study RP-1361 that determined the effect of non-chemical devices on heterotrophic plate count bacteria. The efficacy of five (5) non-chemical devices (NCD) were evaluated for control of planktonic and sessile Legionella populations within a pilot-scale cooling tower system.

None of the five devices tested over the course of the experiment demonstrated a significant reduction in Legionella planktonic (bulk water) or sessile (biofilm) samples in the experimental tower system (T2 Device) when compared to the control tower system (T1 Control). No biological control was demonstrated by the NCD’s evaluated during this investigation.

The results of the field survey were consistent with the pilot study in that both HPC bacteria and Legionella were isolated from cooling towers treated with non-chemical devices. Limitations of the results include that this is a field survey and at the current number of samples for analysis is limited.

The World Health Organization guidelines indicate that although Legionella testing is not considered a control measure, it can be used in the validation of control measures. More extensive Legionella...
monitoring in addition to routine operational controls should be performed on cooling towers using non-chemical methods as their sole control measure for microbiological (Legionella) control.

In conclusion, the non-chemical water treatment devices did not prevent Legionella growth in the model cooling towers.

REFERENCES
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 Owner/Operator has assurance that the tower will perform as specified, provided that its circulating water is within acceptable limits 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.

The history of the CTI STD-201 Thermal Performance Certification Program since 1983 is shown in the following graphs. A total of 22 cooling tower manufacturers are currently active in the program. In addition, 6 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 60 product lines plus 8 product lines marketed as private brands which result in more than 9,000 cooling tower models with CTI STD-201 Thermal Performance Certification for cooling tower Owner/Operator’s to select from. The following table lists the currently active cooling tower manufacturers, their products with CTI STD-201 Thermal Performance Certification, and a brief description of the product lines.

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, PO Box 73383, Houston, TX 77273 for further information.
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<th>Revision Number</th>
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## Cooling Towers Certified by the CTI under STD-201

Internet links for the Manufacturers, their specific product lines, and the selection information for each product line can be found at: [http://www.cti.org/certification.shtml](http://www.cti.org/certification.shtml)

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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

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<tr>
<th>License Type*</th>
<th>Agency Name</th>
<th>Contact Person</th>
<th>Telephone</th>
<th>Fax</th>
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</thead>
<tbody>
<tr>
<td>A, B</td>
<td>Clean Air Engineering</td>
<td>Kenneth Hennon</td>
<td>800.208.6162</td>
<td>865.938.7569</td>
</tr>
<tr>
<td></td>
<td>7936 Conner Rd</td>
<td><a href="http://www.cleanair.com">www.cleanair.com</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Powell, TN 37849</td>
<td><a href="mailto:khennon@cleanair.com">khennon@cleanair.com</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A, B</td>
<td>Cooling Tower Technologies Pty Ltd</td>
<td>Ronald Rayner</td>
<td>61 2 9789 5900</td>
<td>61 2 9789 5922</td>
</tr>
<tr>
<td></td>
<td>PO Box N157</td>
<td><a href="mailto:coolingtwrtech@bigpond.com">coolingtwrtech@bigpond.com</a></td>
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<tr>
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<td>Bexley North, NSW 2207</td>
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<tr>
<td>A, B</td>
<td>Cooling Tower Test Associates, Inc.</td>
<td>Thomas E. Weast</td>
<td>913.681.0027</td>
<td>913.681.0039</td>
</tr>
<tr>
<td></td>
<td>15325 Melrose Dr.</td>
<td><a href="http://www.cattai.com">www.cattai.com</a></td>
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<tr>
<td></td>
<td>Stanley, KS 66221-9720</td>
<td><a href="mailto:cttakc@aol.com">cttakc@aol.com</a></td>
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<td></td>
<td>6430 Baum Drive</td>
<td><a href="http://www.mchale.org">www.mchale.org</a></td>
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<tr>
<td></td>
<td>Knoxville, TN 37919</td>
<td><a href="mailto:tom.wheelock@mchale.org">tom.wheelock@mchale.org</a></td>
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* 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.

### Licensed CTI Drift Testing Agencies

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<tr>
<th>Agency Name</th>
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<th>Fax</th>
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<tr>
<td>Clean Air Engineering</td>
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<td>800.208.6162</td>
<td>865.938.7569</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>Knoxville, TN 37919</td>
<td><a href="mailto:tom.wheelock@mchale.org">tom.wheelock@mchale.org</a></td>
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