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

Houston, Texas, 3-May-2013

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, 2013, at the CTI address listed.
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View From The Tower

Happy New Year 2013 and goodbye to 2012. While many of our related trade organizations have experienced membership declines and related financial problems during the past year, CTI has continued to expand our membership footprint on a North American and Global perspective, and our organization remains financially sound going forward.

The technical papers and educational programs for our 2013 Annual Conference represent a template for CTI as a global leader in all things related to heat transfer and evaporative cooling technology, coupled with the most recent innovations related to sustainability in our multitude of industry applications.

The Cooling Technology Institute has classically been associated with large cooling tower applications in the refining, petrochemical and electricity generating areas. While CTI is primarily focused on the large end user customers, we are placing increased emphasis on packaged cooling tower systems from all of our manufacturers, including recommendations and standards for “Best Practices” for operation from our three standing committees, Performance and Technology, Engineering Standards and Maintenance, and Water Treating.

CTI is looking forward to an excellent turnout for our 2013 Annual Conference which is being held this year at the Omni Bayfront Hotel in Corpus Christi, Texas from February 4th-7th. Our Program Committee has assembled a variety of timely and informative papers from industry experts. Please refer to the Annual Conference News at CTI.org for a detailed list of papers, authors and presentation times. Alternatively, there is a mobile app which contains all of the Annual Conference information and exhibitor info. Go to http://m.guidebook.com/guide/4401/ to download.

In addition to our technical and training sessions, on Tuesday from 4:00-8:30pm, we have approximately 50 table top exhibits sponsored by our CTI member companies. This will offer a great opportunity to meet manufacturers and suppliers and discuss your questions and applications with factory representatives directly.

The CTI Board of Directors consists of nine members who serve three year terms. Each year, three board members step down and three new members are nominated to the board and voted on by the collective CTI membership. I wish to personally thank our three outgoing board members, Frank Foster of Tower Performance, Don Zelek of Brentwood Industries and Dennis Shea of Ascend Performance Materials. Our newly nominated Board Members are Natasha Jones of Bechtel Corp., Steve Chaloupka, Amarillo Gear, and Billy Childrens, Aggreko Cooling Tower Services. In addition I have appointed Helene Troncin, Electricite de France to fill the remaining term of Raul Castillo, who has semi-retired from Dow Chemical. Please join me in welcoming our new BOD members and thanking our outgoing group for their service.

I also wish to thank all of the CTI committee chairs for their dedicated work on behalf of our volunteer organization. Please plan on attending the committee meetings of your choice at our Corpus Christi conference as we always invite new member participation in these workshops.

Finally, my sincere thanks to the CTI executive and administrative staff for all that they do to make my job a pleasure. Don’t forget to make plans now to attend the Summer Committee Workshop at the Hilton Del Mar in San Diego, California, July 7-10, 2013.

Respectfully Submitted,
Jack Bland,
CTI President
2012-2013
The industry's most complete line of quality cooling tower products ... for the smallest HVAC towers to the largest natural draft towers ... leading the way with enviro-friendly innovations like non-glue Mechanical Assembly and anti-microbial AccuShield Products.
Dear Journal Reader,

As I write this editorial, the Mayan long cycle calendar ends very soon. The press coverage has been interesting, and the reactions around the world have been as well. Some very pricey end of the world parties in Europe included.

The US has finished another election, leaving a still-very-divided country struggling over the delays in resolution for the “fiscal cliff”. We shall see what happens.

CTI continues to move forward in making some of its programs stronger, such as the Thermal Certification Program (CTI STD-201 with Eurovent Certification), and bringing new programs into being, such as the publication of custom tower thermal performance testing results by manufacturer name (CTI STD-202). A process to start CTI managed certification of components for such things as flame spread rating or physical properties is moving forward. Interviews for a new CTI employee to be involved in CTI certification are in progress. This is a significant time for CTI.

The current CTI Certification Administrator, Tom Weast, has been leading the Thermal Certification program now for over 20 years, a major milestone. In the last year, Tom was out of the US for many weeks to conduct annual re-verification tests and new line qualification tests, some for new and existing manufacturers. A lot of these were in the third and fourth quarter of the year, a problem which we need to significantly improve for 2013.

This is a time for goal setting for the coming year, and for being thankful for the many gifts in our lives. We at CTI trust you will have enjoyed the Holidays, and wish you all the best for 2013.

Respectfully,

Paul Lindahl
CTI Journal Editor
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Drift Measurement Using Conductivity Methodology: Description, Advantages And Limitations

Vincent Ganzitti
Hamon Thermal Europe

Description of the conductivity methodology

Drift losses definition
Drift loss consists of water droplets emitted from the outlet of the cooling tower and having the same chemical composition as the circulating water. Droplets of condensation are NOT considered as drift loss as they are pure water.

Drift losses measurement principle
The principle of drift losses measurement is described in CTI standard ATC-140. It comprises taking exhaust air samples isokinetically. This means that the air velocity is the same around and at the inlet of the sampling device. This ensures that air streams are not perturbed leading to an over or under sampling.

The air sample is filtered by a glass tube filled with glass balls. The glass balls capture all the droplets and allow the air to pass through. The filter is heated to evaporate the water brought in by the moisture and the drift droplets. When evaporated, the condensation droplets leave no salt as they are made of pure water. The drift, however, leaves all dissolved salt. This method allows distinction between drift loss and condensation droplets. At the end of the tests the salts are recovered from the filter and analysed. The salt quantity in the filter is compared to the salt quantity in the circulating water. This allows prediction of the quantity of water in the air sample also known as drift loss.

To analyse the filter’s salts several techniques are recognized by CTI:
• Inductively coupled argon plasma spectroscopy (ICP) method.
• Atomic absorption method
• Neutron activation analysis

Conductivity was listed amongst them since 1994 and was extensively used in Europe. It was removed in 2011 because it was believed to be imprecise and also probably because it was not well documented. Therefore, this paper presents in detail this methodology and also its limits.

Paper TP12-09 written by Mr Monjoie also demonstrates the validity of the methodology.

Calibration curves
The calibration curve is obtained by diluting a sample of the circulating water with demineralized water. The concentration of the initial sample is taken as reference unit (= 1 gr(*)/l). The sample is then diluted step by step in the ratio of 1/3, 1/10 and so on, going down as close as possible to the demineralized water. With sea water, this could cover a ratio 10^-5. The conductivity is measured at each step so as to determine the relationship with the salt concentration.

Practically speaking, one will take 100ml of circulating water and measure its conductivity and report it in the following datasheet. It will then add 100ml of demi water and report the concentration. It will be associated to a concentration of 0.5. Next, one will add 100ml of demi water and again take note of the conductivity and associated to 0.333 concentration factor. Again one will add 200ml of demi water to reach a concentration factor of 0.1 by adding 100ml of demi water. It is good practice to cover at least three measurements per decade. The example here covers 5 measurements per decade.

Finally the log sheet would look like the following:

Circulating water: 3 000 µS/cm
Sea Water: 50 000µS/cm

The conductivity methodology does NOT directly measure the quantity of salt present in the water. It only measures the conductivity of the water. Indeed, it is not necessary to know the exact concentration of the salt because the drift loss is a ratio: A ratio between the salt in the circulating water and salt in the filter.

From a calculation point of view, working with salt concentration (gr/l) is sometimes easier. As it is unknown here, we will assign the value of 1 gr(*)/l to the circulating water. The asterisk (*) is used to remind us that it is an arbitrary value. Any dilution of the circulating water will also by expressed as gr(*)/l, we would speak of “relative concentration”.

However the conductivity is not always a direct relation to the salt concentration, this is why we need a calibration curve showing the dilution of the circulating water versus its conductivity. This curve is called “The calibration curve”. It is made once for each site and remains valid as long as the chemical composition of the circulating water remains roughly constant.
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The values are plotted on a log-log chart. A typical curve with a circulating water of 30000 µS/cm and a demi water of 1 µS/cm would present like the following graph.

At the beginning, the ratio between conductivity and relative concentration is linear. Later, it becomes asymptotic when reaching the demi water conductivity. This is normal behavior as it represents the limit.

**Analysis of the filter**

Once the calibration curve is made, the sampling takes place. The sampling method and conditions are described in ATC-140. They are similar for both conductivity and ICP analysis.

After sampling, the filter is analysed. It is advised to perform it on relatively short notice (within the hour). It is also recommended to be in a clean environment (chemical lab) to reduce the risk of contamination.

During the analysis and while cleaning the filter prior to sampling, all equipment must be perfectly clean. Practically speaking, one will wash all glassware to be used with demi-water. Ideally, the conductivity resulting from the washes should be the same as for the demi-water. However, this is almost impossible when the demi-water is very pure (conductivity below 1 µS/cm) because water quickly absorbs the CO2 of ambient air. Therefore one will consider the equipment is clean when the washing water doesn’t exceed 1.5 times the demi water conductivity after washing glassware, or 2 times after cleaning the filter.

Handling the filter with plastic gloves is a safe precaution. Indeed, hands are covered with minerals that could potentially contaminate the sample. It is the most frequent cause of contamination.

In order to rinse the filter, a quantity of demi water will be poured through the filter. Typically 100 ml for large filter. The conductivity and the volume of the rinse water will be measured. It is important to measure the volume AFTER the rinse because some of the water will remain inside the filter.
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Using the calibration curve, it is then possible to find the relative concentration of the rinse. Using the one here above. For example, with a rinse conductivity at 100µS/cm it would be 0.0033 gr(*)/l. If the volume of rinse water is 90ml we can deduct that the salt taken out the filter is 0.0033gr(*) / 0.90 l = 0.29 mgr(*).

Several rinses may be required to achieve a proper recovery of all salts. In our example the second rinse was 10µS/cm in a volume of 95 ml. it corresponds to 0.0003gr(*)/l or 0.028 mgr(*).
The third rinse was 1.2µS/cm in 100ml which correspond to 0.0006 mgr(*).

The rinsing process ends when one of the following condition is met:

- The conductivity is less than 2 times the demi-water (level of cleanliness). Less than 2 µS/cm in our example.
- The ratio between the conductivity of first rinse and the current rinse is more than 20. Indeed, with such ratio the remaining salts become negligible.

Those two criteria are critical to have good test validity. Indeed, a common mistake is to carry on rinsing when conductivity drops close to the demi water. Doing this will add more salt coming from potential contamination. The consequence is an over estimation of the concentration of the rinse. Using the one here above, For example, With a demi-water at 1µS/cm, the rinse water should be 4µS/cm. This implies that

$$ G_{rinse} = \frac{V_{demi} G_{demi} + D_{sa} G_{circul}}{V_{demi} + D_{sa}} $$

Where

- $G_{demi}$ is the conductivity of the demiwater (µS/cm).
- $G_{rinse}$ is the conductivity of the rinse water (µS/cm).

The prediction can be used prior to going on-site to decide whether or not the conductivity provides a sufficient accuracy. For drift, a repeatability of 25% is commonly accepted. Therefore a ratio of at least 25% between $G_{demi}$ and $G_{rinse}$ must be achieved. This implies that with a demi-water at 1µS/cm, the rinse water should be 4µS/cm. This rinse conductivity can be approximated by the following equation:

$$ D_{sa} = \frac{Q_{wt} D_{ra}}{100 \times 10^6} \frac{A_n}{A_{sp}} t_e $$

Where

- $t_e$ is the sampling time (sec).
- $A_n$ is the area of intake nozzle on isokinetic device (m²).
- $A_{sp}$ is the total area of sampling plane (m²).
- $Q_{wt}$ is the total waterflow (m³/s).
- $D_{ra}$ is the drift rate (%)"
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washed, leaving salt in it. Secondly, the accuracy required for the volume measurement increases. Any error on it will impact directly the results.

We would typically use a volume of 50ml for the filter described in ATC-140 § 3.10.2, or even more for larger filters.

**Conductivity of the water - G circul**

Obviously a high conductivity of the circulating water will increase the accuracy. Accuracy will be maximum with sea water (around 50 000µS/cm). For brackish water it could be at the limit of acceptance. One way to increase it would be to temporary increase the circulating conductivity for the time of the test. It could be achieved by increasing the cycle of concentration. Some fill manufacturer allows a temporary increase of TSS. However, this rarely exceeds a factor of 1.5.

**Area of intake nozzle – An**

It also seems obvious that the bigger the filter is, the more it will collect drift. Logically, one would tend to increase at the maximum the filter intake this increases the air volume sampled and the quantity of salt caught in the filter. This brings two practical difficulties. Firstly, as the air flowing through the filter increase, the size of the vacuum pump must be increased as well. Secondly, the filter being larger, the quantity of rinse water would also have to be increased, slightly reducing the accuracy.

Altogether, larger filters improve the representativity of the sample but are more difficult and delicate to handle.

**SamplingTime – te**

Increasing the sampling time is the easiest way to increase accuracy. Obviously, the sampling time is limited by human endurance. One would hardly consider a test running for several days, several hours seems a maximum.

Using the formula in the previous chapter we can predict the sampling time depending on the drift rate and the conductivity of the circulating water.

**Fixed Parameters**

The following parameters are fixed for each tower and cannot be changed :

\[ A_{sp} \] is the total area of sampling plane (m²).
\[ Q_{at} \] is the total waterflow (m³/s).
\[ D_{ra} \] is the drift rate (%)

However, one will notice that it is easier to test a tower with a smaller exhaust area than a large one Therefore an induced draft tower will have more accuracy than a natural draught. Indeed, the test is isokinetic which means same velocity around the filter than at the filter intake. If the section is large the air velocity is low, therefore the volume of air captured will be smaller leading to a small quantity of drift. This is the case for a natural draught. On the other hand, if the section is small, the air velocity is high, the sampled volume will be high, as will be the drift and the accuracy. This is the case for a mechanical draught.

Therefore, for a natural draught, it is good practice to use larger filters which allow larger volumes to be sampled even if the air velocities found in those towers are low.

**Theoretical minimum measurable drift rate**

From the above paragraph we can predict the minimum conductivity of the circulating water to measure a drift rate depending of the required precision.

Several parameter have been fixed to typical value : rinse water is 50ml, demi water is 1 µS/cm, water flow is 15m³/h/m² on a induced draft, filters have small intakes.

![Image](image_url)

If we want an accuracy of at least 25%, the circulating water shall be at least 2000µS/cm to measure a drift rate of 0.001%. It shall be at least 20 000µS/cm to measure a drift rate of 0.0001%.

As explained it is possible to extend the sampling time. It will allow measurement of lower drift levels. The following chart present the sampling time required as a function of the drift rate and the circulating conductivity.

![Image](image_url)

It shows that with 16hours sampling it is possible to measure to 0.0001% with a circulating conductivity of only 1000µS/cm. Still the value can even be lower if large filters are used and if rinse water is reduced.

**Limitation of the conductivity methodology**

The methodology is more subject to airborne contamination as sodium is more likely to be present in the ambient air. However, the cooling tower has a washing effect therefore reducing this contamination.
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During the Eurovent drift test campaign, a reputed drift testing agency reported the following:

“The ambient concentration of the tracer elements in the test facility was determined by deploying a high volume sampler near the air inlet of the test cell. Lithium background levels were below detection limits while Sodium background levels were relatively high. Results of drift calculations between Li and Na did not always track with the differences in background concentrations. Highest Na background to sample air concentration ratios were experienced with drift results lower for Na than Li, indicating a thorough scrubbing effect by the circulating water flux in the test cell and negligible potential for contamination of the exhaust sample by ambient minerals pulled into the tower.”

It is to be noted that other methodology (ICP) are also affected by airborne contamination.

Anyway, the consequence of the contamination is an increase of the drift level.

Another limitation is the detection level which is a function of the circulating water salinity. This limitation can be overcome partially by extending the sampling time. It is advised to use the formula on the above chapter to predict the sampling time.

Validation of the conductivity methodology

Paper TP12-09 discusses extensively the validation of the methodology. Additionally we have also performed a cross-check with ICP analysis. To do so, the rinse water was collected after the conductivity analyses. It was sealed and sent to an ICP lab. The Na was analyzed.

The first measurements were made with a circulating water conductivity of 80 000µS/cm. The demiwater was 0.8 µS/cm. The set is made of 31 points. The sampling time was around 1.5 hours.

This set is interesting because it shows that it is possible to measure a low drift level (average is 0.005%) when the conductivity is small. The scatter is slightly higher however the slope of the regression line between ICP and conductivity is similar: 1.055. Again the conductivity tends to overestimate the drift level.

From the measurements we can see that the conductivity matches very well with the ICP analysis. It is also on the safe side: the conductivity tends to slightly overestimate the drift level.

Advantage of the conductivity methodology

The main advantage of the method is its portability which enables performing the analysis on site and having the results immediately available. This allows the tester to provide preliminary results BEFORE leaving the site. Additionally, any sampling problem can be detected when the tester is still on site; allowing repetition of the measurement in the same campaign. When using ICP, failure of sampling leads to a new campaign.

Only one filter is required on site. The same filter can be washed and reused. Rather than sealed and sent for analysis when using ICP.

It is fast, less than 30 minutes are required to analyze the sampling. Thanks to the two advantages above, one can perform more analysis and therefore reduce the consequence of failure. Instead of analyzing the drift for one full cell, one can make 4 analyses per cell (one per radius). If ever the sampling failed because of the weather or the equipment, only one radius would have to be redone instead of the whole cell. This could save a tremendous amount of time on site. Additionally having more analysis allows a better evaluation of the accuracy for the whole these by the scattering of the results.

It is very cheap. Portable conductivity meters are available for less than 100$. However, conductivity meters shall have wide range of measurement 0.1µS/cm to 100 000µS/cm. interestingly, there no need to have a calibrated conductivity meter because the methodology is based on a ratio of measurements made with the same instrument. It is accessible to everybody. There is no need to be a chemical specialist.

It is safe. Indeed the conductivity tends to overestimate the drift level. When there is contamination salt will be added leading to an increase of drift. There is no way to reduce the conductivity by accident.
Additionally, this is a non-destructive methodology. It means that all samples can be sent for ICP analysis later on.

**Conclusion**
The conductivity method is simple, fast, safe and cheap. It allows having results immediately after sampling; reducing the consequence of a sampling failure.

It is reliable for sea water cooling tower. For brackish water, the sampling time should be adjusted to reach the desired accuracy. Obviously the methodology becomes inaccurate when the drift level is very low and when the circulating water has a very low conductivity. However, in such cases, the ICP analysis faces the same challenge. ICP is then limited by the detection level of the instrument. As such, the conductivity is perfectly adapted for the drift measurement and should be reintroduced into CTI ATC-140.
Film Fill Fouling: Updated Methods, Results And Predictions

Kenneth Mortensen Spx Cooling Technologies
Frank Michell American Electric Power

I. History

Problem Description: Film filled counterflow cooling towers, whether natural or mechanical draft, are the product of choice in power and industrial markets today. In a number of cases, older cross-flow splash tower installations have been converted to counterflow film. Fill fouling, discussed in this paper, is the single largest cause of PVC film fill failure in cooling applications. It is important for cooling tower owner, operators, manufacturers, and water treaters to understand the impact of film fill selection, maintenance, and fouling’s progression on tower longevity.

Counterflow Film Fill Fouling - Fouling is the process of deposition of foreign matter, including bio growth, on the evaporative heat exchange surface in this case the plastic film water flow area. In many circulating waters at operating chemistries and with treatment systems in place, this process is controlled so that it does not measurably inhibit the cooling process or allow excessive weight to build up in the cooling tower fill or on structure. In some circumstances, however, fouling is not well controlled and can result in a reduction in the overall cooling efficiency, a manifestation of foulant interfering with air and/or water flow through the film media.

In TP94-05, “Film Fill Fouling in Counterflow Cooling Towers: Mechanism and Design [1], Mortensen and Conley presented strong evidence that the primary cause of film fill fouling was biological growth, with weight gain being accelerated by the capture of suspended solids in the circulating water. Laboratory fouling testing, along with water and deposit analysis supported this conclusion. TP94-05 Figure 4 is given below.

Analysis at that time, identified water borne bacteria producing sticky binder in the biofilm, as Extra Cellular Polysaccharide Producers (ECPS), with the microbial mass cementing or sticking together general debris.[2] These organisms are foulants in a number of industrial processes and tend to thrive in the aerobic (O2 saturated), temperate (80-120degF), and nutrient rich environment such as the one provided in film fill. Figure 1: TP94 05 Fig. 4 [1], documents the laboratory weight gain of High Efficiency Fill [HE], defined as cross corrugated 30 degree angle ¾” spaced film fill, in Silt Only [Silt, S], High Bio growth[Silt + Biological, SB], and Moderate Bio Growth [Limited Carbon, LC] exposure. Weight gain without biological growth is minimal and not catastrophic to the HE film fill pack.

For purposes of this paper, the following definitions will be used:

- High Efficiency Film Fill [HE], is cross corrugated, 30 degree angle, ¾” spaced film fill and is the control for comparing other fill geometries fouling characteristics.
- "Low Clog" (LC) film fill is packing adding 2X + operating life to that of estimated HE Control film fill.
- "Ultra Low Clog" (ULC) film fill is packing adding 4X+ life to that of estimated HE Control film fill.

Solids analysis from these recent inspections supports this same conclusion, characterizing foulant solids as organic binder with 90% inorganic material including aluminum, calcium, iron, and silica. The aluminum, iron, and silica materials indicate soils.

The predominant cause of film fill fouling is biological growth creating substantial detrimental blockage. Silt exposure alone is not the cause. The combination of silt and biological growth can create rapid and catastrophic fouling.
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II. Evaluation Techniques
A. Laboratory Methods
Past: Laboratory studies of fouling mechanisms and cooling tower film fill characteristics were first undertaken in the 1990's to evaluate and optimize cooling tower response to this serious problem. Several fouling mechanisms were considered for investigation the base condition chosen was a 100% bio growth sequence, with comparisons in 100% silt, and a very severe combined silt and bio mechanism. Dedicated test cells were built to accommodate a test fill cube, see Figure 2. These test units featured a miniature counterflow spray system but did not include fan or eliminators. Oxygen saturation of the water stream was accomplished here by using a venturi to entrain air via vacuum. Temperature, nutrient and suspended solids levels were controlled.

Analysis of a plug sample from a lab unit revealed that bacteria potentials are very high at $1.15 \times 10^9$ organisms/ml in the solid. Further analysis identified water borne organisms which produce sticky biofilm material as Extra Cellular Polysaccharide Producers (ECPS) with the microbial mass cementing or sticking together general debris.\(^1\)

Current - In recent years, a multi bay fouling test chamber was designed and built, see figure 3 and 4. It features the ability to expose larger packs of multiple fills to fouling with a single control pack. This chamber provides electronic data logging of both operating and drip dry weights. This chamber provides increased testing capability, while retaining proper cooling tower exposure: temperature, oxygenation, water loading, and allows methodical nutrient additions for growth promotion. Testing in this newly designed fouling chamber is detailed in the Results Section of this paper.

Current Results - The new test unit produces simultaneous results for all test packs and the control as weight-gain versus time. As with previous laboratory fouling testing, the fouling process in an individual pack is greatly accelerated. This testing presents a severe screen for any fouling reduction design. This unit allows rapid evaluations of many possible designs with the comparison being under identical conditions. An example of the output curve is presented in Figure 5. The unit produces continuous operating-weight versus time curve and “drip-dry” points are gathered on a timed basis.
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These “drip dry” points correlate with all the previously generated single unit tests, while the operating weight points can be correlated with field weigh rack data.

Current laboratory methods are more consistent and accurate than at any time in the past. Current laboratory data is reliable as one piece in film fill evaluation for suitability of application. In the “Conclusions” section of this paper, Fouling Performance Modeling (FPM) using available data and site information is discussed as a technique for making fill recommendations.

B. Field Methods: Removal Weighing

Past - In the late 1980’s and early 1990’s, cooling tower customers and manufacturers began recognizing problems with the application of HE film fills under some water conditions. New fill geometries were being identified and evaluated.

Monitoring these new fill shapes has been an important activity in the evaporative cooling industry since that time. Film fill shapes applied in the field in varying and severe water conditions have been monitored primarily by weighing and visual examinations. Tests were done as direct weight gain comparisons of a low clog film fill vs. HE Control pack at the same site. These tests supported the broad conclusions that larger openings, lower angles, fewer layers and reduced texture seem to be essential to achieve antifouling characteristics.

The weight gain improvements, however resulted in some reduction in thermal performance of the evaporative cooling tower installations. Below are pictures from field examinations, Figure 6, 7, and 8:

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pack and can provide drip dry points at the plant shutdowns. Drip dry points correlate with previously generated test information, while operating weight points can be correlated with current lab weight data. As with previous field fouling testing, the fouling process is specific to individual location conditions. Figure 10, below, is an output curve. The test period here is 6 Months.

**Field Fouling Test**

Combining lab and field methods then gives an indication of the fills capability generally and field examination gives specific film fill performance under a site specific set of circumstances. In the Conclusions section of this paper, Fouling Performance Modeling [FPM] using available data and site information is discussed as a technique for making fill recommendations.

**D. Probing: Developing a New Field Method for Monitoring Film Fill**

Method Description - With multiple visits to tower sites, the limited ability to observe fouling from above or below film fill without dismantling whole sections of the tower becomes apparent. There is a limited ability to see into film fill, particularly with layering. Several years ago while examining fill, the author added a step to the evaluation process by inserting a probe into long narrow straight passages of that particular fill pack. In that first instance and subsequent checks, a narrow width tape measure was used as the probe, see picture below. The tape was extended up into the film fill.

Assessing the difficulty of moving the tape through and examining the material output became indicators of the condition of that fill. This technique works best on straight passages, whether angular or vertical, in deep packs, with no change of direction or interface type blockages. This method is simple, inexpensive, and immediate.

**Inspection Results**

Multiple tower examinations have been undertaken by the author in recent years. Descriptions from some of those examinations are given below:

**Eastern Power Plant A** - Fill looks good in the tower interior. A very thin TSS film is on the base level packs, estimated at less than 5 mils thick. The estimated weight is less than 0.5 lb/ft³.

**Eastern Power Plant B** – Film fill looks acceptable in Tower. An accumulation of soils is noticeable, estimated at between 5 and 10 mils thick with an estimated weight less than 1.0 lb./ft³. Solids analysis indicates 5 to 6 % loss on ignition and 6 to 7% organic matter, usually indicative of the biological portion of a fouling solid. Chlorine additions are currently 2X/day. Plant reports indicate in March, 2011 the TSS #’s were very high, ranging from 370 to 912 ppm.

Customer discussion included the following observations, "There is a difference (greater amount) in deposition of silt on the fill in
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the Plant B Cooling Tower inspected a few weeks ago than on the Plant A Cooling Tower fill we inspected in December, 2010. Both towers have the same fouling resistant fill."

"The analysis of the Plant A Cooling Tower fill deposit indicates presence of some organic compounds which acts as a binder for clumping the silt together and adhering it to the PVC Fill sheets. The records indicate that river turbidity of the river at Site B is consistently much higher in magnitude than on the river at Site A."

"The slight build up of silt on the Site B fill is not a serious problem but without taking some measures now to limit bio activity in the circulating water can cause significant issues down the road..."

Plant D - Inspection of a low clog fill with HE overlay revealed significant mud accumulation in areas by probing from underneath. From the top side of the fill was quite clean. Center estimated at drip dry weight of 5 lb./ft³, 1 bay from shell estimated drip dry weight 10 20 lb./ft³, At shell estimated at drip dry weight of 5 lb./ft³.

Eastern Plant C - Film Fill looks acceptable in Plant C. An accumulation of soils in some of the flutes was noticeable, estimated weight of 1.0 to 2.0 lb./ft³. Generally the fill was quite clean with only a thin veneer of silt. Non oxidizing biocide additions, currently 1X/week, and hypochlorite 1X/mo. are maintaining the fill in good condition. TSS condition is modest to low at 25 ppm average, with occasional spikes to 200ppm at this site. Continuing the current biocide treatment in this moderate TSS environment is recommended to maintain the long term condition of the film fill.
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Internal Examination of Film Fill, an extension of the probing method: In one recent examination a boroscope was provided by the site water treatment vendor at the customer’s request. It was used to examine fill flutes of fill from 0 up to 72 into the pack. This technique shows promise by allowing more complete fill condition assessment in situ. Results are shown in Figures 20-24.
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Conclusion - The simple probing examination method described here has been effective in evaluating film fill use in field application. It is recommended for towers without operable weigh rack systems and gives insight into both fill selection and water treatment effectiveness at a specific condition. In order to be effective fill probing must be done diligently and consistently. Internal boroscope examination provides a promising technique for more in depth in situ examination.

III. Results - Fill Capability Assessment

A. Combined Assessment of Results for Fill Longevity

This paper describes laboratory methods for fouling assessment of fill designs and several methods for fouling assessment of installed fills. These methods are best used in combination to arrive at the best fill selection and longevity for the customer.

A concept called Fouling Prediction Modeling [FPM] can be envisioned that blends lab fouling data, field fouling data, fill geometry/characteristics, and site data, into a predicted fill life at an installation location. The site data would include tower design conditions with water quality/treatment information. FPM would combine this in formation and experience with the chosen film fill geometry to derive its expected longevity at site specific thermal, water quality, and treatment conditions. A fill recommendation would be relative to a judgment standard and might express a confidence level for the prediction. Fouling loads that cause thermal degradation are typically 12 - 20 lb./ft$^3$ average measured drip dry after exposure for film fills.

B. Tower Application of Film Fills: What Did Work

Low Clog film fill application began in the 1990's in North America. There are a number of early power industry installations from the 1990 - 1995 time period operating effectively today. Updated LC film fill designs from the 2000's combine improved thermal performance with fouling protection. The growing pool of film filled towers provides operating history.

As a result of an accumulation of data from laboratory, field application, and field monitoring, the use of LC and ULC film fills with specific water quality for each selection have been successful. There are a number of examples of long term installations that are cooling efficiently with little biological and/or solids material accumulating in the film fill. Several are described below:

1. Power Plant A: Repack with LC has been monitored and found effective. This plant applies Chlorine 3 times/day. See Field Notes in Section D for more detail.
2. Power Plant B: Repack with LC has been monitored and found to be effective. This plant applies Chlorine 2 times/day. See Field Notes in Section D for more detail.
3. Power Plant C: Repack with LC has been monitored and found effective. This plant applies Non Oxidizing Biocide 1 times/week and Chlorine 1 time/Month. See Field Notes in Section D for more detail.
4. Power Plant D: After repack with ULC with 1 High Efficiency overlay operating successfully. Water Treatment is chlorine 3 times/day. See Field Notes in Section D for evaluation of the fill that was replaced.
5. Power Plant E: Plant application of HE from the 1980's, with specifically designed application of biocide and dispersant during operation and high rate application with closed blowdown at outages has been successful after initial issues with fouling in the 1990's. The circulating water quality in operation has been 2500 ppm TDS and 30 ppm TSS.
6. Power Plant F: This plant runs HE film fill from the 1980's and 1990's using highly treated sewage effluent as make up and a designed water treatment system. Operation is successful and fill is clean. The circulating water quality in operation has been 2000 ppm TDS.
7. Power Plant G: Repack with LC using river water at 25ppm+ TSS, 4 Cycles. This plant applies chlorine 1time/week.
8. Power Plant H: Repack with ULC and restored thermal performance from a drastic reduction due to fouling. This plant applies chlorine gas to packing and continuous make up disinfection. The plant runs at 1.5 cycles with a TDS of 20,000 - 100,000ppm.

C. Tower Application of Film Fills: What Did Not Work

In general, HE film fills in power plants using river water make up without strict water quality and treatment guidelines eventually failed.

1. Power Plant A - Originally packed with HE film fill fouled in 10 years, see What Did Work above for repack success.
2. Power Plant H - Originally packed with HE film fill fouled at 5 years. Top 1' layer looks clean, varying fouling at interfaces.

Figures 25 and 26: Plant G tower and fill
The plant applies Chlorine 1 time/day and is at or near the ability to discharge from the plant. See "What Did Work" above for repack success.

3. Power Plant I - Originally packed with HE film fill fouled in 5 years. Plant used river water make up, TSS 160ppm.
4. Power Plant J - Initially packed with HE fill, this tower was re packed with ULC.

**Figure 28: Plant J before Repack**

**Conclusions**

1. Film fill fouling remains an industry focus.
2. Owner/Operators consistently indicate they want maximum thermal performance with assurance of film fill fouling protection.
3. Better evaluation tools, techniques, and information are available now than at any time in the past.
4. By using this information improved fill longevity is being achieved.
5. Low-Clog Fill designs vary and owner/operators should seek fills with proven fill track record on thermal and fouling resistance from suppliers who collect this information.
A Synergistic Combination of Advanced Separation and Chemical Scale Inhibitor Technologies for Efficient Use of Impaired Water in Cooling Towers

Jasbir S. Gill, Ph.D., Nalco Company and Yupo J. Lin, Ph.D., Argonne National Laboratory

Introduction

As the population increases, good fresh quality water is much more needed for human use including growing food. Tertiary sewage treated water and sea water (1) has been successfully used in many industrial applications. The use of impaired water is currently not very practical and cost effective, as the inferior water quality results in additional treatment requirements to address the high propensities of scaling, corrosion, and biofouling and to avoid adverse impacts to the environment.

Depending on the impairment the treatment cost is prohibitively high because 1) the current separation technologies are inefficient, and 2) the scaling potential of the impaired waters is generally high and severely limits the number of cycles that can be achieved with current scale control technologies. Scale inhibitors alone can only control deposit up to certain number of cycles of concentration; beyond their maximum limit it does not matter how much inhibitor is added. In these situations the only way to improve water reuse is remove impairment either completely or partially (Figure 1). Operating at low cycles reduces water utilization efficiency and greatly increases the volume of blowdown wastewater, resulting in unacceptable high costs and a significant environmental impact. In this figure, the yellow line represents the scale inhibitors only using existing commercial scale inhibitors while the green line represents the target for new scale inhibitor. The dark blue line represents model water as is while the magenta color represents with at least 50% calcium hardness removed.

Nalco Company by partnering with Argonne National Laboratory (ANL) in this project has developed advanced scale control technologies that will provide cost-effective solutions for recirculating cooling water systems to operate at high cycles using impaired waters. This will reduce the amount of make-up water required and the volume of blowdown generated, resulting in lower treatment cost and less environmental impact. The overall approach is to use synergistic combinations of physical and chemical technologies. More specifically, the paper reports the use of novel membrane separations and scale inhibitor technologies that work synergistically; membrane separations reduces the scaling potential of the cooling water and the scale inhibitors extending the safe operating range of the cooling water system. This approach has not been possible to date because the technical risks involved in integrating these technologies have not been addressed. The new scale inhibitor chemistries developed in this work can handle the higher stress scaling conditions as well as new types of scales from impaired water.

Results and Discussion

Identify Limiting Factors for High Cycles and Quantify Technical Targets:

Potential sources of impaired waters were identified based on literature and industry information provided by Nalco’s Power business unit. As the first step to determine the cycle-limiting factors of the impaired waters, the characteristics of various impaired waters were collected and evaluated. There are several sources of water that are used for cooling water application

- Ground water
- Surface water
- Tertiary sewage treated water (municipal waste water)
- Produced water
- Sea water/brackish water

General impairment with ground water in addition to hardness, alkalinity, and silica is the presence of iron and manganese. Surface water contains high suspended solids and many times colloidal silica in addition to dissolved silica and other ions mentioned in the
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ground water. Surface water, however, very rarely contain iron and manganese. The challenges with municipal treated waters (sewage treated water) are the presence of variable phosphate, ammonia and biological material. Produced water is not used very commonly for cooling tower. There has been a recent trend in the use of sea or brackish water being used in power plants in coastal areas (1). The impairment of these waters is due to the corrosive nature, which is overcome by using corrosive resistant metallurgy. Cooling towers using brackish or sea water are generally run at lower cycles due to abundance resource and easy discharge without impacting the environment. In this study we focused on high hardness, high alkalinity, and high silica waters and in general high total dissolved solids (TDS).

Table 1 shows that produced water characteristics can vary significantly from site to site, with respect to the total dissolved solids and the ion profile. Two common potential cycle-limiting minerals are calcium carbonate and calcium sulfate. These waters often contain very high levels of bicarbonate (HCO3-) ions and the ion profile. Two common potential cycle-limiting factors, and silica/silicate is an issue for the western region. The concentration of phosphate in some reclaimed municipal effluents is high enough to potentially cause calcium phosphate scaling, and this can be a challenging issue, especially if silica is also present at high concentrations. The presence of iron and aluminum, due to their uses as treatment additives in upstream treatment processes, also present potential iron and aluminum fouling issues. However, the extent of potential iron and aluminum fouling appears to be controllable with current cooling water treatment technologies.

Development of High Stress Calcite and Silica Scale Control Chemistries:
Scale formation in cooling water systems occurs when mineral salts precipitate from the water phase because the solubility of the particular mineral has been exceeded (i.e., the water is supersaturated with the mineral). Supersaturation of any mineral is defined by the following relations,

Supersaturation = Activity product of scale forming ions/ Ksp

Where, Ksp is the thermodynamic equilibrium solubility constant of the mineral.

The process of scale formation from a supersaturated solution involves a series of steps, including nucleation, crystal growth and deposition on the heat exchangers. Chemical scale inhibitors (also known as antiscalants) control scale formation by a variety of mechanisms: threshold inhibition, crystal modification, sequestration, or dispersion. In terms of their chemical nature, scale inhibitors include inorganic polyphosphates (e.g., hexametaphosphate), organophosphonates (e.g., 1-hydroxyethylidene-1, 1-diphosphonic acid) and polymers (e.g., polyacrylate).

Antiscalants for calcite (calcium carbonate) and silica/silicate scale control are currently available. However, for high stress conditions (at high supersaturation ratios) these antiscalants are either ineffective or uneconomical. Scale inhibitor chemistries (including new molecules, polymers, and formulations) were evaluated under high stress chemistry to develop new antiscalants that will be superior to the existing antiscalants in terms of cost and performance. The evaluations were performed initially in bench tests and, subsequently, in the pilot cooling towers.

The term silica is often used loosely to include both silica and silicates, which are, in fact, two distinct families of silicon-containing compounds. Silica refers to SiO2, including the crystalline quartz and the non-crystalline amorphous silica, resulting from polymerization of silicic acid, H2SiO3. Silicates refer to the compounds formed by reacting ionized silicic acid with metals, such as calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), zinc (Zn), etc. It is also very common for silica/silicates to coprecipitate on suspended solids or other precipitating minerals. The solubility of silica is approximately constant in the pH range of 6 to 8 and increases at pH > 8.5. The solubility of silicates follows the opposite trend, and silicate precipitation generally occurs only at pH > 8.5. Silica/silicate control using chemical inhibitors include inhibition of silicic acid polymerization and dispersion of silica/silicate crystals. Amorphous silica solubility increases with increasing temperature while the solubility of silicates decreases with increasing temperature. Most of the time in cooling towers amorphous silica is deposited on the high efficiency fill and silicates are found on the heat exchangers surface in systems with moderately low silica levels. On the carbon
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steel heat exchanger surface due to the presence of hydroxyl groups, silica can directly deposit as silicates or even monomeric silica. Calcium carbonate precipitation is directly a function of hardness, carbonate alkalinity, temperature, TDS and pH. Most of the time calcium carbonate precipitation is controlled by adjusting the pH of the recirculating water. There are several drawbacks to control calcium carbonate precipitation by acid feed. Reduction in carbonate alkalinity by addition of sulfuric acid is also responsible for adding to the greenhouse gasses by emitting 0.73 ton of carbon dioxide for every ton of carbonate alkalinity reduced with sulfuric acid.

- Corrosion.
- Other potential scales such as calcium and barium sulfate (if sulfuric acid is used for pH control).
- CO2 emission as a result of carbonate alkalinity neutralization.
- Cost.
- Safety due to acid handing risk.

Solubility of calcium carbonate is inversely proportional to temperature and thus is a very common scale on the heat exchangers. Scale inhibitors have been used but largely in conjunction with pH adjustment for high cycles of concentration or high alkalinity waters.

**Calcium Carbonate Scale inhibitor:**

For an initial quick screening of different molecules at various concentrations a stagnant flask test was developed. The simple impaired is prepared using calcium chloride and a mixture of sodium carbonate and sodium bicarbonate. An 80/20 mixture of sodium bicarbonate/sodium carbonate in addition to providing the required alkalinity provides a buffer at pH 9.0. These flasks are dosed with different amounts of different inhibitor and are incubated for 24 hours in a water bath at 55 oC. At the end of the incubation time, each test solution is filtered through 0.22 μm membrane filter, while the solution is still hot. The filtrate is analyzed for calcium concentration using Atomic absorption spectrophotometer and complexometric titration to determine the %age inhibition using the following equation.

\[
\% \text{ Inhibition} = \frac{VE - Vo}{VT - Vo} \times 100
\]

Where: 
- \(VE\) = Total Calcium as mg/L for treated test sample
- \(Vo\) = Total calcium as mg/L for untreated (blank) test sample
- \(VT\) = Total calcium as mg/L for calcium reference (initial s

The flask, which contains no inhibitor gives \(Vo\), is considered at no inhibition (0%) and if \(VE\) (treated with inhibitor) is equal to \(VT\), it will give complete inhibition (100%). \(VT\) is determined from a flask, which contains only calcium and no alkalinity (or theoretical initial amount of calcium added to each flask. Initially to create conditions of calcite saturation of 250X, the following composition of the water was synthesized:

- 150 mg/L Ca++, 600 mg/L Alkalinity as CaCO3 (80/20 NaHCO3/Na2CO3), 266 mg/L Chloride, and 276 mg/L sodium.

The results of this study are shown in table 3.

<table>
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<th>Inhibitor</th>
<th>Concentration mg/L</th>
<th>% Calciate Inhibition</th>
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</table>

**Table 3. Results of calcium carbonate inhibition with different inhibitors**

L99BO is a known phosphonate, which is effective in the test conditions; however this inhibitor can undergo degradation to orthophosphate under high bleach use, however, it has shown good stability with stabilized/unstabilized hypobromous acid oxidative environment. In the cooling towers, oxidizing biocides are often used to control microbes in the water biofouling. New compounds, 5636-130 and 5636-130B, were synthesized and evaluated. These new compounds are deemed more stable in an oxidizing environment than LLB90 but the performance was not up to the level of LLB90.

**Table 4. Silica testing with laboratory prepared inhibitor sample**

These results in table 4 shows that the silica inhibitor is capable of handling silica as SiO2 at up to 300 PPM. In subsequent field trials the results were even more encouraging.

**Ion Removal:**

One of the membrane systems being tested by Argonne for the removal of scaling components is resin wafer electrodionization (RW-EDI). EDI is an industrial process that incorporates ion-exchange (IX) resin beads into an electrodialysis (ED) stack. ED is an electrically-driven membrane-based separations process. Commercial EDI systems are constructed by filling the diluate channel in an ED stack with loose ion exchange resin beads. Argonne has immobilized the loose IX resin beads with polyethylene resins to form a porous resin wafer (RW) material. A typical EDI system schematic is shown in Figure 2.

![Figure 2: Schematic of the EDI system used for scaling ions removal](image)

The RW-EDI platform enables in-situ pH control by using the water splitting reaction which eliminates or minimizes the need for acid or base additives. The RW-EDI platform provides flexibility in terms of membranes used and their configuration. Additionally, the
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Electrodialysis (ED) System:
Two different systems were tested. While investigating hardness removal in simulated make-up water, a four-cell pair stack comprised of Ameridia’s CMX-s and AHA-1 ion exchange membranes was used. Hardness removal from simulated 10-cycled power plant cooling water was done with a 6-cell pair ED stack using Ameridia’s AM-1 and CM-1 ion exchange membranes.

Electrodeionization (EDI) System:
The Argonne EDI resin wafers were fabricated from commercial grade gel-type strong acid cation and strong base anion exchange resins. The resin wafers with different ratios of cation/anion exchange resins were fabricated using Argonne’s patented process (Patents 6797140, 7306934, and 7452920). Commercial polymeric ion-exchange membranes were used to assemble the RW-EDI stack. Different membrane configurations were tested during process development. A commercial ED stack was used as the base template to assemble the EDI stack. Two different EDI stack sizes were employed which had a cross-section membrane area size of either 14 cm2 or 195 cm2. Argonne’s in-house gasket material was used to seal the resin wafers in the stack.

The feasibility of using ED to reduce the hardness and hence the scaling potential of power plant recirculated cooling water and make up water was tested at the bench-scale. Ten liters of simulated make up water, which contained 995 mg/L of NaCl equivalent, was tested in a four-cell pair ED stack which used Ameridia’s CMX-s and AHA-1 ion exchange membranes. The results showed a 99+% removal of salts from the simulated solution with low power consumption. Simulated 10 cycled cooling water containing 8500 mg/L of NaCl equivalent and 1.3 meq hardness was tested in a six-cell pair ED stack built with Ameridia’s AM-1 and CM-1 ion exchange membranes. This test showed a 99+% removal of salts from the simulated solution with very low power consumption. The divalent cations were removed preferentially over the monovalent cations. These results suggest that it is technically and economically feasible to use ED for the separation of scaling species from reused water.

Feasibility of using EDI to reduce alkalinity in simulated recirculated cooling water and make up water was also studied. Reducing alkalinity could potentially increase the number of cycles of concentration. Bench-scale EDI stacks were assembled using Ameridia’s CMX-s and AHA-1 ion exchange membranes and porous ion-exchange resin wafers. Initial screening runs were done with a four–cell pair mini-stack (14 cm2 membrane area/cell pair) while subsequent runs were done with a larger six cell-pair stack (195 cm2 membrane area/cell pair). Two different simulated waters were used – one with 2500 ppm of NaCl equivalent and 2700 ppm of alkalinity and the other with 3500 ppm of NaCl equivalent and 6400 ppm of alkalinity. The results showed low power consumption and over 98% removal of the alkalinity from the simulated waters.

In addition to the removal of hardness and alkalinity, the removal of silica was also studied with bench-scale ED and EDI. These technologies were tested using a simulated impaired water solution which contained 200 ppm of silica. Both ED and EDI demonstrated the ability to remove silica from the simulated water. The power consumption for EDI was approximately 25 – 30% less than the power consumption observed for ED. These results are shown in tables 6 through 8.

A series of tests were done to determine the effect of stack configuration and the type of ion exchange membranes on the EDI system’s alkalinity removal efficiency. Table 6 shows the optimized performance while Table 7 shows the estimated capital cost based on the process performance as shown in Table 8.

The EDI system’s selectivity was improved by changing the ratio of cation and anion ion-exchange resin beads in the wafers. Three different wafers were tested: an anion-excess resin wafer, a cation-excess resin wafer and a wafer made with equal amounts of cation and anion resins. Of these three, it was found that the wafer made with an excess of cation resin gave the best separation efficiency. An EDI stack with these optimized resin wafers was then tested. Two different simulated waters were used – one with 9600 ppm of NaCl equivalent and 4600 ppm of alkalinity and the other with 3500 ppm of NaCl equivalent and 6400 ppm of alkalinity. The results showed low power consumption and over 98% removal of the alkalinity from the simulated waters.
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ditions. An anti-fouling chemical developed by was also tested but the precipitation that was causing the membrane fouling did not decrease. In the enhanced process, the removal efficiencies of hardness, alkalinity and total salt removal were improved, as shown in Table 9. The cost of water desalination using EDI was estimated to be approximately $0.05/barrel of water.

<table>
<thead>
<tr>
<th>Process Range</th>
<th>Processing Flux (μA/cm²/hr)</th>
<th>Power consumption (kW/100 gpd)</th>
<th>Salt Removal (%)</th>
<th>Hardness Removal (%)</th>
<th>Alkalinity Removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 to 59 ppm</td>
<td>19.5</td>
<td>0.57</td>
<td>87.0</td>
<td>83.2</td>
<td>86.0</td>
</tr>
<tr>
<td>500 to 50 ppm</td>
<td>19.2</td>
<td>0.54</td>
<td>95.1</td>
<td>88.8</td>
<td>95.5</td>
</tr>
</tbody>
</table>

Table 9. Desalting Performance of Revised EDI System

Pilot study with PCT (EDI and Scale Inhibitor):

Finally after all the optimization studies the integrated program was evaluated using the PCT. The economics of water desalination using EDI was estimated to be around $0.05/barrel water (table 8); that figure includes both capital and operating costs.

A synthetic impaired water is brought into the EDI unit and the soften water (with impaired ions removed) is used as a makeup water to the Pilot Cooling Tower. The unit was properly sized to meet the makeup requirements for the PCT. Several runs were planned to evaluate the efficacy of the concept in terms of maximizing the cycles, economics of >95% ion removal (power consumption), partial removal of impaired ions and combination with inhibitors, and ion removal from the makeup water as well blowdown water.

We conducted this study by approaching from two different scenarios:

1. Removing the impaired ions using EDI upfront from the makeup water
2. Removing the impaired ions using EDI from the blowdown of the cooling tower

Both approaches provided excellent results indicating the possibility of operating cooling tower using water with impaired ions close to zero liquid discharge. In this system the small wastage of the water came from blowing down the concentrate (about 23 liters) twice per week and another small volume (about 20 liters per week) for cleaning in place (CIP) and the rinse. The results of these studies showed approximately 90% reduction in the water wastage. The concentrate tank (i.e., waste water recycled tank) conductivity is increased from 350 μS/cm² to >30,000 μS/cm², although some of the conductivity in the concentration tank comes from sodium chloride added as a means of conducting solution. In a zero liquid discharge system, removal of TDS from the blowdown stream is more cost effective than removal of TDS from makeup water, due to processing of less volume through EDI, even though former requires higher power consumption than the latter. A long-term integrated evaluation (550 hours) of the optimized EDI system and the inhibitor resulted in 90% decrease in water wastage.

Conclusions

In the final analysis for any size cooling tower the water consumption is through evaporation, blowdown and some leaks. The evaporation rate depends on the recirculating rate and delta temperature; it remains constant at any cycles of concentration. Increasing cycles of concentration from 5 cycles to 10 cycles reduces blowdown by 55% and the blowdown rate is 25% of the evaporation rate, which means 75% water consumption is due to evaporation. By further increasing cycles of concentration from 10 to 15 cycles, there is further reduction of 15% in blowdown rate; however 93% water consumption comes from evaporation. Thus there is a much more water savings from 5 cycles to 10 cycles than going from 10 cycles to 15 cycles of concentration. Beyond15 cycles of concentration, there is practically very little water savings. Process was optimized by reducing the impairment ion by 50% and then maintaining zero liquid discharge by using a low level of scale inhibitors and oxidizing biocide.

Acknowledgements

Financial support for this project was provided by Nalco Company and DOE (DOE Award Number: DE-FC26-06NT42721). Dr. Seth W. Snyder, Mr. Michael Henry and Ms. Patricia Gillenwater of Energy Systems Division, Argonne National Laboratory are thanked for delivering results under CRADA#C0605001. The author is also grateful for the contribution of various other team members from Nalco Company - Dr. S.P.Tsai, Dr. S. Kidamibi, Dr. Frank Lu, Ms. Cheryl Williams, Mr. Dan Pruss, Dr. N Greene, Dr. K. Fivizzani, Dr. A. Sommese, and Dr. J. Schwartz.

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Structural Integrity Of Hyperbolic Cooling Towers With Imperfections In Geometry And Verticality

Narendra Gosain, Prasad Samarajiva and Farouk Mahama
Walter P. Moore And Associates, Inc.

ABSTRACT
Due to the large size of concrete hyperbolic cooling towers and difficulties encountered during construction, it is not always possible to maintain dimensional accuracy of the towers. Imperfections in the intended geometry and verticality can have an impact on the stresses in the thin concrete shell structure. Using an existing hyperbolic cooling tower as an example and some possible imperfection scenarios a parametric study is conducted to investigate the effect of such imperfections on elastic stresses in cooling towers when subjected to dead loads and wind loads.

INTRODUCTION
The sheer scale and geometric complexity of concrete hyperbolic cooling towers makes it very challenging to construct such structures to the exact geometry assumed in design calculations. However, limited guidance is provided in the literature regarding the effects of imperfections on the behavior of cooling towers. This may have partly been because of the difficulty in modeling such imperfections due to limited computing ability prior to the advent of personal computers and structural analysis software. In the late seventies Croll, Kaleli, Kemp and Munro (1) conducted a study aimed at simplifying the modeling of imperfections in hyperbolic cooling towers. They approached the problem by simulating geometric imperfections using a static normal pressure distribution which was then applied to the perfect tower geometry. Shiro and Yoshitsura (2) conducted a study on the effect geometric imperfections on the distribution of stresses in cooling towers. Their study showed that the circumferential component of stress was strongly influenced whereas the meridional component of stress was slightly influenced by the imperfections modeled.

This paper aims to investigate the effect of imperfections in geometry and verticality on the development of tensile stresses in hyperbolic cooling towers. The reinforcement provided in design of cooling towers beyond code specified minimums is primarily dependent on the net tension obtained when tensile stresses due to wind loads are superimposed on the precompression stresses due to dead loads. The presence of imperfections may lead to amplification of the net tension such that the reinforcement provided assuming an ideal structure may not be adequate to perform its intended function. This may lead to the premature formation of cracks and the inability of the concrete shell to develop the design capacity, thereby compromising the integrity of the structure.

COOLING TOWER MODELING
An existing hyperbolic natural draft cooling tower was used for the parametric study. The as-designed tower geometry, which was obtained from original construction drawings, was used as a baseline from which the geometric imperfections were modeled. The height of the tower was approximately 140 m (460 ft.). Along the circumference of the basin were 40 pedestals into which two diagonal circular columns framed. Each column also framed at the top into a ring beam at the bottom of the veil. The diameter of the tower at the bottom of the veil, throat, and top cornice were 97 m (320 ft.), 56 m (183 ft.), and 62 m (205 ft.), respectively. The thickness of the reinforced concrete veil wall varied from 23 to 25 cm (9 to 10 in.) and increased to 91.4 cm (36 in.) at the ring beam and top cornice. The veil was reinforced with interior and exterior mats of Grade 60 (i.e. yield strength of 414 GPa (60,000 psi)) reinforcement in both the vertical and circumferential directions.

The veil was cast-in-place reinforced concrete slip-form construction with the concrete placement lift height being 1.5 m (5 ft.). There were a total of 88 lifts in the veil. There were also 90 vertical ribs presumably designed and constructed for the purpose of mitigating wind-induced vortices.

A three-dimensional model of the cooling tower was created using the structural analysis software package SAP 2000 developed by Computers & Structures, Inc. Columns were restrained against translation and rotation at the foundation level since flexibility of the foundation system was not considered in the analysis. Three-dimensional shell elements were used to model the ring beam, veil, and cornice. The columns were modeled with three-dimensional frame elements. A representative image of the finite element model is shown in Figure 1.

Geometrically Imperfect and Out-of-Plumb Models
The as-designed geometry of the cooling tower described in the previous section was modified to simulate deviations in geometry including out-of-plumb and geometric imperfections. Though actual imperfections in geometry on the surface of a cooling tower can be quite complex, simplified scenarios were modeled with guidance on accepted construction tolerances from ACI 117-10 “Specification for Tolerances for Concrete Construction and Materials and Commentary” (3). The scenarios listed below were modeled for this study:
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The tower was assumed to lean in the windward direction above the ring beam elevation. No deviation in plumbness was considered in the columns supporting the veil.

**Geometric imperfections**

- Veil section halfway between ring beam and throat (Figure 3)
  - Increase in diameter by 0.75% (below ACI 117-10 tolerance limit)
  - Increase in diameter by 1.00% (ACI 117-10 tolerance limit)
  - Increase in diameter by 2.50% (above ACI 117-10 tolerance limit)
- Section at throat of veil (Figure 4)
  - Decrease in diameter by 0.75% (below ACI 117-10 tolerance limit)
  - Decrease in diameter by 1.00% (ACI 117-10 tolerance limit)
  - Decrease in diameter by 2.50% (above ACI 117-10 tolerance limit)
- Veil section halfway between throat and cornice (Figure 5)
  - Increase in diameter by 0.75% (below ACI 117-10 tolerance limit)
  - Increase in diameter by 1.00% (ACI 117-10 tolerance limit)
  - Increase in diameter by 2.50% (above ACI 117-10 tolerance limit)

For each of the geometric imperfection scenarios considered deviations were assumed to span a vertical height of 9 m (30 ft), which is about 6 lifts in height, with the maximum deviation in geometry at the sections listed above. In addition, each geometric imperfection scenario was considered to span circumferential angles of 90°, 180°, 270°, and 360° centered on the windward meridian. Between the windward meridian and the boundaries of the imperfection band, deviations from the design geometry were linearly interpolated. This was done to approximate a smooth imperfection and to reduce stress concentrations caused by abrupt changes in geometry.

**ANALYSIS**

The cooling tower models were analyzed under the action of dead and wind loads. Dead loads were generated by the analysis software based on an input density of 2400 kg/m³ (150 lbm/ft³) for reinforced concrete. A wind pressure distribution specific to hyperbolic cooling towers was derived from formulas in the publications, *Wind Effects on Structures* (4), *Handbook of Structural Engineering* (5), and supplemented with information from ASCE/SEI 7-05 “Minimum Design Loads for Buildings and Other Structures” (6) such that the pressures were compatible with the basic wind speeds and topographic conditions at the location of the tower. Figures 6 and 7 present the wind pressure contours associated with a 100 mph 3-second gust wind speed. Stresses due to dead and wind load were combined using the following design load combination from ASCE/SEI 7-05:

\[ 0.9D + 1.3W \]

where,

- \( D \) is the stress due to dead load and \( W \) is the stress due to wind load.

Since the windward meridian of a cooling tower is subjected to the most severe tensile stresses under wind loading, stresses along this meridian were of interest in this study (“Complex Structural Analysis Simplifies Repair Phasing in Restoration of Hyperbolic Cooling Towers” (7)). To investigate the effect of the considered imperfection scenarios on the potential for cracking, maximum principal stresses along the windward meridian were plotted. A tensile strength of 2485 MPa (383 psi or 55 ksf) for the 27.6 GPa (4000 psi) veil concrete, was also plotted to establish a baseline stress beyond which the veil concrete was expected to crack. This tensile strength is the stress corresponding to a strain of 0.0001 in concrete (“Reinforced Concrete, Mechanics and Design” (8)). It was expected that a significant portion of the tower would experience stresses higher than the tensile strength since the load combination considered was at the ultimate limit state. The difference in stress between the geometrically imperfect models and design geometry is however an indicator of the additional reinforcement, if any, that would be required to ensure that the design strength is achieved.

**RESULTS**

**Imperfection in Verticality**

Figure 8 shows results from the out-of-plumb model. It is evident from the figure that an out-of-plumbness within the ranges considered had virtually no effect on the tensile stress distribution along the windward meridian. It is also interesting to note that even at a deviation of 5%, which is significantly higher than the ACI 117-10 tolerance limit of 0.83%, there is only a very slight increase in stress in the bottom region of the veil.

**Geometric Imperfections**

Though analyses for geometric imperfections were conducted for deviations ranging from 0.75% to 2.5% of the diameter spread over a range of 90° to 360° around the circumference, results for the ACI 117-10 tolerance limit of 1% and 2.5% diameter deviation for the 90° circumferential deviations were considered adequate to describe the behavior of the tower for illustration purposes. Figure 9 and Figure 10 show the stress distributions for geometric imperfections of -1% and -2.5% (decrease in diameter), respectively, centered at the throat of the tower. A tensile stress increase of 59% occurred at the throat for the 1% case while the 2.5% case showed an increase in tensile stress of about 250% beyond the tensile stresses in the geometrically perfect model. However, the tensile stress for the 1% case was still below the concrete tensile strength, but in the 2.5% case, there was an approximately 80% increase in tensile stress beyond the tensile strength of concrete. This indicated that imperfections beyond the tolerance limit have a significant impact on the resulting tensile stresses. The plots also show that the circumferential extent...
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of the geometric imperfections did not have a significant impact on the tensile stresses along the windward meridian, especially in the vicinity of the imperfection. However, a general trend toward reduction in tension with increasing circumferential extent of imperfection was noted at locations between elevations 23 m (75 ft.) and 70 m (230 ft.). The trend was more pronounced in the 2.5% case than in the 1% case since the degree of imperfection in the former case was more severe.

Figure 11 and Figure 12 show stress distributions for geometric imperfections of 1% (increase in diameter) at elevation 54 m (178 ft.) (midway between ring beam and throat) and elevation 120 m (393 ft.) (midway between throat and cornice), respectively. One main observation that can be made from comparing Figures 9, 11, and 12 for the 1% deviation case is that the change in stress for the same percentage of imperfection decreases as the location of the imperfection increases in elevation. For the geometric deviation midway between ring beam and throat (Figure 11), the maximum principal stress at elevation 54 m (178 ft.) changed from tension to compression. For the geometric deviation midway between throat and cornice (Figure 12), there was a slight increase in tension at elevation 120 m (393 ft.). While the change in principal stress from tension to compression at elevation 54 m (178 ft.) reduces the likelihood of cracking, it can increase the potential of local buckling.

It was expected that an increase in the magnitude of geometric imperfection would lead to higher changes in stresses at and adjacent to the location of imperfection. This is shown in Figures 13 through 15 for an imperfection extending through 90° in the circumferential direction. The 90° case is shown since it was determined that the circumferential extent of imperfection had negligible impact on the change in stresses (see Figure 9 and Figure 10).

CONCLUSIONS

- The following conclusions can be drawn from this parametric study:
  - Imperfections in verticality (out-of-plumbness) up to 5% of the veil height of the cooling tower above the ring beam have a negligible impact on the distribution of stresses on the windward meridian of hyperbolic cooling towers. Larger deviations of plumbness were not included in this study since it was considered to be beyond practical considerations.
  - Geometrical imperfection in the diameter equal to or beyond specified tolerance limits leads to significantly higher changes in stresses from the baseline state.
  - For repairs to existing hyperbolic cooling towers with deteriorated and spalled concrete, it is advisable to perform a survey of the as-built condition and note the variations in geometry. An analysis should then be done to evaluate the effect of reduction of the concrete thickness of the veil subjected to wind.
  - It is to be noted that in the case of the hyperbolic cooling tower used in the study, the effect of geometric imperfections in the diameter was not significant on the stresses when the imperfection occurs midway between the throat and the cornice. However, midway between the ring beam and the throat geometric imperfections in the diameter had a significant impact of stresses.

- From the analysis performed, it was seen that the stress distribution along the height of the cooling tower did not vary significantly in the windward meridian with increases in the circumferential extent of local imperfections in geometry of 90°, 180°, 270° and 360°.
- Even if no repairs are planned for the thin shell hyperbolic cooling towers, it is suggested that the facility owners should document the plumbness and geometrical imperfections of their existing cooling towers. This will proactively provide an awareness of the susceptibilities or safety of their existing cooling towers when subjected to externally applied loads in their geographical region.

ACKNOWLEDGEMENTS

The authors appreciate very much the discussion on the construction practices in building these massive cooling towers with Dattatray Mahajan of Paharpur U.S.A., Inc. This was very helpful in the authors’ selection of the various geometrical imperfections used in the study in this paper.

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Figure 1. Finite element model

Figure 2. Imperfection in verticality/out-of-plumb

Figure 3. Increase in diameter (bulge) midway between ring beam and throat

Figure 4. Decrease in diameter (constriction) at throat

Figure 5. Increase in diameter (bulge) midway between throat and cornice

Figure 6. Wind pressure contours in PSF (elevation: wind from right hand side)

Figure 7. Wind pressure contours in PSF (plan view: wind from right hand side)
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Figure 8. Stress distribution on windward meridian for imperfection in verticality

Figure 9. Stress distribution on windward meridian for 1% reduction in diameter centered at throat (elevation 329 ft.)

Figure 10. Stress distribution on windward meridian for 2.5% reduction in diameter centered at throat (elevation 329 ft.)

Figure 11. Stress distribution on windward meridian for 1% increase in diameter centered midway between ring beam and throat (elevation 178 ft.)

Figure 12. Stress distribution on windward meridian for 1% increase in diameter centered midway between throat and cornice (elevation 393 ft.)

Figure 13. Stress distribution on windward meridian for 90° circumferential imperfection centered at throat (elevation 329 ft.)
Figure 14. Stress distribution on windward meridian for 90° circumferential imperfection centered midway between ring beam and throat (elevation 178 ft.)

Figure 15. Stress distribution on windward meridian for 90° circumferential imperfection centered midway between throat and cornice (elevation 393 ft.)

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Mohan Krishna Myneni
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Introduction

Just like any other item, structure or system, even cooling tower materials, cooling technologies and cooling tower structures are developed. Cooling tower structures range from wooden structure across concrete structure to steel structure or fiber reinforced plastic (FRP) structure. Even fan unit has history of its own. Fan blade shape, impeller’s hub size and different materials are developed to increase fan impeller efficiency. Integral part of the whole fan unit is a motor. Standard solution includes gear box, driving shaft and motor. But what is standard solution? Today’s trend is to eliminate critical maintenance parts, to be environment friendly and extend total service time. Based on this description standard solution can be slow-running motor, which is directly coupled with fan impeller, where all mentioned advantages are included. Last but not least is the heart of cooling tower – cooling fill. We can discuss both main types – splash or film, several cooling fill materials, cooling fill geometry, flute size and type of sheets connection can be discussed as well.

The point of all aspects mentioned above is to increase cooling tower capability and reduce power consumption.

For cooling tower manufacturers it is always better, if a completely new cooling tower is requested. However, due to economic reasons, some clients ask for cooling tower refurbishment and intensification of cooling process.

RCC cooling tower replacement by steel structure cooling tower

Existing RCC cooling tower

Existing cooling tower was built by Yugoslavian company in 1975, as a compressor cooler for car production plant in Mlada Boleslav, Czech Republic. The structure of double cell cooling tower size 13600mm x 6800mm was made of concrete reinforced by steel as well as both fan stacks. Cooling tower cladding was made from asbestos corrugated plates (Fig.01). RCC fan deck was equipped with monorail hoist, which was used for fan unit maintenance operation. Cooling technology such as cooling fill and water distribution system were made from asbestos corrugated plates or asbestos pipes respectively. Cooling tower basin, partially placed above ground, was not divided into separate cells like cooling tower, but one basin was built for two-cell cooling tower.

Fig.01 Existing RCC cooling tower

Based on client’s review, the original intention was to redevelop civil part of cooling tower and replace existing asbestos cooling fill, water distribution system and drift eliminators. Existing cooling tower basin should be repaired due to water leakage (Fig.02).

Fig.02 Water leakage from basin
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Refurbishment
During the first days of refurbishment, it was observed, that the concrete structure degradation is worse than it had been expected. During cleaning with pressure water, almost the whole steel reinforcement was exposed (Fig.03). Based on this, it was decided to arrange a completely new concrete structure review, which was followed by decision - to replace the existing old RCC structure by a new one.

Advantages of steel structure
- Construction speed
- Easy manufacturing at company production plant
- Low weight of structure, compared with RCC structure
- Long service life – with respect to using modern treatment method
- Easy disassembling of cooling tower – after service lifetime
- Complete recyclable construction – environmental friendly

Temporary Cooling
As mentioned above, double cell cooling tower is used for compressor cooling. Due to this reason, it was not possible to switch off both cells. With respect to this fact, only one cell was switched off and second cell was still under operation. To ensure full-load cooling tower operation, two temporary units of FANS micro coolers type CTF 10 were connected into the cooling circuit (Fig.5). One cooling tower cell together with two micro coolers was able to provide almost the whole cooling capacity. Flexibility is the advantage of FANS micro coolers. This type of cooling tower is very easy to erect and connect because of micro cooler size and its own cool water basin. FANS micro cooler type CTF 10 is equipped with slow running asynchronous motor type PM 8 with 8 kW power output. Standard cooling fill used in this type of cooling tower is 21mm cross fluted channel film type, but cooling fill can be changed with respect to cooling water quality.

Existing cell demolition and basin refurbishment
When the micro coolers were connected into the cooling circuit, one cooling tower cell was switched off. With regard to static and dynamic aspects, this disconnected cell was cut off from the other one, which was still operating. Switched-off cell was dismantled very carefully. At first, fan unit, drift eliminators, cooling fill and water distribution system incl. spray nozzles were dismantled. As depicted on Fig.07, hot water riser was kept almost up to cooling tower inlet. After the cooling technology disassembling, prefabricated RCC fan stack, asbestos cladding and fan deck were dis-
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mantled and demolished (Fig.08) concrete cooling tower skeleton was dismantled beam by beam (Fig.09).

During the whole cooling cell demolition, second cell and common cold water basin were operating normally.

Due to the condition of cooling tower superstructure concrete, testing samples from cooling tower basin were taken (Fig.10). These samples gave us information about the current condition of the basin civil part. Except visible cracks and other small damages, quality of concrete material and reinforcement steel was suitable. Cooling tower basin was completely redeveloped, cracks and expansion joint were repaired (Fig.11). During the refurbishment, redevelopment quality check was done by tear-off test (Fig.12).

Because of different steel structure anchoring, concrete prefabricated blocks by size 800 x 700 mm (Fig.13) had to be prepared and well drilled/fixed to existing concrete foundation blocks (Fig.14). Each of these new prefabricated blocks was equipped with four anchoring bolts dia. 25mm. In order to reach better anchor strength and solidity, well leveled anchoring plate was casted in concrete.
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Steel structure cooling tower

Steel structure, manufactured in company production plant was transported to site, where it was assembled (Fig. 17). Steel elements were put together with high strength bolts. As mentioned above, cooling tower has been replaced part by part. Because of this, central transversal axis of the cooling tower is shifted by 400mm and whole cooling tower structure is asymmetric. Each cell consists of nine columns, where three side columns are identical for both cells.

To speed up the erection, fan deck along with FRP fan stack were preassembled at site workshop and finally placed on cooling tower by mobile crane (Fig. 18).

Cooling tower steel structure including fan deck is treated by hot dip zinc with its own minimal layer thickness 70µm (according to EN ISO 1461 standard).

Some of the cooling technology items such as main water distribution pipes and service construction were installed during steel structure erection. When the structure was ready, preassembled cooling film fill, PVC water distribution pipes, drift eliminators (Fig. 19) and fan unit were installed (Fig. 20). To approach fan-deck, cooling tower is equipped by cage ladder. To enter the cooling cell, service manhole for each cell is placed on fan-deck.
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Conclusion

Due to a very bad condition of RCC structure, existing cooling tower has been replaced by steel structure cooling tower type CTF. Because of compressor cooling, it was not possible to switch off both cooling cells at the same time and whole replacement had to be done during operation. Concrete cooling tower has been demolished cell by cell and replaced by steel structure cells, first cell in June/July 2000 and second one in November/December 2000. Whole cooling tower has been commissioned in January 2001.

Refurbishment of common cooling tower basin was done during 9 days of a complete shutdown.
To arrange full requested cooling performance, two temporary units of FANS micro coolers type CTF 10 were connected to the cooling circuit.

After the refurbishment, steel structure cooling tower has been commissioned for SKO-ENERGO, Mlada Boleslav, Czech Republic and is working satisfactorily from the date of commissioning to present.

References:
[1] www.fansct.com

Special thanks to Mr. Zdenek Dolezal and his team from SKO-ENERGO, Mlada Boleslav, Czech Republic for their kind help and cooperation.

### Table 1. Design Data

<table>
<thead>
<tr>
<th></th>
<th>Original Cooling Tower</th>
<th>Cooling Tower type CTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of erection</td>
<td>1975</td>
<td>2000</td>
</tr>
<tr>
<td>Structure material</td>
<td>concrete</td>
<td>steel</td>
</tr>
<tr>
<td>Water flow per tower</td>
<td>600 m³/h</td>
<td>600 m³/h</td>
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<tr>
<td>Inlet temperature</td>
<td>28°C</td>
<td>28°C</td>
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<tr>
<td>Outlet temperature</td>
<td>25°C</td>
<td>25°C</td>
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<tr>
<td>Wet bulb temperature</td>
<td>19°C</td>
<td>19°C</td>
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<tr>
<td>Cooling fill</td>
<td>Asbestos corrugated plates</td>
<td>PVC film type fill</td>
</tr>
<tr>
<td>Structure loading by cooling fill</td>
<td>840 kg/m²</td>
<td>85 kg/m²</td>
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<tr>
<td>Cell size</td>
<td>6800 x 6800 mm</td>
<td>6050 x 6550 mm (6850 x 6550 mm)</td>
</tr>
<tr>
<td>Fan diameter</td>
<td>4500 mm</td>
<td>4500 mm</td>
</tr>
</tbody>
</table>

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A State-Of-The-Art Chemistry And Thermal Based Toolset For Developing And Optimizing Power Plant Water Balance Models

Daniel J. Robinette, P.E.
Rocky Mountain Water Engineering, Llc

Introduction
The US draws roughly 350 billion gallons of fresh water per day, (Kenny, 2009). Of this 350 billion gallons per day, irrigation consumes 128 billion gallons per day, or 37 percent of the fresh water total. Personal consumption accounts for approximately 30 billion gallons per day (10%) of the fresh water total. But the largest use of fresh water is for thermoelectric-power generation – approximately 143 billion gallons per day (43%), of the fresh water total.

It can be shown that a single 500 megawatt coal-fired power plant equipped with a wet main cooling system will evaporate an amount of water equivalent to that used by 72,000 people (Robinette, 2008). Power plant water consumption was not a serious issue 30 to 50 years ago when many large base-loaded power plants were designed and built to use fresh water or even municipal drinking water as makeup to their main cooling systems. However, it is becoming a serious issue now due to increasing scarcity of fresh water and ever-increasing human population demand for personal use. Because the thermoelectric-power industry is the largest single user of fresh water in the United States, a competition for fresh water has developed between power plants and people.

Power plants are coming under increasing pressure to stop using drinking water and fresh water in their main cooling systems. As a bellwether state, California has essentially banned any new power plants from withdrawing fresh water or drinking water. When fresh water is not available, power plants face the choice of cooling with air, or sources of water with degraded chemistry (water that is unsuitable for human consumption or crop irrigation).

The “heart” of a power plant is the steam turbine-generator. The turbine is driven by high pressure steam that exhausts to the main condenser after its useful energy has been extracted and converted to electricity. The main condenser is a heat exchanger that uses coolant to absorb the large amount of latent heat that is released from the turbine exhaust steam as it changes phase from vapor to liquid. The turbine must work against the backpressure in the main condenser, and coolant properties are one of the factors that affect backpressure.

Water is a better heat medium (coolant) than air for lowering backpressure because it has a higher capacity for absorbing heat and it can absorb a given amount of heat over a smaller surface area as opposed to air. Thus, all else being equal, water reduces the turbine backpressure more than air and requires a smaller condenser. It is therefore the heat medium of choice for cooling a power plant and explains why so many power plants use wet cooling systems. According to the Department of Energy, 100% air cooling is 2 percent less energy efficient, on average, than 100% wet cooling.

Another factor that gives water an advantage over air for cooling a power plant, is that air temperature exhibits greater diurnal swings than water temperature. A dry cooling system becomes less efficient as outside air temperature rises. In very hot weather, air-cooled power plants may lose as much as 25 percent efficiency.

The above reasons explain why water is “in demand” as a power plant coolant, whereas air is usually considered a “last resort” – to be used only if sufficient water cannot be obtained economically. If sources of water with degraded chemistry are available, there is an incentive for power plants to use such water as opposed to air. A new paradigm is emerging where the value of water is increasing relative to fuel which in turn drives water conservation (minimization of consumptive losses). Cases are beginning to emerge where the costs associated with makeup water and wastewater are becoming major budget line items similar to the cost of fuel. In some cases, it may be strategically and/or economically advantageous to use more fuel if the tradeoff is to use less water.

Traditional Water Balance Approach
Traditionally, water balances have been produced by using drawing or flow-charting software that has limited computational abilities. Thus, a traditional water balance requires flow rates and other process variables to be calculated separately using hand calculations or third-party software tools. The results of the calculations are then manually incorporated into the water balance flow diagram by a draftsman that must also enter a table of water flow rate values and other properties for each stream. The finished product has no underlying “intelligence” to adjust to the effects of changing input variables that inevitably differ from the original design basis as time and circumstances change. Clearly, this limits the usefulness of a traditional water balance to a single set of conditions (per drawing),
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- Efficiency can be increased
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Deterioration of the fill is an issue both in terms of money and impact on the environment. Cooling towers which use broken or clogged fills face decreasing efficiency and hence reduced production. Scheduled replacement of the fill is costly; moreover this is a highly polluting intervention which calls for correct disposal procedures. LOLIPAN fills are made of filled polypropylene, are resistant to wear and tear and insensitive to deterioration and dirt.

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LOLIPAN is particularly suitable for counter-flow cooling towers.

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and when conditions change, they become obsolete and updates are usually too expensive and time-consuming to execute.

**Enter the Water Balance Model to Meet the Needs of the New Paradigm**

The methodology for the Water Balance Model (WBM) takes advantage of spreadsheet software to advance the state-of-the-art in water balances far beyond the traditional approach. With the WBM, the user simply “dials-in” a change in variables, and then observes the outcome as the effects of the change cascade throughout the entire water balance - just like it would in the actual plant. This innovative approach makes the WBM a powerful tool.

Unlike expensive commercial software products, the WBM is intentionally designed to “interact” with the user rather than force the user to follow rigid procedures that result in output that the user cannot verify due to the proprietary nature of the software.

The interactive capabilities of the WBM are ideal for conducting “what-if” studies. When used by power plant management, operational, engineering, chemistry and maintenance personnel, the WBM is a valuable tool for optimizing water-related processes, planning and evaluating capital improvement projects, preventing corrosion and fouling, and many more applications.

The value of the WBM is that it enables the user to make the right decisions for minimizing operational, maintenance and capital costs while maximizing reliability and extending the life of the plant – especially when the plant is forced to use less water, and/or, water of degraded quality relative to fresh water.

**The Importance of the Water/Thermal Connection (Water/Energy Nexus)**

Water and energy are inextricably linked in that it requires energy to pump and treat water, and it requires water to produce energy. This water/thermal connection is best exemplified by three interconnected components that comprise the “heart” of a Rankine cycle power plant – the Power Cycle, Condenser and Cooling Tower. The Power Cycle uses steam to drive the turbine which produces useful work from the energy transported by water/steam throughout the cycle. Figure 1 shows a diagram from the Rankine Power Cycle module that is part of the water balance modeling toolset. Figure 2 shows the Condenser which removes the waste heat from the turbine exhaust steam thereby causing a phase change to occur. Once again, water is the heat medium for this energy transfer. Figure 3 shows the simultaneous heat and mass balance from the Cooling Tower module while Figures 4 and 5 show the Merkel curves and design and characteristic curves respectively. The calculations are in accordance with Cooling Technology Institute guidelines. The cooling tower dissipates the waste heat from the condenser to the atmosphere primarily by evaporation which is a consumptive loss of water.

**The Importance of Standardization**

The concept of water balance standardization evolved from the author’s development of numerous water balances from which the observation was made that almost all power plants have a need for certain types of water such as raw water, service water, cooling water and high-purity water. Likewise, all plants that use water usually generate wastewater. It is apparent that these functional categories of water are based on water chemistry specifications, thus, it is water chemistry that drives the water balance design. Furthermore, by grouping similar functional categories of water together, a standardized water balance could have a consistent look and feel that would facilitate comparison of one standardized water balance to another. Any differences between the water balances that are being compared can then be examined in more detail and might lead to valuable discoveries relative to water conservation or cost minimization opportunities.

This ability to compare standardized water balances is demonstrated by Figures 6 and 7 that are positioned vertically on the page to facilitate a top-to-bottom comparison of the two water balances that are depicted.

**About the Standardized Water Balance Diagrams.** The standardized water balance diagrams given in Figures 6 and 7 represent two different power plants with all of the individual water production and consumption equipment at each plant categorized and “summed-up” into common process areas (blocks on the diagrams). These blocks are based on a particular function that alters water chemistry such as a Cooling Tower. Each block on the diagram represents one or more underlying modules that are linked to it from the WBM, so it is possible to “drill down” to view the individual modules if additional detail is needed.

In addition, water chemistry is taken into account by using color-coding to indicate the Total Dissolved Solids (TDS) concentration of the streams leaving each particular block. Underlying “Streams Modules” capable of complex chemistry calculations are used to track the TDS as well as other water chemistry parameters.

In a standardized water balance, the major flow paths are always from left-to-right and top-to-bottom. Thus, the makeup water enters in the upper left quadrant and the outfall leaves in the lower right corner of the diagram. TDS concentration for the streams leaving a block is indicated by the color within each particular block as referenced to the TDS/color legend shown on the right side of Figures 6 and 7.

**Water Balance Comparison.** By comparing Figures 6 and 7, it can be observed that both plants have essentially the same level of TDS for influent water, but there is a wide difference in outfall TDS concentration between the two water balances. This difference in outfall TDS naturally segues into the question of; which plant is the most water reuse efficient? To answer this question we must examine the differences between the two water balances, and then apply two water conservation efficiency parameters known as “Cycles of Operation” (COO) and “Recovery%”. These parameters are analogous to the master variables of “Cycles of Concentration” (sometimes referred to as concentration ratio) that is commonly used in evaporative cooling processes such as cooling towers, and “Recovery” which is common terminology for membrane processes such as reverse osmosis.

**Benchmarking Differences in Figures 6 and 7.** It can be observed that the left half of the diagrams shown in Figures 6 and 7, or front-end of the plants, show the “low TDS” water production areas, while the right half of the diagrams, or back-end of the plants show the “high TDS” or wastewater handling facilities. A visual comparison of Figures 1 and 2 reveal several significant differences:

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2. PP1 has facilities for treating and recovering wastewater (as indicated by a recycle stream) while PP2 does not.

   Note: The Membrane-Based Water Recovery System (MBWRS) at PP1 was shut down when Figures 6 and 7 were made.

3. PP1 discharges to a river while PP2 discharges to a sewer. This seemingly minor difference has important implications with respect to environmental regulations that govern discharge constituent concentration.

Water Conservation/Reuse Efficiency. We shall now quantify the degree to which water is reused within a site water balance using the water balances depicted in Figures 6 and 7 and the parameters of COO and Recovery%.

\[
Recovery\,\% = \left(1 - \frac{1}{COO}\right) \times 100
\]

For Direct Discharge power plants, Cycles of Operation (COO) is defined as the total flow rate of all water streams into the plant divided by the total flow of liquid water leaving the plant.

For Zero-Liquid-Discharge power plants, COO is the total flow rate of all water streams into the plant divided by the sum of flow rates of all liquid streams destined for final disposal of wastewater (evaporation ponds, drum dryers, dry scrubbers, etc.).

As mentioned previously, COO is analogous to the master variable “Cycles of Concentration” (COC), in a cooling tower or boiler. Like COC, the higher the value of COO, the more the water is reused within a plant, which in turn reduces source water consumption.

“Recovery” (expressed as a percentage) is related to COO as follows:

Where: COO is the cycles of operation as defined above, and Recovery% is a measure of the extent to which water is internally recycled within a plant with 100% being the maximum possible.

Based on the normalized ("n") flows, the COOs for the power plant water balances shown in Figures 6 and 7 are 9.7 (90% recovery) and 5.1 (80% recovery) for PP1 and PP2 respectively. Thus, it can be concluded that PP1 is using water more efficiently than PP2 and the main difference is that cooling tower blowdown is being reused in the flue gas desulfurization systems at PP1, but is directly discharged at PP2.

It is interesting to note, that PP1 would achieve COO of 28.1 (96% recovery) if the MBWRS were brought on-line.

The Importance of Water Chemistry

Water is known as the “universal solvent” because it has the unique ability to dissolve a large number of different substances and can hold a large amount of soluble salts in solution. This latter ability is characterized by salinity, or total dissolved solids concentration and depends on the types of salts in the water. Figure 8 shows salinity levels for various categories of water. As a point of reference, seawater is shown at its typical TDS level of 35,000 mg/L, but pales in comparison to the amount of TDS in a saturated solution of sodium chloride. Hyper-saline salts would be loosely defined as those that are more soluble than sodium chloride such as magnesium chloride and calcium chloride.

Referring to Figure 8, it can be seen that Reclaimed Water (tertiary treated municipal wastewater) is approximately one order of magnitude more degraded in quality than Municipal Drinking Water. Similarly, seawater is two orders of magnitude more degraded than Reclaimed Water and three orders of magnitude more degraded than Municipal Drinking Water.

As one might expect, the cost of using water in industrial applications increases with TDS content. Figure 9 illustrates this point by showing the results of an economic analysis that was conducted for a southeast cogeneration plant and reveals that O&M costs increased in proportion to TDS (over a range from 0 to 2,000 mg/L TDS).

This adverse impact of TDS on plant economics is caused by the changes in water properties that are brought about by the dissolved salts, such as increasing the corrosivity to equipment and slowing reaction kinetics that make it more expensive to purify water as TDS increases. From practical experience we know that when the salinity level reaches that of seawater, the water is devalued to the point that one of the few practical industrial applications seawater is used for is non-contact cooling water.

Economic issues aside, the extent to which a power plant can internally recycle (conserve) water is ultimately dictated by water chemistry of which salinity is a large part. As a general rule, as the TDS of the source water entering a plant increases, the ultimate COO and Recovery% decrease.

Conclusion: In order to optimize a water balance for the greatest possible water reuse, water chemistry is a key variable and must be included in the analysis.

Case History Demonstrating the Importance of Chemistry

In November of 2008, a combined cycle power plant equipped with air-cooled condenser and brine concentrator, was forced to dispose of concentrated brine by way of a hazardous waste disposal site at a cost of approximately $1 per gallon. This expensive means of disposal was necessary because the Rotary Drum Dryer that was built with the plant had suffered major mechanical problems and was out-of-service on a semi-permanent basis. As a short-term fix, the plant (located north of Las Vegas) had installed two 32’ x 60’ Solar Tanks of plastic construction to hold the brine. The intention of using the open tanks was to reduce the wastewater volume through evaporation. However, it was discovered that the brine stopped evaporating and never reached complete dryness even after long periods of exposure to the sun and without fresh brine inflow.

After a year or two, the solar tanks started to leak, and because they were considered temporary, no secondary containment had been installed. In the short-term, the leaks in the solar tanks were patched, and plans were made to replace the solar tanks with permanent solar evaporation ponds. An accurate Water Balance Model (WBM) was developed for the plant, in support of the evaporation pond effort. The water balance would be used to quantify the solids and liquid flow rates upon which the new evaporation ponds would be sized.

Since the evaporation of concentrated brine in the solar tanks had apparently stopped, and the same phenomenon might occur in the new solar ponds, an investigation to determine the root cause of the problem was conducted.

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the brine in the solar tanks had stopped evaporating. One of the papers was a study at the Bonneville Salt Flats (Turk, 1970), and the other described a study of evaporation at The Dead Sea (Oroud, 1994). Both papers essentially concluded that concentrated brine would stop evaporating if when the specific gravity reaches 1.37. In order for the specific gravity to reach that level, salts must be more soluble than sodium chloride. Magnesium chloride is such a salt, and it was found that the source water used at the site has an abundance of magnesium and chloride. Thus, it was concluded that the hyper-soluble salts had resulted in an increase in brine specific gravity that slowed-down and eventually stopped the brine from evaporating under normal solar insolation (radiant energy from the sun).

This inability to evaporate past a specific gravity of 1.37 would be expected to leave a “heel” of concentrated brine in the new solar ponds which would have to be sized to account for the brine accumulation. An engineering design and cost estimate for the new Solar Ponds was completed, and it was found that the ponds would be much too extensive to retrofit into the existing plant. Thus, a decision was made to cancel plans for the Solar Ponds in favor of re-commissioning the RDD.

It can be concluded that the presence of highly soluble salts was a “fatal flaw” in the design of the solar evaporation ponds at this particular site. The major lesson learned was to always take water chemistry and its impact into account when designing a major capital project.

The Importance of Climate

To build an accurate water balance model, accurate climate data must be used. A climate change study was recently completed for the Las Vegas and Tucson areas using downloaded weather data from the National Climatic Data Center. For the Las Vegas area, it was found that both dry bulb and wet bulb temperatures have changed significantly in the past 10 years as compared to previous periods of record (see Figures 10a & 10b). However, this was not the case for the climate of Tucson which showed virtually no climate change (see Figures 11a and 11b).

Referring to Figures 10a and 10b for Las Vegas, the average deviation of the 2001-2008 dry bulb temperature data from the two previous Periods of Record (PoR) show that dry bulb temperature is 2.6 to 3.8 degrees warmer. Moreover, the “bulge” that has developed in the normally “bell-shaped” curve for the months of April and May, suggests that winter has become shorter, and spring arrives earlier than in the past.

These warmer temperatures for Las Vegas have a large cumulative effect on consumptive water demand for evaporation processes such as cooling towers and evaporative coolers as demonstrated by Figure 12.

To assure accuracy in water balance models, local hourly dry bulb and dew point temperatures for the most recent ten years (8,760 readings per year) should be downloaded. Hourly data is necessary to characterize evaporation from intermittent evaporative processes such as combustion turbine evaporative coolers that, as a rule, only operate when temperatures are above 60 deg F. Visual Basic for Excel (VBE) subroutines coupled to a “psychometric calculator” workbook can then be used to calculate the wet bulb temperature and relative humidity (from dew point and dry bulb temperatures).

For plants that do not have intermittent evaporative cooling processes, monthly average climate data for the most recent 10 year period-of-record is sufficient.

Water Balance Modeling Toolset

As might be expected, the WBM requires information that sets the basis for its calculations. It also requires physical and chemistry property information for water and air. How this is handled by the WBM is described below.

User Friendliness

There are three primary features that make the WBM easy to use and understand:

1. A model operates much like the actual plant and that imparts an intuitive familiarity with cause-and-effect,
2. Microsoft Excel is used as the all-in-one development and operating platform and most technical and operations personnel are already familiar with Excel which has become a “standard” for workplace computers, and
3. As mentioned previously the WSM is intentionally designed to foster greater understanding of the power plant water balance and underlying modules by working interactively with the user rather than producing output that the user is not comfortable with.

The Advantages of Excel. Excel is the best software product available for producing WBM applications because it contains both the drawing tools and computational capabilities that are necessary to build, run and maintain sophisticated models. Other “flow-charting” type programs such as Visio and AutoCad contain drawing capabilities, but they come up short in the ability to perform complex mathematical calculations that are necessary for process modeling. Process simulation software such as Aspen and OLI could be used, but these types of programs are very expensive compared to Excel and usually do not support the type of water chemistry calculations that are needed (they are geared towards non-water applications). Commercial simulation software is also complicated and difficult to use as compared to Excel – especially for chemistry calculations.

Excel offers the advantage of being able to locate notes and calculation results near the streams and equipment images that they pertain to. Another advantage of Excel over other commercial software is the ability to program and use time-saving Visual Basic for Excel (VBE) macros. The VBE language is included in Excel for no additional cost.

There are also many Excel add-ins available for no charge such as steam tables developed by The International Association for the Properties of Water and Steam (IAPWS). Excel is also very well documented and there are numerous reference books available that contain pre-programmed mathematical algorithms in the form of Visual Basic for Excel (VBE) procedures.

Since most technical and operations personnel already have a basic working knowledge of Excel, it is easy for WBM users to come up to speed on a WBM very quickly – especially when automation is included in the form of VBE subroutines.

Figure 13 shows an example of the Main Block Diagram (MBD) from a completed model for a combined cycle plant. Figure 13 shows an assemblage of blocks that represent individual process modules and provides an overview of the entire model. Adjacent
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to Figure 13 in the actual WBM, are the parameters which control
the WBM such as links between the blocks shown on the MBD and
individual process modules, diagnostics and additional information
that is necessary to run and evaluate the WBM. These features can
be thought of as the “control hub” for the entire WBM.

As exemplified by Figure 13, each diagram has the capability of
displaying three operating scenarios that are commonly needed for
water balances: 1) normalized annual average, 2) peak, and 3) user-defined operating conditions. Figures 14a and 14b show the
output reports that are linked to the MBD, while Figure 14c depicts
the streams properties table that is linked to the Streams modules. Optional “what if” equipment is depicted in dotted lines.

Figure 15 shows an example of an individual module – in this case,
the Brine Concentrator module.

**Process Modules**
The WBM features numerous modules that are linked together
to give the model intelligence. Major modules that are currently
available are listed below.

**Water/Thermal Connection**
- Power Cycle (Rankine, Brayton, and Combined)
- Condenser (Steam)
- Cooling Towers (Conventional and Hybrid)
- Cooling Lakes, Ponds and Canals

**Water Chemistry**
- Streams (water chemistry, diagnostics, saturation ratios via built-in equilibrium model, scaling indices)

**Fuel Usage and Flue Gas Desulfurization**
- Boiler Furnace (combustion calculations)
- Flue Gas Desulfurization Absorbers (with many variations)
- Gypsum Plants for FGD

**Water Treatment Processes**
- Lime Softening (with many variations)
- Filtration (many variations)
- Reverse Osmosis
- Ion Exchange
- Vapor Compression Evaporators
- Vapor Compression Crystallizers
- Solar Evaporation Ponds

**Economic Evaluation**
- Life Cycle Cost (Capital Recovery Method)

**Diagnostics**
- Mass Balance

**Miscellaneous**
- Piping Network Simulation (Hardy Cross Method)

**Properties of Moist Air**
The psychrometric properties of air are provided by a workbook (block) that performs psychrometric calculations that are based on
an algorithm published by the American Society of Refrigeration
and Heating Engineers (ASHRAE Technical Committee 1.1 Thermodynamics and Psychrometrics).

**Water and Steam Properties**
The properties of water and steam are provided by an add-in that runs as a set of Visual Basic for Excel functions. The add-in calculates enthalpies and other properties of water and steam based on
temperature and pressure inputs.

**Water Chemistry Equilibrium Model**
A spreadsheet based equilibrium model is available for use with
the WBM Streams Modules. It is very useful for predicting and
quantifying the amount of a mineral species that will form within
the streams that are being simulated. The equilibrium model is based on the public domain code available from the U.S. Geological Survey known as WATEQ4F (Ball, 1991).

For those that have used expensive commercial equilibrium models,
the non-proprietary equilibrium model will be much appreciated.
It has a very large database of minerals and can be customized as
needed.

**Potential Uses of WBM and Return on Investment**
Potential uses of the WBM are virtually unlimited due to the large library of process modules that have been developed since Excel
1997 became available. Below are some potential uses of the WBM
that provide a return on investment.

- Boiler Combustion Efficiency Monitoring
- Condenser Performance Monitoring
- Cooling Tower Performance Monitoring
- Generic Chemical Treatment Program Design
- Diagnostics and Troubleshooting
- Green House Gas Emission Calculations
- Life-Cycle Cost and Technology Evaluations
- Problem-Solving and Optimization
- Water Systems Management

A WBM can vary in complexity from a relatively simple “block diagram” type that only provides underlying modules for a few
of the blocks (uses industry standard defaults instead) and has no stream TDS color-coding, to a level of sophistication that includes
underlying process modules for every block and stream arrow. In
general, the more detailed a model is, the more capability and po-
tential for cost savings there are.

It has been found that the initial investment for developing a cus-
tomized WBM for a plant typically pays for itself in several ways:
1) by avoiding unnecessary costs – the WBM is a valuable tool for
making more accurate decisions on equipment size and selection, 2) by minimizing O&M costs – the WBM allows individual processes
to be optimized and problems to be detected and solved, and 3) by
minimizing capital expenditures – the WBM can be used to plan
ahead and evaluate equipment alternatives.

**References**
ASHRAE Technical Committee 1.1 Thermodynamics and Psy-
If the cooling water temperature drops by 1°C, the refrigerator can get 6.5% Energy Saving. The high-performance cooling tower provides a remarkable reduction of operating cost and effective performance of the refrigerator.


**Figures**

![Figure 1a. Rankine Power Cycle Module – Mass and Heat Balance (“Ladder” Diagram Format)](image)

![Figure 1b. Regenerative Rankine Cycle – Thermal Cycle Analysis](image)

![Figure 2. Condenser Module](image)
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Figure 9. Cost Increase Caused by Salinity at ZLD Cogeneration Plant

Figure 10a. Las Vegas Dry Bulb Temperature

Figure 10b. Las Vegas Wet Bulb Temperature

Figure 11a. Tucson Dry Bulb Temperature

Figure 11b. Tucson Wet Bulb Temperature
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Figure 12. Increased Evaporation Caused by Climate Change

Figure 13. Water Balance Model Main Block Diagram

Figure 14a. Example of Water Balance Model Output in Process Flow Diagram Format for Reporting Results (Sheet 1 of 2)

Figure 14b. Example of Water Balance Model Output in Process Flow Diagram Format for Reporting Results (Sheet 2 of 2)

Figure 14c. Sheet 3 of Process Flow Diagram Streams Properties Table

Figure 15. Brine Concentrator Module
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How “Green” Is The Cooling System

Roy Holliday, Gary E. Geiger and Peter Geuns
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ABSTRACT
Design, operation and treatment of cooling systems can encompass many techniques to fulfill both the desires of Industry and Management to improve its environmental image. Environmental impact reaches much further than the “greenness” of a given cooling water treatment chemical in the discharge from a cooling system. When assessed in depth, traditional chemicals or treatments may be “greener” than conventionally imagined or portrayed. Non-Chemical Devices (NCDs) have great appeal when talking of the impact of treatment chemicals. Marketing of some treatment chemicals emphasizes their biodegradability. Some aspects of environmental impact of various approaches to the design, operation and treatment of open evaporative cooling systems are discussed.

1. FACTORS AFFECTING THE ENVIRONMENTAL IMPACT OF COOLING SYSTEMS
There are many approaches that can be implemented in order to reduce or minimize the environmental impact of an open evaporative cooling system. However, it is practically impossible to accurately assess and/or quantify the total impact of a cooling system upon the environment. The first thing that many people envisage as potentially affecting the environment is the chemicals used for the treatment of the cooling water. However, other factors that must be taken into account are the design and operation of the cooling system.

1.1. Design of the Cooling System
Most industrial cooling systems are of an open evaporative system design with a cooling tower providing the majority of the heat dissipation. Additionally, once through and closed cooling water systems are employed, depending on the availability of water and process considerations. Of the three, the lower environmental impact would be expected to be from a closed cooling system design. This is correct from the water consumption, water and chemical discharge for a fin-fan, radiator or dry cooling tower type design, provided they are without leaks. Other designs dissipate the heat from a closed cooling system through a water to water heat exchanger, whereby, ultimately the heat dissipation is through a secondary once-through or open evaporative cooling system, in which the main environmental impact is that imposed by the secondary system. As the name implies, once-through cooling systems use water from a river, lake or the sea as the heat sink and return the hot water to the source.

An example of the difference in water consumption between an open evaporative and once-through cooling system is illustrated in Table 1. The once-through cooling system would use or consume 80 times more water than the open evaporative cooling system. In theory, a primary closed system should not consume any significant volumes of water on a consistent basis. However, since the dissipation of heat is only by sensible heat loss with air, through a metal wall, the heat transfer area required is significantly higher than open evaporative system, and the footprint of the system consequently greater.

Selection of metallurgies within the system is often based on operational requirements, process side compatibility, corrosion resistance, heat transfer properties, and cost of equipment in various metallurgies. However, the favored metallurgy for industrial applications is low carbon steel (LCS). Particularly for heat exchangers, metallurgy can influence environmental impact. The impact will mainly be associated with the discharge of corrosion products and the treatment chemicals used to retard corrosion. An example is copper from corrosion of copper or copper alloys. In some applications or parts of the world, the copper concentration in effluent is regulated. If a system were entirely constructed of corrosion resistant material such as stainless steels, titanium and/or plastic, then there may be no need to include corrosion inhibitors in the cooling water treatment program. Nevertheless, some chemical treatment of the cooling water may still be required to control scaling, deposition and microbiological activity.

With an open evaporative cooling system the material of construction of the cooling tower can have a potential impact. Historically, towers and packing were made of wood, which had to be chemically treated to prevent fungal attack. The wood used to be impregnated with a copper/chrome/arsenate combination, which today is not the normal practice because of the environmental impact of the chromium content. Nevertheless, this has to be taken into account when disposing of wood from towers containing wood previously treated in this manner. Similarly the use of asbestos cement board (ACB) is no longer practiced, but presents a concern for safe disposal. Plastics are now commonly used, particularly for cooling tower packing or fill. Fiberglass is replacing treated wood as the material of choice for the cooling tower. This can also impact the environment in relationship to manufacture, non-renewable raw material source, and disposal.

1.2. Operation of the Cooling System
From an environmental point of view the main elements of operational significance are operating time, make up water quality, point of blowdown discharge and any effluent treatment applied, and, in the case of an open evaporative cooling system, operating hydraulics of the system. Operating time and evaporation rate are dictated by the: plant, process, production, heat load and design and/or process requirements. Water usage is a function of the design or type of the cooling system and, in the case of an open evaporative system, the evaporation rate and cycles of concentration at which the system is operated.

1.3. Treatment of the Cooling Water
Corrosion, scaling, fouling and microbiological activity need to be maintained under control and at an acceptable level in order to maintain production efficiency and avoid unscheduled outages. A traditional chemical treatment program typically consists of a corrosion inhibitor(s), scale inhibitor(s), dispersant(s) and biocide(s). Environmental impact depends upon the ecological properties and toxicology of the individual chemicals used and their possibly interactions. Other specific parameters such as Adsorbable Organic Halides (AOX), phosphorus and nitrogen content and other param-
Polyaspartic Acid (PASP) and Carboxymethyl Inulin (CMI) have exhibit some degree of biodegradability. Two products, namely inhibitors are generally organic compounds and hence potentially been considered and/or promoted for chemical treatment of cooling radation routes. Some biocidal actives commonly used may be rendered less toxic or biocidal by neutralization, hydrolysis, oxidation, or other deg-}

A biodegradable biocide is somewhat of an oxymoron. However, some biocidal actives commonly used may be rendered less toxic or biocidal by neutralization, hydrolysis, oxidation, or other deg-}

In some parts of the world, the use of chromate as a corrosion inhibitor in open evaporative cooling systems has ceased. When used in a closed system the major environmental concern is related to leaks and drainage during maintenance work. If used in an open evaporative system a chromate removal system would typically be used to remove chromate from the blowdown prior to discharge from the cooling system. However there is still a discharge of water containing chromate into the environment through windage, drift and leaks. The chromium removed in the chromate removal system also needs to be disposed of, this in itself also potentially impacting the environment. Nevertheless, the elimination of chromate from the majority of cooling water treatments applied globally over the past few decades is probably one of the greatest efforts taken to reduce the environmental impact of cooling water treatment programs. Over a slightly longer timeframe, the use of certain types of persistent biocides, such as mercury compounds and chlorophenols, have also been eliminated, again drastically reducing environmental impact. Although some biocidal materials are known to have a bad impact upon the environment, tributyltin oxide (TBTO) being one example, they are still used in treatment programs in some parts of the world. And now one comes to an important fact when considering green cooling water treatment programs, costs. In general, green options tend to be more expensive. A balance between costs and payback for a green program often limits the choice or use of more environmentally friendly programs unless dictated by discharge regulations, or the cost associated with effluent water treatment.

2. BIODEGRADABLE CHEMICALS

An approach to reduction of environmental impact can be the use of treatment chemicals that are biodegradable.

Carbon steel corrosion inhibitor programs often include inorganic inhibitors such as zinc, phosphate or molybdate, either alone or in combination. Organic molecules can also be used as corrosion inhibitors, which, by virtue of their organic nature or structure, may exhibit some degree of biodegradability. However, these can be relatively weak as corrosion inhibitors and require high concentrations or supplemental additions of inorganic inhibitors. For inhibition of yellow metal corrosion, organic triazole (azole) compounds are traditionally used.

A biodegradable biocide is somewhat of an oxymoron. However, some biocidal actives commonly used may be rendered less toxic or biocidal by neutralization, hydrolysis, oxidation, or other degradation routes.

The most common area where biodegradable compounds have been considered and/or promoted for chemical treatment of cooling water is for deposit control, more specifically scale inhibition. Scale inhibitors are generally organic compounds and hence potentially exhibit some degree of biodegradability. Two products, namely Polyaspartic Acid (PASP) and Carboxymethyl Inulin (CMI) have for some time been promoted as biodegradable molecules that are calcium carbonate scale inhibitors. These molecules occur in nature. PASP is a polyanodic protein residue, which, in nature, interacts and modifies inorganic crystallization. PASP is synthesized rather than extracted from natural sources. CMI is a naturally occurring polysaccharide used by some plants to store energy and is typically found in roots of the plant.

There are various methods that can be used to determine the biodegradability of a molecule. However, data using such specific methods is often not available since the tests have not been performed. One method of estimating relative biodegradability is to compare the Biological Oxygen Demand (BOD) with the Chemical Oxygen Demand (COD). Both are typically reported as milligram of oxygen per gram (mg O2/g), and the biodegradability can be estimated using equation below.

Essential criteria are that the treatment chemicals are also effective in performance and acceptable application cost.

There are two main concerns with respect to using readily biodegradable materials in cooling water treatments. The first is the loss of active concentration and therefore efficacy of the molecule as biodegradation occurs, thereby requiring higher applied dosages, and subsequently higher cost, in order to maintain an effective concentration. The second is the effect upon microbiological growth and activity within the cooling system. Increased microbial activity may require the use of additional biocide(s) to control biofilm formation. This can increase treatment costs and environmental impact.

Therefore, as appealing as the use of biodegradable chemicals may be for the treatment of cooling water, several factors other than the degree of biodegradability need to be taken into account.

3. COMPARATIVE EFFICACY OF SCALE INHIBITORS

As previously indicated, there are several organic chemicals that exhibit efficacy as scale inhibitors, in particular calcium carbonate scale inhibitors. By virtue of their organic structure it is possible that they are biodegradable to some degree. Some molecules are claimed to be biodegradable and are specifically marketed under this banner. In some instances this raises an interesting question as to whether the biodegradability is a property of the main active component or of byproducts or contaminants acquired during manufacture. The intention of this project was to look at efficacy of molecules recently introduced into the market as being biodegradable, and compare their performance and environmental profile with readily available traditional scale inhibitors that are commonly used.

The efficacy of various recognized calcium carbonate scale inhibitors was tested using a Bench Top Unit (BTU) as shown in Figure 1, which evaluates synthetic cooling water under dynamic heat transfer conditions. For these studies the BTU utilized a 316 grade stainless steel heat exchanger tube with a skin temperature of 60°C. The water velocity was maintained at 1 m/s (3.3 fps) and the half-life of the system was 1.25 days. The chemistry of the synthetic cooling water is given in Table 2. Orthophosphate, 2.5 ppm as PO4, was included to provide some minimal corrosion inhibition of low carbon steel, and 7 ppm of a sulfonated acrylic terpolymer (SAT) incorporated as a calcium phosphate inhibitor. The relative scale/precipitation inhibition efficacy of the inhibitors was determined by increasing the pH of the treated cooling water to a point where calcium carbonate precipitation or deposition occurred. This was judged by observation of the heat exchange tube and by reduction of calcium and alkalinity concentrations, and subsequently pH, of the recirculating water.

The Langelier Saturation Index (LSI) of the cooling water chemistry
at which failure occurred, namely deposition of calcium carbonate, was calculated and used as an evaluation of efficacy of the inhibitor. The scale inhibitors evaluated and their active concentration are given in Table 3. Results of the evaluations are summarized in Table 4 and illustrated in Figures 2 and 3. Table 6 provides the relative performance rating in order of decreasing performance.

The corrosion rate of low carbon steel, copper and admiralty brass (ADM) was measured by weight loss techniques using corrosion coupons. The objective of this was to determine if the scale inhibitors had any significant influence on corrosion. Some of the scale inhibitors evaluated are known to have corrosion inhibition properties, although the concentration required for corrosion inhibition is typically higher than that used for scale inhibition and that used in these studies. Therefore, the prime objective of these studies was to assess the relative impact of the molecule on the corrosion potential of the treated cooling water. Theoretically, the increase in pH and approach to a point of calcium carbonate deposition would be expected to reduce the corrosion rate of low carbon steel in any case. Corrosion rate data are summarized in Table 4 and relative performance rating is provided in Table 6, in order of decreasing performance. Photographs of corrosion coupons exposed in the evaluations are shown in Figures 4.1 through 4.14. These show the condition of the coupon as removed at the end of the evaluation and after processing and cleaning.

In practice, in a system containing copper or copper alloys an azole would be included for corrosion inhibition of yellow metals. These evaluations deliberately did not include an azole in order to evaluate the effect of the inhibitor of yellow metal corrosion.

A baseline corrosion rate for untreated water was not possible since excessive calcium carbonate deposition would occur immediately in the absence of a scale inhibitor.

### 3.1. Environmental Profile of Treatment Chemicals Evaluated

Although “biodegradability” is one motivating factor in reducing the environmental impact of a cooling water treatment program, other factors or constraints may be considered and in some parts of the world. One factor that is particularly pertinent to many conventional calcium carbonate inhibitors is phosphorus content. Historically sodium hexametaphosphate was used as a calcium carbonate inhibitor. In the early seventies organic phosphorus compounds (phosphonates) became popular as calcium carbonate inhibitors, being highly effective and not suffering the hydrolysis and reversion to orthophosphate experienced with sodium hexametaphosphate. The use of zinc with phosphorus-based corrosion and scale inhibitors can also impose discharge limitations, since zinc is regulated as a heavy metal in many parts of the world. Nitrogen content may also be of concern in some applications. Of the scale inhibitors studied, Aminotrimethylene Triphosphonic Acid (ATMP) and Diethylenetriaminemethylene Pentaphosphonic Acid (DTPMP) are the only molecules that contain nitrogen, each containing 5% N. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) of molecules used in cooling water treatment programs, and/or of the overall treatment program, are other parameters that may also be of concern with Local Water Authorities. Where available, relevant data on these parameters for the scale inhibitors studied is given in Table 5. One has to be aware that data provided by suppliers or manufacturers generally relate to the commercial product supplied, which is often an aqueous solution of the active component, as opposed to the pure active component. Therefore the concentration of active component within the commercial product must be taken into account. Similarly, as mentioned before, the published biodegradability is that of the solution, which may contain impurities or contaminants which are also biodegradable or that may be the sole biodegradable content of the commercial product.

There are several protocols used to assess biodegradability and BOD and the results obtained from different test procedures are not necessarily comparable. This sometimes makes it difficult to compare the biodegradability of a range of molecules.

Over the past few years halogen or chlorine stability has become an issue with respect to marketing of cooling programs and/or components. This can be applied to calcium carbonate inhibitors, phosphonates in particular. From an environmental aspect degradation of a compound during halogenation can reduce efficacy of the molecules and/or require higher concentrations to be applied in order to compensate for their loss. The classification or judgment of halogen stability of a compound is often taken as a simple “It is” or “It is not” halogen stable, in many cases the relative degree of stability is ignored or infrequently stated. However, no standard protocol is available to assess halogen stability so it is difficult to compare relative stability from published material. Phosphonates are generally regarded as “not halogen stable”. Aminotrimethylene Triphosphonic Acid (ATMP), Diethylenetriaminemethylene Pentaphosphonic Acid (DTPMP), and Hydroxyphosphono Acetic Acid (HPA) are significantly degraded by chlorine. Hydroxyethylene Diphosphonic Acid (HEDP), Carboxymethyl Inulin (CMI), and to a lesser extent Polyaspartic Acid (PASP), are moderately resistant to chlorine and, although not totally halogen resistant, Phosphonobutane Tricarboxylic Acid (PBTC) and Phosphonocarboxylic Acid Mixture (PCM) have a fairly good resistance to degradation by chlorine. The other inhibitors studied would typically be regarded as halogen stable.

Although the major part of the environmental impact of concentrates on the Environmental Fate and Effect of the molecule, the manufacturing process and basic raw materials should also be considered in the broader picture. Certainly from the renewable raw material aspect, CMI, which is derived from roots of the chicory plant, Cichorium intybus, and classed as a “biopolymer”, is very favorable.

### 3.2. Comparative Treatment Costs

It is difficult to accurately compare cost of the various molecules evaluated. The price of the commercial product offered by the supplier or manufacturer largely depends upon annual volumes purchased and possibly other commercial agreements. The cost of the active compound will depend upon the price offered and concentration of the compound in the commercial product. Low active concentration materials will incur higher costs for transportation and the container than that of high active concentration products. Concentrations of actives applied in the evaluations were very much comparative “ball park” concentrations. Actual treatment costs may be lower if the concentration was optimized and the applied concentration required in practice was less than that used for the evaluations.

The total cost of chemicals used to construct and apply the appropriate treatment program will normally include the cost of corrosion inhibitors, polymers and those required to control the microbiology of the cooling system. As such, the individual cost of the scale inhibitor would normally be a relatively small contribution to the overall treatment cost. A scale inhibitor that permits a cooling system to be operated at higher cycles of concentration (higher concentration factor) would typically reduce operating costs by virtue of lower water usage and discharge.

However, for the purpose of comparative cost effectiveness of the inhibitors, the contributory cost of the inhibitor at the concentration applied in the studies has been calculated. The comparisons have
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been made based on three categories. These are related to relative cost of the active inhibitor component, cost related to concentration used and maximum LSI attained and cost related to LSI achieved and LCS corrosion rate observed. Formulae used for these calculations are given in Table 7.

From these equations the inhibitors that have the better cost-effectiveness in each of the individual categories will be those with the lower product cost and higher concentration of active component, higher LSI achieved, lower observed LCS corrosion rate and higher biodegradability. Within these categories, the inhibitors were ranked and listed in order of decreasing cost-effectiveness in Table 8, and incorporating biodegradability in Table 10. Table 9 lists the inhibitors in order of decreasing performance with biodegradability factored into the rating. In the case of LSI achieved and unit cost of active component, where the numerical value was the same or very similar, the ratings have been grouped. In this case components within the grouped ranking are listed alphabetically as opposed to performance. Similarly, where no price and/or biodegradation data is available these components are listed alphabetically.

4. NON-CHEMICAL DEVICES

In many people’s eyes this is the ultimate solution, not just from an environmental impact point of view but also Health and Safety, transportation, handling and storage of chemicals, and potentially economics. Historically, there have been many devices marketed with various claims, mainly scale inhibition and control of system microbiology, but some also claim control of corrosion and general deposition. Obviously the greatest appeal is to use such a device to eliminate the use of biocides, which, by the nature of their function within a cooling water treatment program, tend to have a significant potential impact upon the environment and hazards related to handling.

There is a vast array of devices offered, including systems based on magnetic, electrical, ultrasonic and hydrodynamic cavitation techniques. Apart from some of the claims made for some of the devices, some of the described mechanisms by which they are purported to work are sometimes difficult to believe(2). Despite the claims, most applications using non-chemical devices often fail to live up to claims and/or produce acceptable results(3,4). There is no doubt that there are some applications where the devices may be successful, often in the eye of the beholder. These are sometimes found where the cooling system and its operation have been adjusted such as to allow the device appear to work. Sometimes, although somewhat defeating the object, non-chemical devices are supplemented with treatment chemicals.

5. ZERO BLOWDOWN

As a concept zero blowdown has been discussed for several decades. Being pedantic, zero blowdown as envisaged is in essence zero purge since there will still be some non-evaporative loss or “blowdown” through windage and drift losses and possibly some through leaks or involuntary water losses from the cooling system. The basic approach to zero blowdown applies techniques to reduce the concentration of total dissolved solids (TDS) in water. One approach is applied to make up water so as to enable operation at higher cycles of concentration, the other applied to the purge or blowdown discharge from the system, sometimes referred to as “blowdown softening”, thereby enabling the purge or blowdown to be recycled back into the cooling system as opposed to being discharged to the environment.

The simplest approach to pretreating make up water to enable operation at higher cycles of concentration is to soften the make up water to remove hardness salts. This allows higher cycles with respect to scaling or calcium carbonate, but other components may restrict the cycles of concentration at which the system can be operated. This restriction may be the result of materials of construction of equipment within the system, an example of which is stainless steel which may restrict the concentration of chloride permitted in the cooling water. Another may be regulatory restrictions applied to discharge from the system or plant, such as sulfate or salinity. More complete reduction of total dissolved solids in make up water is desalination using thermal or membrane techniques such as reverse osmosis (RO) or reverse electrodialysis (EDR). Sometimes demineralized water is used as cooling system make up, which is not exactly the most economic use or best use for such good quality water. One major drawback of removal of TDS from the make up water and therefore operating with low TDS and low calcium and alkalinity in the cooling water is that the cooling water becomes aggressive with respect to the corrosion potential towards low carbon steel. This may in turn result in the need to use higher concentrations of corrosion inhibitors and to increase the pH of the cooling water in order to try to control corrosion. This obviously increases environmental impact because of additional chemical usage for treatment.

A preferred approach is, where possible, to use a blend of the low TDS water and high(er) TDS or hardness water as make up. This may enforce some blowdown but would yield less corrosive water and allow lower concentrations of treatment chemicals, such as corrosion inhibitors, to be used. “Matter can neither be created nor destroyed” and the TDS components removed by RO or EDR techniques are discharged in the brine effluent from the unit. Dilution of make up water TDS concentration by the reuse of condensate or other low TDS water is another approach that may allow for operation at higher cycles of concentration. Steam condensate, provided it is not contaminated, is better reused in the boiler or steam generation system(s). Process condensate can be contaminated which may result in the need for increased use of treatment chemicals, which may negatively affect the environmental impact of the treatment program.

The use of membrane techniques on purge or blowdown water may, in some cases, be limited, restricted or even not possible by virtue of the compatibility of membranes with the composition of the water, often treatment chemicals and in particular polymers and in some cases biocides. This may make this technique impractical or require additional or targeted removal of chemicals from the treated water. Such techniques may include filtration of the purge or blowdown water using an activated carbon or anthracite filter. This adds extra capital and operating costs.

6. SUMMARY

The studies indicated that, possibly with the exception of Carboxymethyl Cellulose (CMC), the performance of calcium carbonate scale inhibitors can be grouped into three main performance categories based on the LSI that could be achieved, basically all being acceptable performance. Within the top performance group were traditional phosphonate compounds and CMI, which is “marketed as being biodegradable”. Therefore, one can say this “biodegradable” or “green” inhibitor is among the best performing calcium carbonate inhibitors that were evaluated. However, at use concentration, CMI had a significant detrimental impact upon LCS corrosion and is an expensive product and hence is within the lower half of the cost-performance ratings, being as much as fifteen times higher than the use cost of some of the traditional phosphonates commonly used. A similar cost penalty, in the order of ten times higher use cost compared to some of the traditional phosphonates, is incurred with other “biodegradable” inhibitors such as the Maleic Acid Homopolymer (MAH) and Terpolymer (MAT), and these inhibitors also exhibited...
a high LCS corrosion rate at use concentration. Even taking into account a factor for the degree of biodegradability, MAH and MAT are five to eight times more expensive and CMI in the order of twenty to twenty five times more expensive than these traditional phosphonates of a scale inhibition cost performance basis.

There is no doubt that biodegradability is a desired property of chemicals used for cooling water treatment. However, one must look at the biodegradability and environmental impact of the overall treatment program, which, apart from scale inhibitor, would typically include corrosion inhibitors, polymeric dispersants and chemicals for the control of microbiological growth. The polymeric dispersants are not inherently biodegradable and neither are the commonly used cost effective inorganic corrosion inhibitors. As a rough guide it may be expected that the “biodegradable” calcium carbonate inhibitor, at the use concentration evaluated in these studies, would only contribute about 30 to 50% of the overall inhibitor program.

There is also an underlying concern that biodegradation of the inhibitor may result in proliferation of microbial populations in the cooling system and/or required the use of higher concentrations to compensate that lost though biodegradation in order to maintain effective performance. The relevance of these concerns will depend upon the degree of biodegradation with time and the half-life of the cooling system. The reported biodegradation is typically over 28 days whereas the half-life of a cooling system may typically be in the order of 3 to 5 days. One really needs to consider the successive and cumulative biodegradation with time and review this in relation to the half-life and depletion within the cooling system, rather than the resultant biodegradation over 28 days.

Overall, on a cost-performance basis the biodegradable inhibitors exhibited a significant penalty in the shape of increased cost. Although a higher LCS corrosion rate was exhibited in the studies using these biodegradable inhibitors, this could be countered by incorporating increased corrosion inhibition, in the form of higher concentrations of corrosion inhibitor, within the overall treatment program. Even though the phosphonates ATMP and HEDP have a lower biodegradability than some of the other inhibitors specifically regarded as biodegradable, from a cost performance point of view these were consistently superior. In addition, other phosphonates evaluated, namely DTPMP, HPA and PBTC, consistently appeared in the top portions of the performance and/or cost performance tables. ATMP, DTPMP and HPA are not halogen stable and therefore would consume more halogen when halogen is used for microbiological control. This is a slightly negative aspect with respect to environmental impact, plus, if the reaction with halogen resulted in production of AOX, this would be regarded as a negative property for these phosphonates. Therefore, HEDP and PBTC would appear to be the best cost performing inhibitors, taking into account a factor relating to the biodegradability of the individual inhibitors. Of these two HEDP is more cost-effective than PBTC, by a factor of three times on a use cost and performance basis, and because the biodegradability of PBTC is about half that of HEDP, HEDP is about ten times more cost effective than PBTC taking into account a factor related to the degree of biodegradability.

Of the molecules marketed as being “biodegradable”, Polyaspartic Acid (PASP), although not the best in basic performance, is comparable to the phosphonates on a cost-performance and cost related to biodegradability basis. However, once again PASP is not that stable in the presence of chlorine, this having a similar negative influence with regard to halogen stability, and possibly production of AOX.

For the specific biodegradable inhibitors these studies used a baseline 6 ppm active concentration, which compared to the 1.5 or 3 ppm used for the traditional phosphonates, contributed to the negative impact on cost performance. A more favorable cost performance could be achieved if lower concentrations could be used, and this is possibly an area where further studies may be warranted. However, on a use cost incorporating a factor for biodegradability the use concentration would need to be 1 ppm or less for these to be comparable to traditional phosphonates.

There are other virtues of these biodegradable materials such as halogen stability, phosphorus concentration, BOD and COD that may help offset the higher cost by incurring lower cost for discharge or effluent. All of these aspects need to be enumerated and the cost of applying a “green(er)” cooling water treatment program judged against the enhanced image and favorable publicity that would hopefully ensue with such a change. As regulatory pressure on discharge and environmental impact increased, which it will continue to do in future, some of the inherent benefits of these biodegradable inhibitors will increase in value or return on investment, eventually possible making the increased use cost acceptable.

REFERENCES

2. Laronge T. M., “‘Tis the Season”, Industrial Water Treatment, November/December 1996.

TABLES

<table>
<thead>
<tr>
<th>Recirculation Rate or Throughput Rate</th>
<th>10,000 m³/h (44,029 gpm)</th>
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<td>Temperature Drop across Tower or Temperature Rise across Plant</td>
<td>7°C (12.6°F)</td>
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Design and Operation of System | Open Evaporative | Once Through |
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<td>Blowdown Rate</td>
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<td>Make Up Rate or Overall Water Consumption</td>
<td>126 m³/h (550 gpm)</td>
<td>10,000 m³/h (44,029 gpm)</td>
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Table 1

| pH | 8.5 (increased to failure) |
| Conductivity | 2,700 μs cm⁻¹ (micromho) |
| M Alkalinity | 300 ppm CaCO₃ |
| Total Hardness | 1,100 ppm CaCO₃ |
| Calcium Hardness | 800 ppm CaCO₃ |
| Magnesium Hardness | 300 ppm CaCO₃ |
| Chloride | 520 ppm Cl |
| Sulfate | 290 ppm SO₄ |
| Silica | 50 ppm SiO₂ |
| Orthophosphate | 2.5 ppm PO₄ |
| Sulfonated Acrylic Terpolymer | 7 ppm active polymer |
| LSI at 60°C (140°F) | +2.5 (increased to failure) |

Table 2
### Table 3

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration of Active Molecule Applied</th>
<th>LSI at 60 °C (140 °F) at Failure</th>
<th>Corrosion Rate measured on Coupons</th>
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<td>CMC</td>
<td>6 ppm</td>
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<td>3 ppm</td>
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<td>HEDP</td>
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<td>0.02 mm/y (0.9 mpy)</td>
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<td>MAC</td>
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<td>PCM</td>
<td>6 ppm</td>
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### Table 4

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<th>Component</th>
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<th>COD mg O2/g</th>
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<td>&gt;20% OECD 301A</td>
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<td>DTPMP</td>
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<td>33% OECD 302B</td>
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<td>500</td>
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<td>HEDP</td>
<td>30% P</td>
<td>93% OECD 302B</td>
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<td>HPA</td>
<td>22% P</td>
<td>93% OECD 302B</td>
<td>2</td>
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<td>MAC</td>
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<td>MAH</td>
<td>Zero</td>
<td>&lt;5% OECD 302B (35 days)</td>
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<tr>
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<td>Zero</td>
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<td>Zero</td>
<td>46% OECD 302B</td>
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<td>5% OECD 302B</td>
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<td>PASP</td>
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<td>68% OECD 301B</td>
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<td>15% OECD 302B</td>
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<td>10% P</td>
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<td>410</td>
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### Table 5

Some Comparative Data relative to Structure, Ecology and Stability of Scale Inhibitors Studied
Table 10
Relative Rating based on Use Cost and Cost Performance incorporating Biodegradability

FIGURES

Figure 1
A Bench Top Unit as used for the Evaluations

Figure 2 Performance LSI Attained and LCS Corrosion Rate

Figure 3 Corrosion Rate

Figure 4.1
1.5 ppm ATMP Before and After Cleaning

Figure 4.2
6 ppm CMC Before and After Cleaning

Figure 4.3
6 ppm CMI Before and After Cleaning

Figure 4.4
3 ppm DTPMP Before and After Cleaning
Figure 4.5 1.5 ppm HEDP Before and After Cleaning

Figure 4.10 6 ppm MAT Before and After Cleaning

Figure 4.6 3 ppm HPA Before and After Cleaning

Figure 4.11 3 ppm PAA Before and After Cleaning

Figure 4.7 6 ppm MAC Before and After Cleaning

Figure 4.12 4 ppm PASP Before and After Cleaning

Figure 4.8 6 ppm MAH Before and After Cleaning

Figure 4.13 3 ppm PBTC Before and After Cleaning

Figure 4.9 6 ppm MAS Before and After Cleaning

Figure 4.14 6 ppm PCM Before and After Cleaning
Cooling Technology Institute
Licensed Testing Agencies

For nearly thirty years, the Cooling Technology Institute has provided a truly independent, third party, thermal performance testing service to the cooling tower industry. In 1995, the CTI also began providing an independent, third party, drift performance testing service as well. Both these services are administered through the CTI Multi-Agency Tower Performance Test Program and provide comparisons of the actual operating performance of a specific tower installation to the design performance. By providing such information on a specific tower installation, the CTI Multi-Agency Testing Program stands in contrast to the CTI Cooling Tower Certification Program which certifies all models of a specific manufacturer’s line of cooling towers perform in accordance with their published thermal ratings. To be licensed as a CTI Cooling Tower Performance Test Agency, the agency must pass a rigorous screening process and demonstrate a high level of technical expertise. Additionally, it must have a sufficient number of test instruments, all meeting rigid requirements for accuracy and calibration.

Once licensed, the Test Agencies for both thermal and drift testing must operate in full compliance with the provisions of the CTI License Agreements and Testing Manuals which were developed by a panel of testing experts specifically for this program. Included in these requirements are strict guidelines regarding conflict of interest to insure CTI Tests are conducted in a fair, unbiased manner. Cooling tower owners and manufacturers are strongly encouraged to utilize the services of the licensed CTI Cooling Tower Performance Test Agencies. The currently licensed agencies are listed below.

### Licensed CTI Thermal Testing Agencies

<table>
<thead>
<tr>
<th>License Type</th>
<th>Agency Name</th>
<th>Contact Person</th>
<th>Telephone</th>
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<tr>
<td>A,B</td>
<td>Clean Air Engineering</td>
<td>Kenneth Hennon</td>
<td>800.208.6162</td>
<td>865.938.7569</td>
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<tr>
<td></td>
<td>7936 Conner Rd</td>
<td><a href="http://www.cleanair.com">www.cleanair.com</a></td>
<td><a href="mailto:khennon@cleanair.com">khennon@cleanair.com</a></td>
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</tr>
<tr>
<td></td>
<td>Powell, TN 37849</td>
<td></td>
<td></td>
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<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>
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<tr>
<td></td>
<td>PO Box N157</td>
<td><a href="mailto:coolingtwttech@bigpond.com">coolingtwttech@bigpond.com</a></td>
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<td>Bexley North, NSW 2207</td>
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<td></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>
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<tr>
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<td></td>
<td>Knoxville, TN 37912</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>
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<tr>
<td>McHale &amp; Associates, Inc</td>
<td>Thomas Wheelock</td>
<td>865.588.2654</td>
<td>425.557.8377</td>
</tr>
<tr>
<td>4700 Coster Road</td>
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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 29 cooling tower manufacturers are currently active in the program. In addition, 7 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 76 product lines plus 12 product lines marketed as private brands which result in more than 11,000 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.
### 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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## Cooling Towers Certified by the CTI under STD-201

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# Cooling Towers Certified by the CTI under STD-201

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38 Participating Manufacturers
88 CTI Certified Product Lines
11,570 CTI Certified Tower Models

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Certification Validation Number
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- Rich Harrison, Jr.  ATC-105 Task Group Chairman

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