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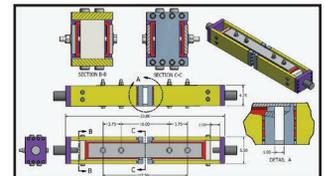


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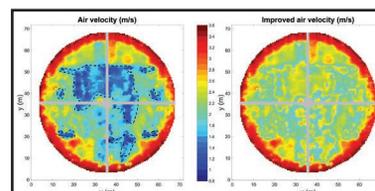
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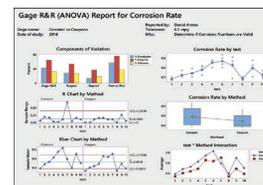
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For Immediate Release
Contact: Chairman, CTI
Multi-Agency Testing Committee

Houston, Texas
2-January-2020

Cooling Technology Institute, PO Box 681807,
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nounces its annual invitation for interested thermal testing agen-
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testing program to service the industry. Interested agencies are
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Future Meeting Dates

**Annual
Conference**

February 9-13, 2020
The Westin Galleria
Houston, TX

February 7-11, 2021
Sheraton New Orleans
New Orleans, LA

February 7-11, 2022
The Westin Galleria
Houston, TX

**Committee
Workshop**

July 12-15, 2020
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Steamboat Springs, CO

July 11-14, 2021
The Inn at Loretto
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70 YEARS



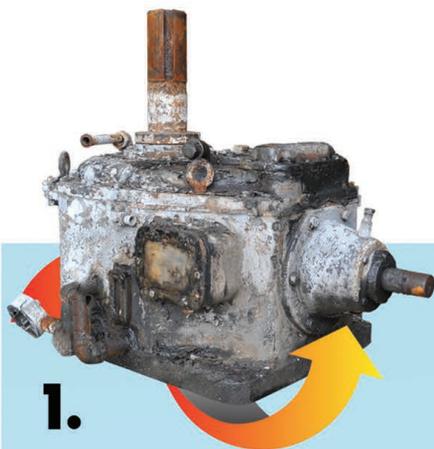
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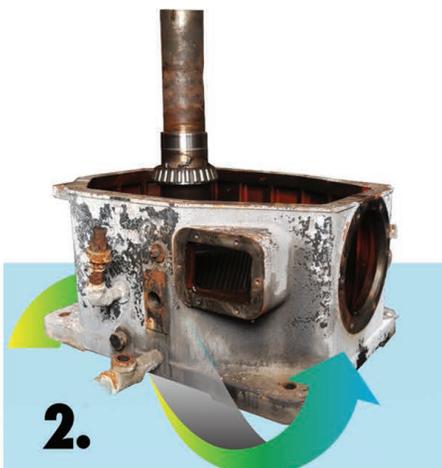


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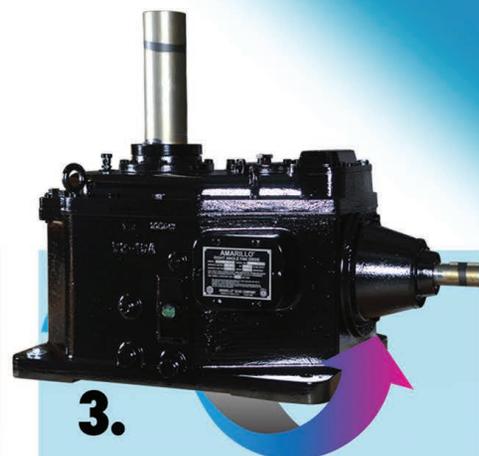
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MEMBER

View From The Tower

As many of you know, the focus of my day job is Legionella control, but it does not stop there. I am active with ASHRAE, serving as Secretary of the SSPC 188 committee that developed and maintains the first standard to address Legionella in the United States. The need for my work to focus on this topic was, in part, spurred by the New York City and state regulations of 2015. I am also active within CTI's efforts in this area, on the committee developing Guideline 159, Practices to Reduce the Risk of Legionellosis Associated with Heat Rejection Equipment Systems. For those who are familiar with the development of this document or have been awaiting its publication, you know that this has taken quite some time. (Some of you may know that getting the ANSI/ASHRAE standard published also took a long time.) I am happy to report that the CTI Guideline 159 has been approved by the Board of Directors. Getting to consensus can be a journey when the goal is to provide a valuable product. As we enter 2020, other states, with the purpose of protecting people from the hazards of Legionella, appear to have proposed regulations for cooling towers on their legislative dockets. While I am happy to see reference to parts of the ASHRAE standard, it is in everyone's interest to review and carefully examine these proposed regulations and not speed down the road to approval.

As I reflect on the two years of my term as CTI President, I would like to highlight some of the accomplishments and ongoing work of CTI:

- The continued success of the Thermal Certification Program with Mike Womack as Thermal Certification Administrator.
- The implementation of the Pitot Tube Study.
- ATC-105, Acceptance Test Code – first and most comprehensive revision since 2000.
- ATC-105DC, Acceptance Test Code for Dry Fluid Coolers – First code to address dry cooling performance.
- ATC-128, Code for Sound from Water Cooling Towers – significant revisions based on extensive testing and sound modeling work.
- A test code to address performance testing for adiabatic cooling equipment is in development.



- WTG-130, Methods for Cooling Water Systems Microbial Monitoring – a new document in the WTG 130 series.
- Water Treating is continuing work on a Best Practices document which will be the subject of the Water Treating Panel at the CTI 2020 Annual Conference.
- Dennis Shea has advanced the Products and Material Certification Program. We have signed a contract for testing and as this goes to publication, testing should be underway for the first product certifications.

As I wrap up my term as president, I am in awe of the talent and dedication of the individuals who contribute to CTI. I am witness to the efforts of those who participate and recommend that we foster the continuation of participation from our member companies and individuals. I want to recognize and thank the Past Presidents Council for their guidance and help with my requests, the functional and standing technical committee chairs for their successful work, and the Board of Directors (BOD) for their service and support. Thank you to the outgoing board members; Peter Elliott of ChemTreat, Inc., Kent Martens of SPX Cooling Technologies, and Janet Stout of Special Pathogens Laboratory.

I especially want to thank the CTI administrative staff with Angie Montes and Kelli Velasquez under the direction of Vicky Manser. They keep CTI operating, organize and execute the CTI annual conferences and summer workshops, and have been a tremendous help to me during my presidency. I know they will provide the same help to our new President, Chris Lazenby, of Southern Company Services, Inc. Having served with Chris on the BOD, I am confident of his ability to lead CTI as we enter a new decade. Congratulations and welcome to the new BOD members; Jon Bickford of Alliant Energy, Jennifer Hamilton of Evapco, Inc., and John Zibrida of Zibex, Inc.

It has been my honor to serve as your CTI president for the past two years. I appreciate everyone who has served CTI and has supported and helped me through my term. There is great satisfaction in service to this organization and I recommend that everyone participate in some way to keep CTI the leading organization in the cooling industry.

President Elect 2020-2021

Chris is a Principal Engineer with Southern Company, working as part of the company's Technical Project Solutions organization in Birmingham, AL. He has close to twenty-five years of experience in the utility industry, the vast majority of that in the area of power plant cooling systems and equipment. In his current role he provides guidance and input for design, operation, maintenance, and retrofit of cooling system equipment for Southern Company's existing coal, natural gas, and nuclear generating fleet.

Chris has co-authored papers and made technical presentations at various organizations including the



Cooling Technology Institute (CTI) and the Electric Power Research Institute (EPRI). He has also served on multiple CTI, EPRI, and ASME task groups and code committees related to condensers, cooling towers, and other cooling system equipment and testing. Chris has also chaired the Owner/Operator group at CTI as well as been a member of the Board of Directors.

Chris holds a Bachelor of Mechanical Engineering from Auburn University and a MA in English from the University of Alabama-Birmingham. He is a registered Professional Engineer in the states of Alabama and Minnesota.



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Editors's Corner

Dear Journal Reader,

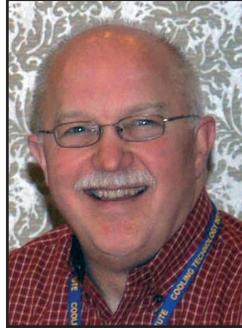
CTI meets in Houston in February. We look forward to seeing you there.

Following the recent Editor's Corner format, some of the highlights of recent activity are as follows:

Unfortunately, after multiple attempts we have still not gotten confirmation that California will, after input from CTI and other organizations, stay true to the term sheet with DOE in which heat rejection equipment is excluded from their fan regulations per the CTI definitions (Title 20). Title 24 covers building energy efficiency, and we expect them to re-open pursuit of increased minimum efficiency for cooling towers, with which CTI continues to be engaged.

ASME proposed a change to remove the exemption for small diameter tubing and equipment from the Boiler and Pressure Vessel Code. For many years, this exemption has led to the design of small diameter tubing and equipment in other standards without adverse safety issues. CTI, along with multiple other organizations, commented against the proposed rule change. ASME committee deferred action and it is in discussion within the ASME committee for the next cycle. CTI is engaged as are other organizations. This could have a very significant impact on any of the tubular exchangers used widely in our industry.

On the Legionella management front, the CTI and ASHRAE guidelines are moving toward completion this winter. Another document is in progress for multiple building water hazards, including Legionella. This standard is ASHRAE SPC514, with a target of completion within 2 years. The



membership, which includes some previous NSF444 members and new members under the ASHRAE process, is in place, and the committee began to meet in September as an ASHRAE standards committee. Helen Cerra is the official CTI organizational representative on the committee, and Frank Morrison is her alternate.

The new Pitot tubes using the tip design resulting from the CTI funded research project are now in use on a global basis. Additional research is in progress in the R&D committee to refine the application of calibration data using the new design.

CTI is approaching its 70th anniversary, a major milestone for the organization. CTI started in 1950, as the third attempt to build a cooling tower oriented organization - look for more information on that in a future editorial. The history of cooling towers is much older than 1950 and, as many of you know, quite a few of you in our industry have been sharing old pictures and other information about the early history of cooling towers with me. Please continue to share what you find. I'm moving slower than I'd hoped, but intend to keep on it. As of now, it appears the oldest "cooling tower" was by Santa Fe Tank & Tower in the early 1890s in the Los Angeles area. It was a very large evaporative condenser, with a tall spray chamber surrounded by louvers as a "blow through" atmospheric tower. It served an ice-making plant. The industry has had a long and interesting history.

Respectfully,

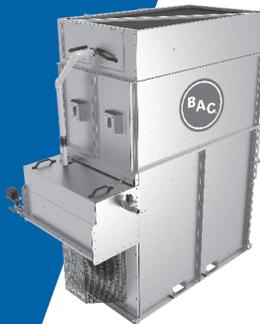
Paul Lindahl, CTI Journal Editor



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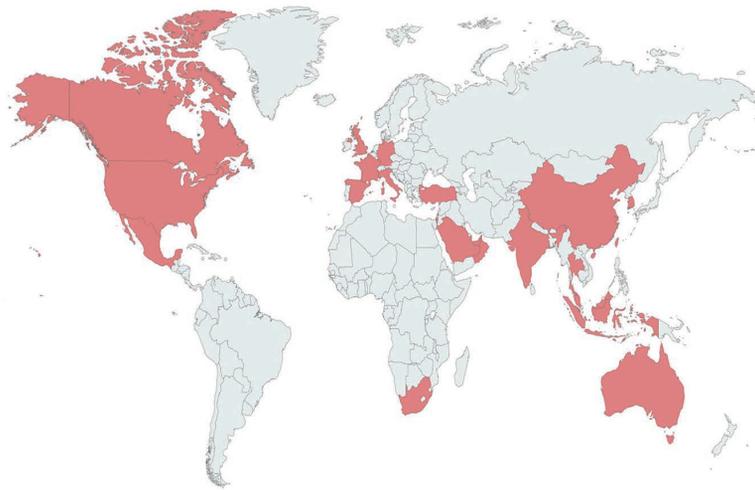
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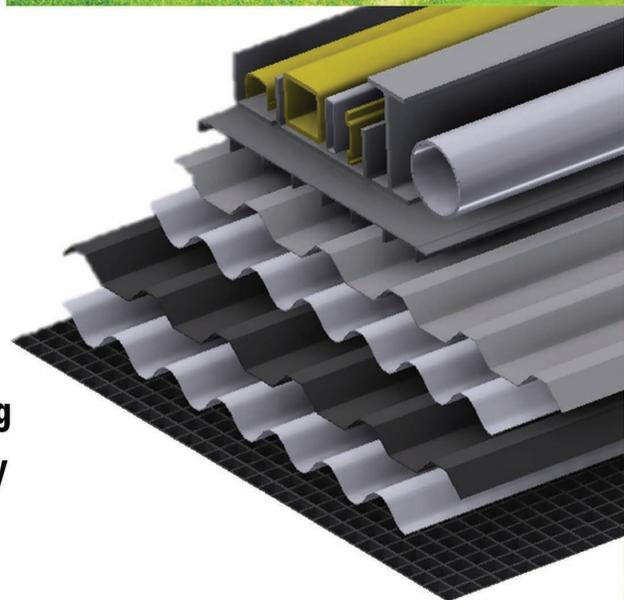
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Bolted Structural Connections In Fiberglass Materials

Mark Martich; Cyrco, Inc.

Abstract:

This paper compares several methods of connecting fiberglass reinforced pultruded plastic (FRP) structural members to tubular sections using bolted designs that are commonly used in the cooling tower industry. The study compares theoretically predicted values with full-scale actual laboratory test results.

The geometry of the structural members studied herein are representative of the diagonal bracing typically found in cooling towers, but the results are not limited to just those members, nor only to the FRP structures found in cooling towers.

Introduction And Background:

Typical FRP diagonal bracing geometry used in cooling towers was chosen for this study. Diagonal bracing is responsible for preventing lateral movement of the structure under loading. These loads result from winds, seismic activity, and vibrations from the equipment (e.g. pumps, fans, flowing water, etc.). They carry the accumulative static and dynamic lateral loads, fluctuating widely in magnitude between tension and compression, cyclically fatiguing the members and connections. These forces result in bearing shear stress in the connections of structural members. Reliable connection performance under this cyclic loading is essential for long-term mechanical stability over the expected life of the structure.

FRP materials, as well as both bolted and adhesive connection methods, have been very well characterized by both industry and academia. FRP manufacturers frequently endorse making combination connections by using an epoxy-type adhesive in combination with fastening screws to apply pressure to the connection while the adhesive cures. The screws also contribute to the peel strength of the joint. Properly executed, these adhesive combination connections have been proven over long periods of time to effectively carry required loading, distribute stress uniformly, and increase joint stiffness – all resulting in superior fatigue and impact resistance.⁽¹⁾

The quality of these adhesive connections is highly dependent on proper preparation of the glued surfaces, as well as the ambient temperature and humidity conditions at the time the connection is made. Unfortunately, this has proven to be challenging for cooling tower construction or reconstruction, since field conditions and operator skill levels vary widely. The amount of time needed to make the connections is also significantly longer than simple bolted connections. The time-windows for tower maintenance are frequently limited by site down-time constraints. Also, verification of the connection integrity is virtually impossible after-the-fact. Finally, removing or replacing a structural member for any reason at a later date is problematic.^(1,2)

As a result, bolt-only connections are the preferred connecting methodology in the cooling tower industry. Several factors are generally known to affect bolted-joint bearing strength. For example, fastener threads in the bearing areas are known to reduce bearing load capacity and accelerate hole deformation under fatigue loading.^(3,4) Plastic bushings and stainless-steel bearing sleeves have



Mark Martich

been added to both increase the shear bearing area and protect the FRP from the fastener's threads.^(5,6) Clamping pressure and washer diameter are known to have a significant impact on connection strength. Increasing fastener torque (clamping pressure) and washer diameter and thickness can significantly increase the static strength capacity by increasing the friction in the joint and distributing it over a larger area.^(7,8,9) Loose bolts should always be avoided, particularly under reversed cyclic loading conditions.

However, the cooling tower industry is not unified when it comes to the specifics of bolting structural members to hollow tubular FRP structural members. FRP manufacturers caution against applying clamping/compression on unsupported cross-sections of tubular structural members.^(3,10) When compression is required for maximum joint

strength and stiffness, FRP manufacturers recommend using spacer blocks to prevent bolt tension from damaging the column profile.^(10,11) This adds material cost and installation labor time, but compression in the connection creates what may be referred to as a strong "friction-type or slip-critical joint."⁽¹²⁾



Figure 1: Excessive Compression On Unsupported Frp Structural Tubing

Without internal support in the tube, applying even relatively low levels of tension in the connections (e.g., only 13-16 N-m (10-12 ft-lbs) of fastener torque on a Ø12.7 mm (Ø½") fastener) results in cracking of the tube (inelastic failure) in the fastener location, as well as at the tube's corners, as shown in Figure 1. This failure mode ensures there is little-to-no tension in the connecting bolt and the connections will loosen over time due to creep.⁽¹³⁾ Unfortunately, Figure 1 is a very common field observation throughout the cooling tower industry.⁽¹⁴⁾

A compromise solution used in the industry to the problem of not significantly compressing the tube while avoiding the added cost of inserting spacer blocks or full-width support tubes is to treat bolted connections to tubular columns as bearing-only or “pinned” joints, idealized by a clevis pin and hairpin cotter retainer. One practical implementation is making connections by using self-locking nuts and only lightly tightening the nuts. These nuts are about 3 times the cost of standard nuts and limits installation to hand tools and proper operator training and technique.

Another approach suggests applying an anaerobic locking compound to the nut and “finger-tightening” standard nuts to secure assemblies.⁽⁶⁾ It is common practice to use stainless steel fasteners in cooling towers for corrosion resistance since they generate an oxide film for corrosion protection. However, during assembly the oxides are broken, possibly even wiped off. This reduces corrosion protection and can result in galling, leading to thread seizure. To protect against this occurring, CTI recommends applying a thread lubricant when using stainless-steel fasteners.⁽¹⁵⁾ Some anaerobic locking compounds do offer some degree of lubrication before curing.⁽¹⁶⁾ Careful adhesive selection and proper application is critical. Again, installation is limited to hand tools and proper operator training and technique.

An alternative method commonly employed is to use a helical-spring split locking washer under the nut and only tightening the fastener until the spring washer is compressed – essentially using the washer as a “torque gage”. Compressing a typical Ø12.7 mm (Ø½”) stainless-steel split locking washer only requires about 1.4 to 2.7 N-m (1 to 2 ft-lbs) of torque on the fastener, producing little-to-no tension on the connection and results in no damage to the FRP tube.⁽¹³⁾ This is commonly referred to as a “snug-tight” connection.⁽¹²⁾ This makes the use of power tools possible but dangerous. Many installers in the industry limit operators to using only hand tools to avoid the condition shown in Figure 1. This requires additional installation labor and quality monitoring. But more importantly, bolts installed with this limited-tension method are frequently found to be completely loose and even missing entirely due to tower vibrations and thermal cycling (creep) over time. A helical-spring lock washer is effective only when one of the materials being fastened (e.g. lumber) are soft enough for an edge of the spring washer to dig into one of the surfaces. Since neither the nut, the washers, nor the FRP are soft enough, by the time the helical washer is flattened, helical-spring washers are effectively useless for locking in this application.⁽¹⁶⁾

Figure 2 shows examples of such disorders at one recently-inspected site. Alarming, this follow-up inspection was done less than six months after its initial installation. The photos shown in Figure 2 were not isolated cases within this large installation. More disturbingly, this condition is commonly the case found during many tower inspections.⁽¹⁴⁾

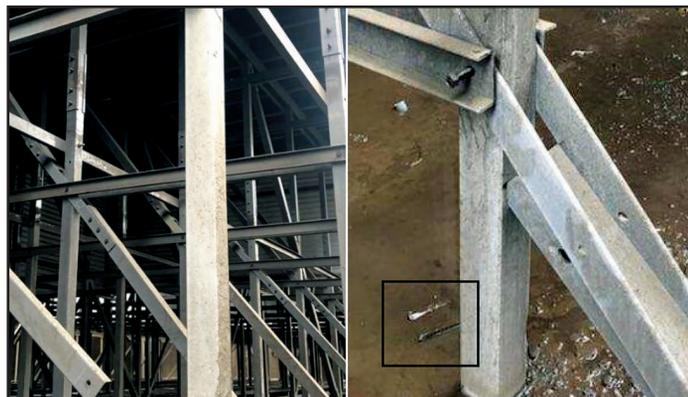


Figure 2: Loose And Missing Bolts Found During Site Inspection

Regardless of the implementation method, pinned connections have been shown to be inferior to properly executed combination adhesive-mechanical connections in terms of ultimate tensile and compression strength. Pinned connections produce ultimate yield strengths that are only about 60 percent as strong as classical theory would predict or as comparable adhesive/fastener combination connections. Adhesive connections have been demonstrated to be as strong as the polyester-to-polyester shear strength of the connected substrates.^(2,17)

Even more importantly, however, pinned connections cannot, by definition, contribute any torsional moment resistance needed for structural stiffness against the fatigue loading from the shifting cyclical compressive and tensile forces existing in the diagonal members. Practical joints are rarely loaded in pure shear or tension. Indeed, field inspections of FRP towers that have been in service for several years with pinned connections shows clear indication that the clearance holes of pinned FRP connections have elongated from cyclic wear, particularly near the top of the tower where deflections are greatest.⁽¹⁴⁾ Figure 3 shows two such examples. Note that the bolt thread pattern is worn into the hole in the picture on the left. The hole on the right had been dramatically elongated before the bolt finally fell out.



Figure 3: Damaged Bolt Holes Of Pinned Connections

An adhesive connection or a properly-designed and installed bolted connection with sufficient clamping pressure supplies resistance to bending and cyclic forces.⁽¹⁸⁾ The purpose of this study is to compare the performance of various versions of pinned bolted connections to FRP tubes with bolted connections that are design for compression and tightly clamped.

Test Methodology:

This study is limited to the more severe tensile rather than compression loading in composite joints. Composite joints subjected to compression loading are less sensitive to joint geometry and are generally stronger than joints subjected to tensile forces. Members are loaded in the lengthwise orientation according to the direction of the pultrusion to utilize the maximum tensile strength available from the FRP. All edge distances exceed the minimum recommendations relative to bolt diameter. As such, the predicted failure mode is bearing failure, rather than failure by tension or shear out. Bearing failure is caused by the bearing pressure forces from the bolt applied to the hole boundary producing delamination of the composite.^(7,9,18,19) Historically, bearing failure has been defined as 4% elongation of the bolt-hole diameter. No appreciable load capacity can be expected after the 4% diameter elongation is met. Any further elongation of the holes only allows the structure to become loose and unstable.^(4,17,18,19)

The FRP materials used for this test are fire retardant polyester, compliant with CTI industry standards.^(20,21) Cross-sectional dimensions of the tubes are 88.9 mm square x 6.4 mm thick (3.5” square x 0.25” thick). Cross-sectional dimensions of the straps are 76.2 mm wide x 9.6 mm thick (3.0” wide x 0.38” thick). Fastener materials are all of S30400-grade stainless steel, Ø12.7 mm-13 (Ø½”-13) UNC. One flat washer is placed below the head of the bolt. One flat washer and one helical locking washer is placed under the

nut. All threads are lubricated with a graphite-petrolatum anti-seize compound.

Five different bolted-joint configurations are examined as described in Table 1.

CONF. NO.	SHEAR BUSHING INSERT	TUBE CLEARANCE HOLE	STRAP CLEARANCE HOLE	TIGHTENING CONDITION/JOINT TYPE
№ 1	NONE	Ø14.3 mm (Ø0.56")	Ø14.3 mm (Ø0.56")	SPLIT WASHER FLATTENED (SNUG-TIGHT/PINNED)
№ 2	STANDARD PLASTIC PARTIAL-LENGTH SHEAR BUSHINGS ^(a)	Ø26.4 mm (Ø1.04")		SPLIT WASHER FLATTENED (SNUG-TIGHT/PINNED)
№ 3	FULL-LENGTH S.S. SHEAR TUBE ^(b)	Ø20.3 mm (Ø0.79")		38-41 N-m (28-30 ft-lbs) TORQUE ^(d) (TIGHTLY CLAMPED)
№ 4	MATING FULL-LENGTH PLASTIC SHEAR BUSHINGS ^(c)	Ø26.4 mm (Ø1.04")		SPLIT WASHER FLATTENED (SNUG-TIGHT/PINNED)
№ 5	MATING FULL-LENGTH PLASTIC SHEAR BUSHINGS ^(c)	Ø26.4 mm (Ø1.04")		38-41 N-m (28-30 ft-lbs) TORQUE ^(d) (TIGHTLY CLAMPED)

Table 1: Test Configurations

- a. Standard Partial-Length Bushings: 25.4 mm O.D. x 14.3 mm I.D. x 12.7 mm long (Ø1.00" O.D. x Ø0.56" I.D. x 0.50" long). Polycarbonate plastic material.
- a. Stainless-Steel Tube: 304 ASTM A269 Seamless Round 19 mm O.D. x 14.2 mm I.D. x 88.9 mm long (Ø0.75" O.D. x Ø0.58" I.D. x 3.50" long).
- a. Mating Full-Length Shear Bushings: 25.4 mm O.D. x 14.3 mm I.D. x 44.5 mm long (Ø1.00" O.D. x Ø0.56" I.D. x 1.75" long). Polycarbonate-blend plastic material. These are similar to the standard shear bushings described in (a) above that are also commercially available in 44.5 mm (1.75") lengths.⁽⁶⁾ But, this is a newly-designed, custom-molded component. It has been designed with the added feature of a larger, thicker integral washer/flange to better distribute compression stress and increase friction in the connection. It also adds self-retention features to snap into the clearance hole, facilitating more efficient field assembly (patent pending).
- a. 39 N-m (29 ft-lbs) of applied torque results in approximately 20.5 kN (4600 pounds) of clamping tension in a lubricated bolted connection (KEST = 0.15). 20.5 kN (4600 pound) is about 75% of the stainless-steel's bolt proof strength.^(22,23) This is generally recommended best practice to achieve tightly-clamped bolted connections.^(18,23)

The five configurations described in Table 1 are illustrated in Figures 4A-4D:

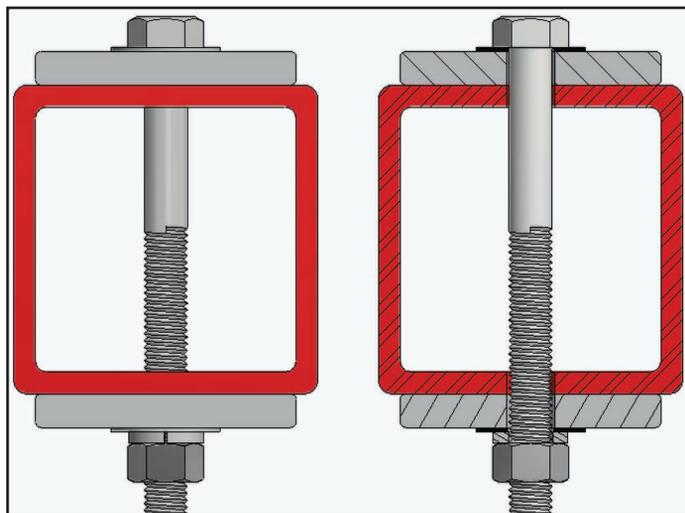


Figure 4a – Configuration № 1 No Shear Bushings: Snug-Tight Tension (Pinned Connection)

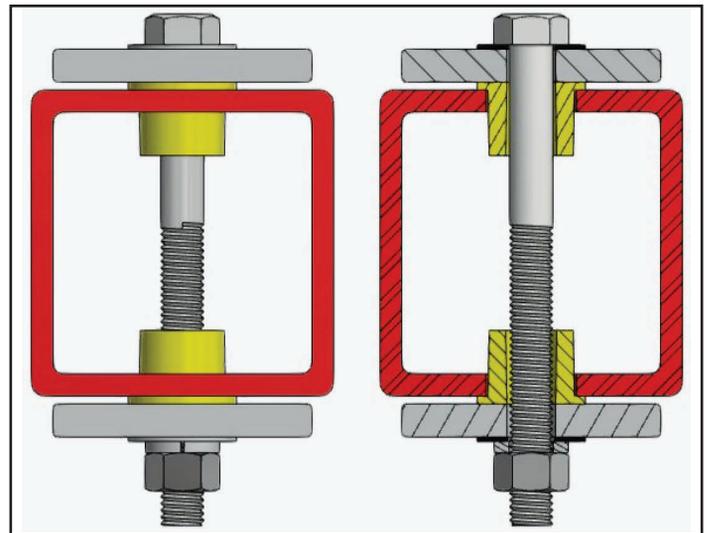


Figure 4b – Configuration № 2 Standard Flanged Plastic Partial-Length Shear Bushings: Snug-Tight Tension (Pinned Connection)

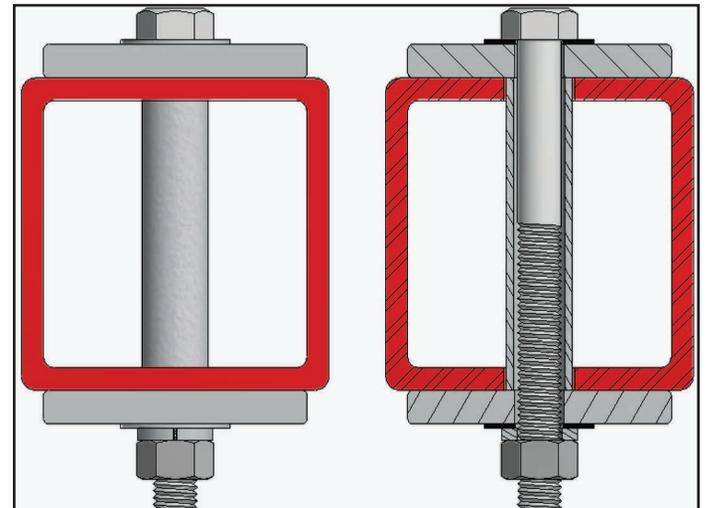


Figure 4c – Configuration № 3 Stainless Steel Full-Length Support Tube/Shear Bearing: 39 N-M (29 Ft-Lbs) Torque (Tightly Clamped Connection)

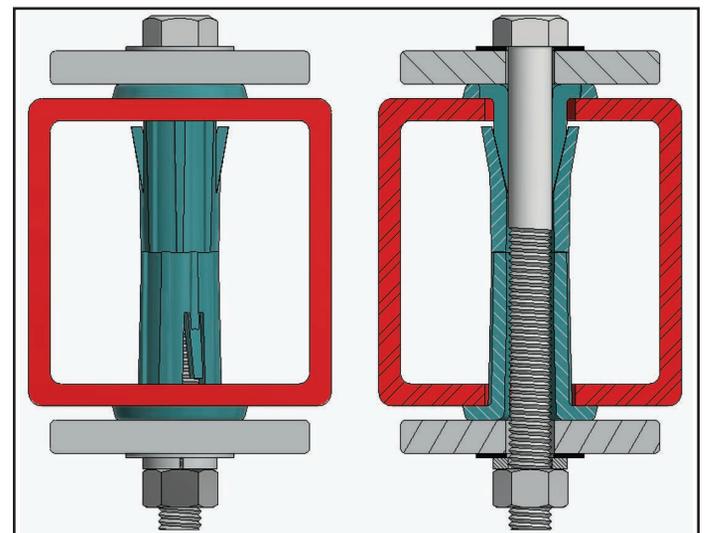
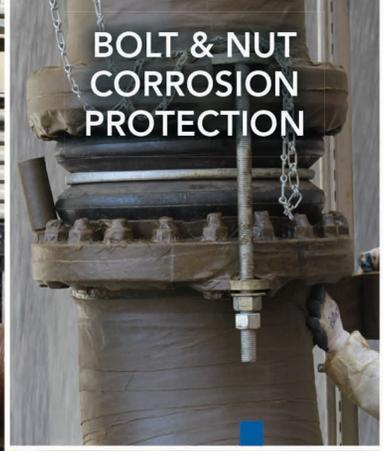


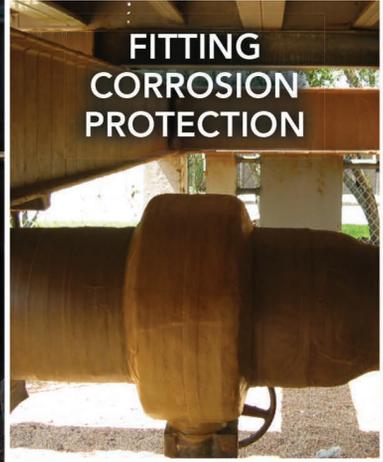
Figure 4d – Configurations № 4 & № 5 Mating Full-Length Shear Bushings Tested Under Two Conditions: Snug-Tight Tension (Pinned Connection) And 39 N-M (29 Ft-Lbs) Torque (Tightly Clamped Connection)



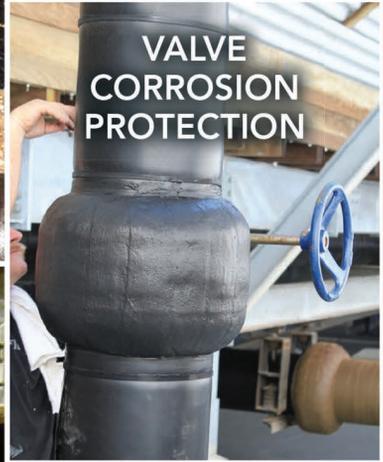
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A test fixture designed to perform this testing is shown in Figure 5. It is comprised of two identical yokes to hold the specimens under test by clamping the tubes and interface them to an Instron® 3384 Tester, as shown in Figure 6. As stated above, the scope here is limited to tensile-only testing, although the fixture is capable of compression testing (and, hence, cyclical testing) as well for future work.

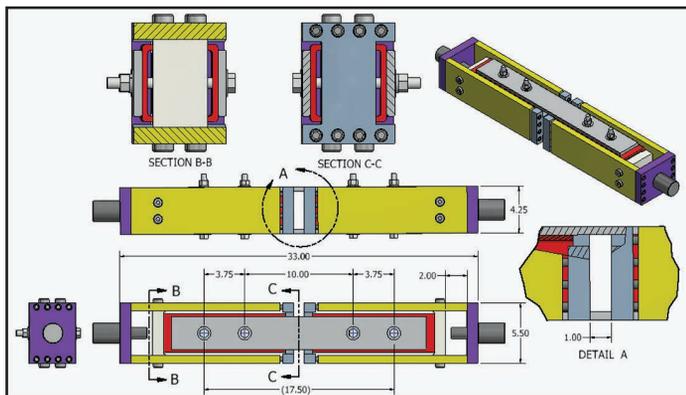


Figure 5: Tensile (Or Compression/Cyclical) Test Fixture

Since this system is more complex than a single bolt/hole configuration, a gage length of 254 mm (10”) is used and a marker set on the output curves at the 10.2 mm (0.4-inch) elongation point (4%) to use as an arbitrary reference point to compare results with those of the references previously cited above.

It is important to note that there is significant “slack” in the pinned test specimens due to the clearance holes in the four connections. A pre-load of 1.3 kN (300 pounds) was placed on all test specimens under test (both pinned and clamped) before the bolts were either snug-tightened or torque-tightened to remove this slack. This is needed to “normalize” the graphical representations of the data. Otherwise, there are long and varying levels of “dead-time” at the base of the curves of the pinned specimens while the slack is taken out of the system.



Figure 6: Fixture With Test Specimen Mounted To Tensile Tester

Three samples of each of the five configurations in Table 1 are tested by increasing tensile force at a rate of 2.54 mm/min (0.10 in/

min) to failure. Elongation is recorded in the process. The slopes of the force-strain curves (elastic modulus of the systems) are compared for each configuration. Higher elastic modulus is indicative of the stiffness of the structure and its resistance to cyclic fatigue loading.^(24,25,26,27)

Ideally, a more statistically significant number of samples of each configuration would be tested (30 or more), but pragmatic constraints limited the number to only three.

Finally, one new sample is assembled with the mating plastic shear bushings and a structural member attached to one side of the tube only. The purpose of this test is to determine the worst-case safety factor of the bushing’s ability to protect the FRP tube under compressive torque loading. This configuration is shown in Figure 7. The bolt is tightened beyond the recommended 39 N-m (29 ft-lbs) of torque until audible cracking in the tube is heard. Audible cracking is indicative of the fibers in the composite breaking and the beginning of degradation of the FRP.⁽²⁴⁾ The tube will only take a few N-m (ft-lbs) of torque beyond this point before it catastrophically fails as shown in Figure 1.⁽¹³⁾

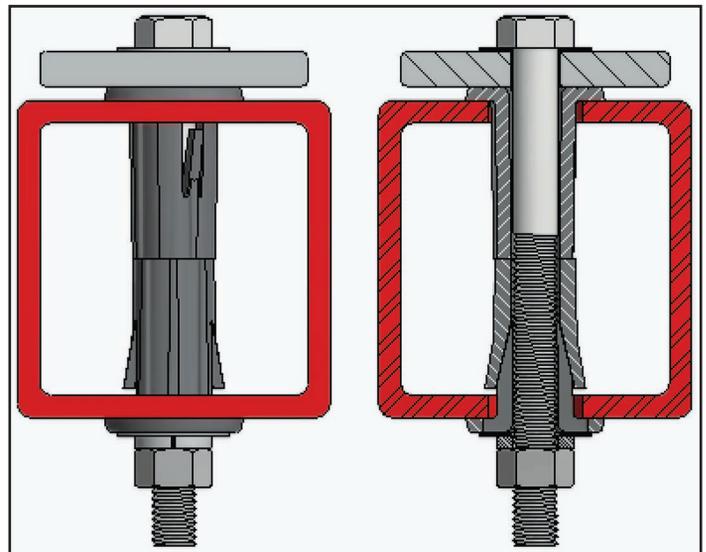


Figure 7 – Configuration № 6 Mating Shear Bushings: Compression Safety Factor Test

Predicted Results:

Tensile Testing

As stated above, the predicted failure mode during the testing is bearing failure. Based on data in the public domain and conventional engineering analysis, the ultimate predicted failure values and modes for the samples being tensile tested are summarized in Table 2.

CONF. NO.	TUBE STRENGTH kN (POUNDS)	STRAP STRENGTH kN (POUNDS)	PREDICTED FAILURE POINT
№ 1	67 (15,000)	100 (22,500)	TUBE
№ 2	133 (30,000)	100 (22,500)	STRAP
№ 3	117 (26,250)	100 (22,500)	STRAP
№ 4	133 (30,000)	100 (22,500)	STRAP
№ 5	133 (30,000)	100 (22,500)	STRAP

Table 2: Theoretically Predecited Results

For reference, extrapolating the methodology detailed in Reference 17, the theoretical strength of an 8-screw, 100 mm long (4” long) epoxy adhesive connection to a 76.2 mm wide (3.0” wide) strap is about 98 kN (22,000 pounds).

Bushing Compression Testing

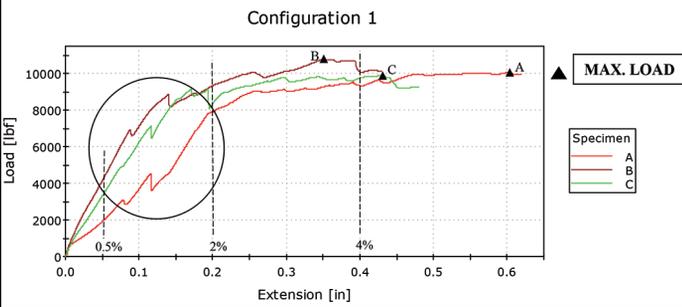
For the one sample being tested for bushing/FRP tube compression failure (Figure 6 – Configuration № 6), based on the mechanical design of the mating shear bushings and the published properties of the plastic polycarbonate-blend material, the failure mode is predicted to be compression/cracking of the bushing’s flange at 31 kN (7,000 pounds). This is slightly higher than the theoretical yield strength of the bolt (about 29 kN (6,500 pounds)), so it is expected that there could be some inelastic deformation of the bolt.^(11,22) The torque value at which this would occur is, therefore, unpredictable.

Also, it is expected based on the development history of this component that the bushing without the benefit of the structural member over it to distribute the compressive force is the one that will first show evidence of damage. The washer on the bushing without the benefit of the structural member to distribute the load will be deformed and drawn into the clearance hole.

The full-length stainless-steel bearing tube is not tested in this fashion because its theoretical compressive strength of the steel tube is more than 40kN (9,000 pounds), far exceeding the bolt’s tensile yield limit.^(13,22)

Actual Results & Interpretations – Tensile Testing:⁽²⁸⁾

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 4% STRAIN: kN (Pounds Force)	LOAD AT 0.5% STRAIN kN (Pounds Force)	MODULUS AT 0.5% STRAIN kN/mm (Pounds Force/Inch)
A	44.80 (10,071)	41.59 (9,349)	8.54 (1,921)	6.72 (38,420)
B	48.00 (10,790)	44.89 (10,092)	18.43 (4,144)	14.51 (82,880)
C	44.05 (9,902)	43.37 (9,751)	14.68 (3,301)	11.56 (66,020)
MEAN	45.61 (10,254)	43.29 (9,731)	13.88 (3,122)	10.93 (50,914)



Configuration 1

Configuration № 1

(Figure 4A – No Shear Bushing/Pinned Connection)

As the pictures in Figure 8 show, the failure points are the bearing surfaces in the tubes (as predicted). The straps and bolts showed no visible deformation. These results mimic those reported in the prior noted references: Ultimate failure occurs very near the 4% elongation value at loads that are far lower than theoretically predicted. Additional loading simply tears the bearing surfaces out catastrophically. More significantly and surprisingly, however, the curves above show the bearing areas distinctly breaking down along the way to 4% elongation, notably near the 1% and the again at the 2% elongation levels. (These were audible events during the testing.) From this testing, a case could be made that the samples actually failed when the curves began to flatten at 2% at 35.6 kN (8,000 pounds). Were these samples of metal construction (ductile in nature), they would be classified as “yielding” at this point. The modulus calculation for this configuration was done at only 0.5% strain for this reason. These values are highly varied and of questionable significance. The pictures in Figure 8 point to the reason that the bearings failed at less than two-thirds of the theoretically predicted levels. The predicted values assume negligible clearance and inelastic bodies, i.e., it assumes the bearing pressure is uniformly distributed. The reality, as shown in Figure 9, is that the bearing pressure is concentrated over a much smaller effective area due to the hole clearance needed for practical assembly.⁽²⁹⁾



4% Elongation Point

Failure At >4% Load

Figure 8 Configuration № 1/Sample A: 44.8kN (10.0 K-Pounds)

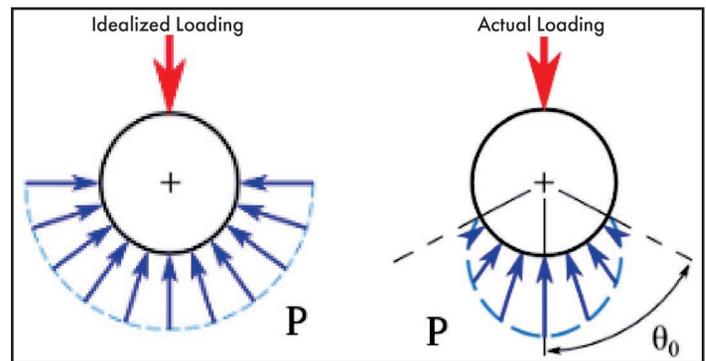
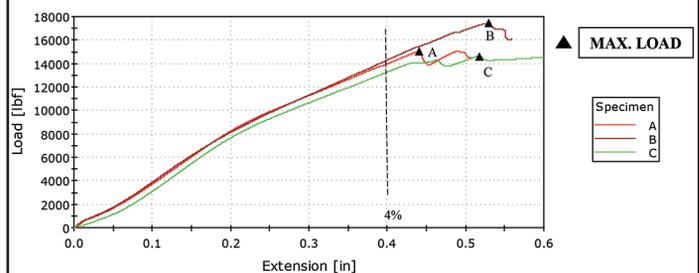


Figure 9: Bearing Pressure Concentration

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 4% STRAIN: kN (Pounds Force)	MODULUS AT 4% STRAIN kN/mm (Pounds Force/In)
A	67.00 (15,062)	62.11 (13,962)	6.34 (34,905)
B	77.63 (17,453)	63.57 (14,291)	6.47 (35,728)
C	65.03 (14,620)	59.02 (13,268)	6.02 (33,170)
MEAN	69.89 (15,712)	61.56 (13,840)	6.28 (34,600)

Configuration 2



Configuration № 2 :

(Figure 4b – Standard Partial-Length Shear Bushing/Pinned Connection)

These curves show the samples behaving much more consistently and predictably with the addition of shear bushings. The bushings double the shear-bearing area and distribute the pressure more uniformly. Catastrophic tear out of the tubes was not observed. This can be seen in the pictures in Figure 10. Theory predicted the failure mode would shift to the strap and should have held to 100 kN (22,500 pounds). The mean was 70 kN (15.7 k-pounds) – 70% of the predicted value. The straps did not have the benefit of a bushing and the effect of bearing- pressure concentration in the straps (as shown in Figure 9) is the likely explanation of the deficit. The bolts also deformed inelastically, indicating that system failure is fairly uniformly distributed across all the components at this point.

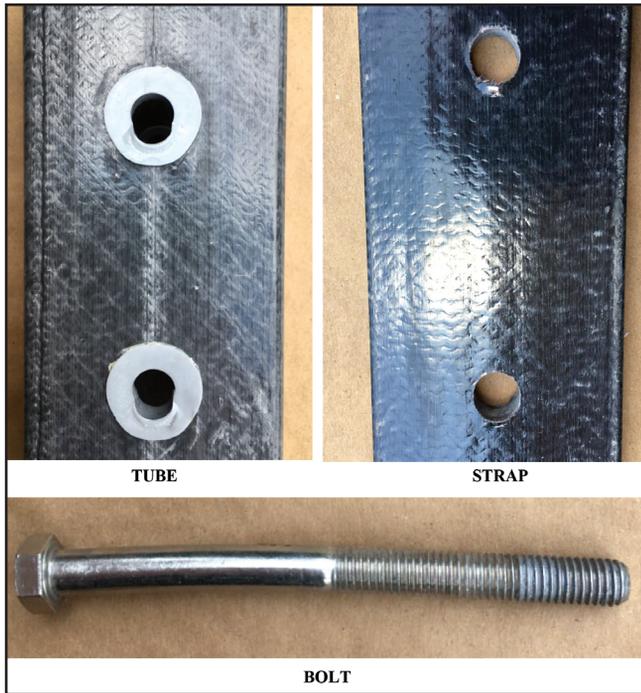
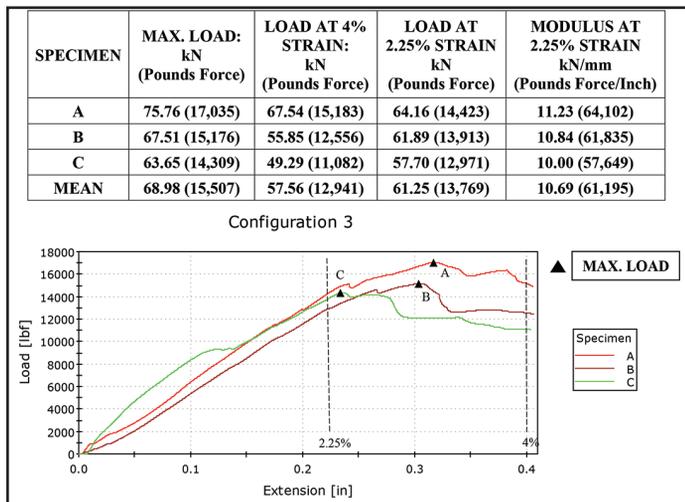


Figure 10: Configuration № 2/Sample B17.4 K-Pounds (77.6 Kn)



Configuration № 3 (Figure 4c – S.S. Full-Length Tube/Torqued Connection)

The pictures in Figure 11 again show the system uniformly failing at the tube bearing surfaces, the strap bearing surfaces, and the bolt itself. The combination of the full-length stainless-steel shear bearing and the clamped connection produced a much stiffer system – about twice that of the plastic bushing in a pinned connection, based on the system’s modulus data. Failure occurred at approximately the same level of loading, but only at half the elongation due to the increased stiffness of the system.

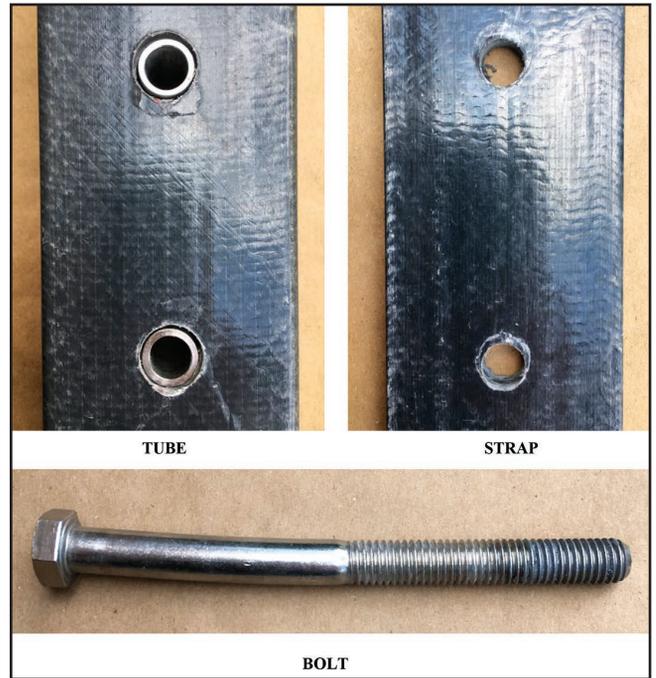
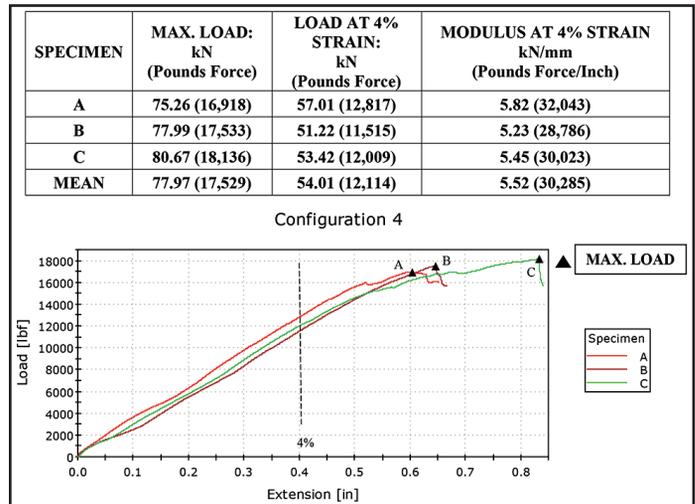


Figure 11: Configuration № 3/Sample A 75.8 Kn (17.0 K-Pounds)

Theoretically, there should not be a significant performance difference between Configuration № 2 and № 4: Both are Ø25.4 mm (Ø1”) shear bushings treated as pinned connections. However, these test results show № 4 produces about 12% higher ultimate strength than № 2 and elongates about 20% further before ultimate failure. This is likely due to the advantage of the larger diameter and thickness of the flanges to distribute the loading, as previously predicted in References 7 and 8.



Configuration № 4 (Figure 4D – Mating Full-Length Mating Bushings/Pinned Connection):

Just in terms of ultimate tensile strength, as theory expected, there was not a significant difference between the pinned of Configuration № 4 and the tightly bolted connection shown here. The failure modes uniformly included the bearing surfaces in the strap and the bolts. The difference between Configuration № 4 and № 5 was expected in joint stiffness, as evidenced by overall system modulus. The tightly-bolted connection did show about an 8% increase in system modulus at 4% strain.

It was noted earlier that 1.3 kN (300 pounds) of pre-load was placed on each specimen before bolts were snug- or torque-tightened to take the slack out before actually performing load testing. This pre-

load is not present in field installations. Unfortunately, this tended to mute the effectiveness of using the slope of the force-displacement curves as a proxy for system stiffness. That said, however, comparing the curves of configuration № 4 (snug-tight) and № 5 (torque-tight), there is a distinctly steeper slope of the curves in № 5 at the start of the test and a knee transition point at 0.5% elongation. This corresponded to a system load of 13.3 kN (3000 pounds). The modulus at this point is very similar to the stiffness performance of the solid stainless-steel tube in a torqued condition



Figure 12: Configuration № 4 / Sample C 80kn (17.5 K-Pounds)

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 0.5% STRAIN kN (Pounds Force)	MODULUS AT 0.5% STRAIN kN/mm (Pounds Force/Inch)	LOAD AT 4% STRAIN kN (Pounds Force)	MODULUS AT 4% STRAIN kN/mm (Pounds Force/Inch)
A	72.91 (16,391)	13.32 (2,995)	10.49 (59,900)	53.98 (12,136)	5.01 (30,340)
B	85.27 (19,169)	13.21 (2,970)	10.40 (59,400)	62.71 (14,098)	6.40 (35,245)
C	73.86 (16,605)	14.00 (3,148)	11.02 (62,960)	58.22 (13,089)	5.94 (32,723)
MEAN	77.35 (17,388)	13.51 (3,038)	10.63 (60,753)	58.30 (13,107)	5.95 (32,768)

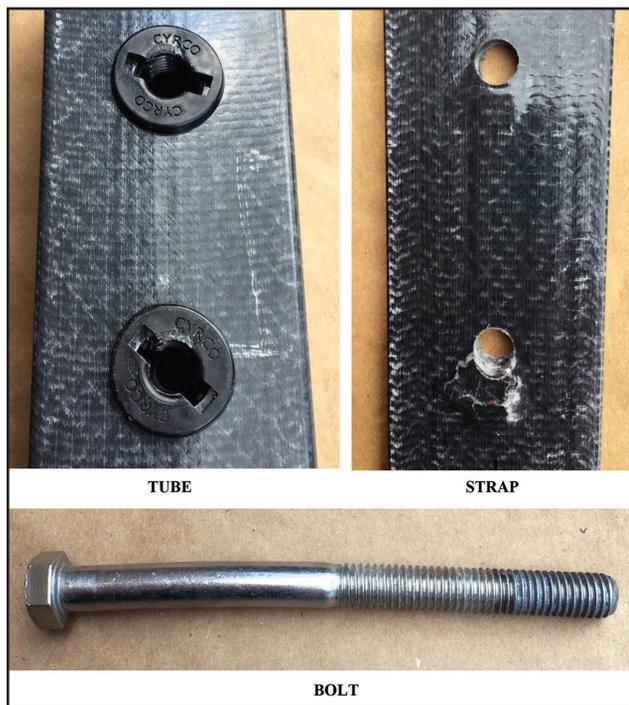
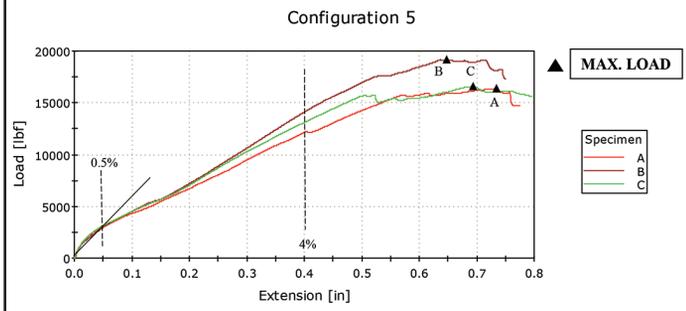


Figure 13 Configuration № 5 / Sample B 85.3kn (19.1 K-Pounds)

Actual Results -- Bushing Compression Testing:

Finally, as stated above, one new test configuration (Figure 6 – Configuration № 6) was built to test the mating, full-length shear bushings’ safety factor under connection torque compression. The bolt was tightened beyond the recommended 39N-m (29 ft-lbs) until audible stress could be heard from the tube, indicating that the fiberglass strands in the FRP were beginning to crack.⁽²⁴⁾ This started at about 79 N-m (58 ft-lbs), although only minor deformation of the FRP tube was evident based on visual inspection. The test was stopped at 84 N-m (62 ft-lbs) when the flange on the shear bushing without the benefit of a structural member over it to distribute the load developed a crack. The components were disassembled for inspection. No permanent (inelastic) deformation or visible physical cracking was apparent in the FRP tube. The tubular areas of the shear bushings did show some signs of the beginning of inelastic buckling as show in Figures 14A & B below. Some compression/ deformation was also noted at the bushing’s interfaces. As expected and stated above, the flange crack developed in the bushing without the benefit of the structural strap above it to distribute loading: The flat washer was inelastically deformed after being drawn into the hole of the bushing, creating a wedge-effect to crack the flange.



Figure 14a Compression Over-Stress Test 84 N-M (62 Ft-Lbs) Torque

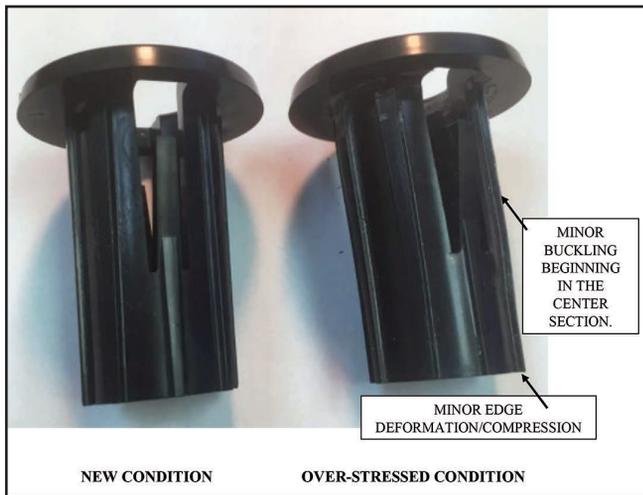


Figure 14b: Compression Over-Stress Test 84 N-M (62 Ft-Lbs) Torque

Summary:

With no shear bushings or with only partial-length shear bushings, bolts cannot be adequately tightened without cracking the FRP tube, so only pinned connections can be attained. This work demonstrates that pinned joints do perform comparably to tightly-bolted connections when considering only their ultimate tensile strength performance.

Various methods have been used to realize pinned connection in the field. Field experience has demonstrated that using a “snug-tight” method as defined by a flattened helical lock washer is inadequate to ensure that the fasteners stay in place for the expected life of the structure. A self-locking nut of some type (Nylok®, Nyloc®, Durlok®, Flexloc®, locking collar, castellated nut, etc.) or an anaerobic adhesive should always be specified for bolted pinned connections. Of course, using clevis pins with hairpin cotter retainers are also a viable option.

Ideally, the shear bushings should run the full-length of the tube and be made of an engineering-grade polymer or stainless steel to protect the tube. This allows standard, lubricated stainless-steel fastener hardware to be used without the addition of adhesives, and the fasteners can be fully tightened to the recommended 75% of their proof load. This will ensure that the fasteners stay tight and a stiff, friction-type clamped connections achieved. Tight connections results in a higher structural stiffness as shown in the higher system modulus numbers.

Using properly designed rigid full-length tubing or mating sheer bushings offers a torque-compression safety factor of at least twice the recommended torque value for the fastener. This torque value far exceeds what common commercially available 9.6 mm (3/8”) square-drive Li-Ion impact wrenches are capable of producing with a 19 mm (3/4”) socket.⁽¹³⁾ So battery-powered impact wrenches can safely be used. The integrity of the FRP tube will not be compromised. The decrease in assembly time and the quality guarantee this offers can offset the added cost of the full-length bushings.

It’s clear from the results summarized in Table 3 below that addition of shear bushings of any type dramatically improves the ultimate performance of bolted connections made to FRP tubes under tensile-loading conditions. With shear bushings, bolt threads are kept out of contact with the FRP tube. Bearing stresses are more uniformly distributed in the clearance holes and the forces in the overall structural system will be better distributed between the tube, strap, and bolt: The bearing surfaces in the FRP tubes won’t be the “weak link”. A much stronger, more consistent, and more durable structure can be expected. It’s not unusual for the diagonal members of typical cooling towers to routinely withstand cyclic loads of more than 27.6 kN (6,200 pounds).⁽³⁰⁾ Peak loading can exceed 37.8 kN (8,500 pounds) during severe hurricane conditions or seismic events^(13,24).

CONFIGURATION	CONNECTION TYPE	AVG. MAX LOAD kN (POUNDS)	FAILURE MODE
№ 1 – NO SHEAR BUSHING/BEARING	PINNED	45.6 (10,254)	TUBE
№ 2 – Ø25.4 mm (Ø1”) PARTIAL PLASTIC SHEAR BUSHING	PINNED	69.9 (15,712)	UNIFORMLY DISTRIBUTED
№ 3 – Ø19 mm (Ø¾”) FULL-LENGTH S.S. SHEAR BEARING	CLAMPED	69.0 (15,507)	UNIFORMLY DISTRIBUTED
№ 4 – Ø25.4 mm (Ø1”) CUSTOM FULL-LENGTH MATING PLASTIC SHEAR BUSHING	PINNED	78.0 (17,529)	UNIFORMLY DISTRIBUTED
№ 5 – Ø25.4 mm (Ø1”) CUSTOM FULL-LENGTH MATING PLASTIC SHEAR BUSHING	CLAMPED	77.4 (17,388)	UNIFORMLY DISTRIBUTED

Table 3

It should be noted when reviewing the actual test data included here that these results were obtained under typical, ideal laboratory conditions: Room temperature and dry. Both CTI and FRP manufacturers recommend derating published material properties for higher temperatures and wet conditions.⁽²⁰⁾ It also must be emphasized again that this work is limited to tensile-only ultimate load testing (see “Future Work” below for additional comments). It’s critical that thorough structural analysis be performed and connections properly designed and tested with adequate safety factors in place to withstand both cyclical and worst-case peak loading.

Future Work:

As noted earlier, this testing was limited to tensile-only loading, primarily to compare bearing joint strength of different bolted connection configurations. In real-world application, the stresses in the connections fluctuate widely between tension and compression (cyclic-fatigue loading). Very limited reference work is available on the fatigue behavior of bolted joints for pultruded composites.^(31,32) From the initial work presented here, there is a reasonable expectation that the performance of tightly-bolted connections using either full-length plastic or metal bushings would far exceed the performance of a pinned connection without the benefit of shear bushings. But, there is clearly an opportunity for valuable future technical contributions to the body of knowledge surrounding these FRP structures: Comparing pinned to tightly bolted connections under cyclic fatigue loading conditions.

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Cold Water Data Collection Method For An Individual Cell Of A Multicell Tower

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Brentwood Industries India Pvt Ltd

Abstract:

There are instances when an owner wants to assess the thermal performance of just an individual cell of a cooling tower as per ATC 105. But the cold-water outlet being common for the entire tower it has been very difficult to devise a method wherein a cell can be isolated from the tower and thermally tested. This paper addresses a solution to this problem encompassing initial ideas, challenges faced, and troubleshooting involved in a fill demonstration test conducted in India as per CTI ATC-105, utilizing a unique, modular and cost-effective test set-up to thermally assess an individual cell of the tower.



Navneet Kishor Dubey

Introduction:

A cooling tower is a direct contact heat exchanger, working with air and water as the two fluids. It utilizes the concept of transfer of latent heat (evaporative cooling) and transfer of sensible heat (convection) between air and water to reduce the temperature of hot water coming in from a process. Cooling towers find application wherever a process dissipates some amount of heat and requires cooling nearest to wet-bulb temperature so that the process runs continuous in operation. One of the major area of requirements of cooling towers are in thermal power plants.

The function of a cooling tower in a thermal power plant is to provide cooling water to the steam condenser. Generally, the basic function of a condenser in a thermal power plant is to convert low pressure steam to low pressure liquid (Refer Figure-1: condenser in a thermal power plant). This conversion in a condenser uses cold water coming in from a cooling tower (in a closed-loop system) to condense the steam coming in from the turbine into water. The efficiency of this conversion of water from steam is highest when the water received from the cooling tower is coldest. The more efficient the conversion of steam into liquid, the more steam is generated per kg of coal burned. Hence, it is essential that the cooling tower performs as per its design.

Due to the importance of the cold-water temperature supplied by a cooling tower, it becomes essential that its performance be monitored periodically, and appropriate measures are taken to maintain its design performance so that the process is not adversely affected. To evaluate a cooling tower's thermal capability CTI suggests the standard specifications of ATC-105, "Acceptance Test Code for Water Cooling Towers". This standard includes crucial guidelines such as conditions of test, instruments and measurements, report of results, evaluation of results etc. in detail.

The Fill Demonstration Test:

A leading thermal power plant in India was facing performance and fouling issues in their induced draft counter-flow tower and was looking for a fill replacement option that will be optimum for their application. To fulfil their purpose, they desired to conduct a one-of-a-kind fill demonstration test. They devised a test plan wherein four consecutive cells out of an inline tower of ten cells were chosen and were retrofitted with four types of fills with different flute orientations namely- cross-fluted (OEM), offset- fluted, vertical-fluted, modular splash. All four cells were retrofitted and, allowing an aging period of six weeks were individually tested to determine their thermal capability along with their weight gain (fouling) simultaneously. The general stipulations for this test were:

1. The cooling tower thermal performance assessment is carried out single cell wise.
2. The capability test of four cells to be carried out on the same period and performance assessment test to be repeated at least 6 times in the first two years.
3. The blade angle of the four CT fans of the cells to be tested was agreed to be same for all the four cells with no change in blade angles of the fan for entire two years of the demonstration program.
4. The water distribution nozzles of all the four cells to be inspected and repaired/replaced before each test to get uniform water flow distribution.
5. No cleaning of fills to be done in the four cells during the demonstration program.
6. Maintenance of proper water quality as per standard guidelines of the power plant was mandated during the demonstration program.
7. Testing, would not be carried out in the months of November through February due to ambient weather condition restrictions.
8. Fill weight to be taken at the locations agreed upon for each cell during the test to observe and record the clogging pattern of the fills in the test cells.

The Problem:

Thermal capability assessment of a cooling tower, requires measurement of following parameters:

1. Circulating Water flow
2. Water Temperature
3. Hot water temperature
4. Cold water temperature
5. Inlet air temperature
6. Inlet wet-bulb
7. Inlet dry-bulb
8. Fan driver output power
9. Wind Velocity
10. Water analysis

An accurate measure of the cold-water temperature is a crucial practice to analyze the thermal performance. Section 3.2.2 of ATC-105 specifies the details on location of cold water temperature measurements for the tower as- "Cold circulating water temperature measurements should preferably be made in a full flowing bleed stream at the circulating pump discharge, and the average corrected for heat added by the pump." The Fill Demonstration Test required all the four cells to be individually tested and to be analyzed for performance and weight gain. Hence, this guideline could not be used. The need was to measure the outlet cold water temperature from each cell and then carry out the comparison. The fact that the tower had a common cold-water basin, rather than having an individual cold-water basin for each cell- presented a challenge to come-up with a way to measure the outlet cold water temperature from each cell.

The Challenge:

The absence of literature to test an individual cell - having a common cold-water basin with the tower with adherence to the well accepted ATC-105 testing procedure was realized. The challenge was to treat each cell as a separate isolated entity and come-up with a way to create a cell's own cold-water basin; collecting all the water exiting from a cell and then using an appropriate arrangement of multiple probes that can measure the temperature of the water coming into the surrogated cold-water basin whilst ensuring that the cold water returns to the common cold basin so that the process is not affected. (Refer Figure-2: the idea of intermediate basin).

The solution of this challenge was to create an intermediate cold-water basin and was carried out in two basic steps:

- **STEP I:**

A way to design and build the intermediate basin.

- **STEP II:**

A way to direct all the cold water falling into the existing cold-water basin to the intermediate basin such that the cold-water measurement could be accurately depicted.

The Solution:

The information provided by the power plant about the tower is as follows:

Inline tower comprising of ten cells. Each cell is divided between two parts at the center along the length with a four-inch partition wall. Each cell has two hot water risers delivering water to the cell. The dimensional details of each cell are as below:

- Design flow per cell = 3333 m³/hr [14,675 gpm]
- Face-to-face length of longitudinal bay = 3963 mm [13ft]
- Face-to-face Length of the cell = 12568 mm [41ft-3in]
- Width of the half-cell = 8992 mm [29ft-6in]
- Width of the entire cell = (2 x 8991.6) + 101.6 mm width of dividing wall = 18084.8 mm [(2 x 29ft-6in) + 4in width of dividing wall = 59ft 4in] – (Refer Figure 3: Dimensions of the cell)

Solution to STEP I:

The intermediate basin was designed to collect the cold water coming from the cell and then to continuously discharge the collected water back to the tower's cold-water basin to without any stagnation of water. A form of water collecting "troughs" was evolved to address the purpose. (Refer Figure 4- Design of Water Trough used as an intermediate basin).

With the presence of three bays and the center-to-center length of each longitudinal bay being 4.26m [14ft], the number of troughs per side was decided to be three for the sake of portability, and length of each trough to be placed in front of each bay was decided to be 4.26m [14ft]. Each trough was designed with integral weirs so that the water flows continuously through the weirs into the existing cold-water basin. Cold water temperature collecting probes were fastened in front of the weirs so that they received fresh and well-mixed cold water continuously.

The dimension and number of weir notches in each trough depended on the flow through each weir. To establish a correlation between weir dimension and flow through each rectangular weir, the Francis formula was applied:

$$q = 3.33 \times (b - 0.2h) \times h^{\frac{3}{2}} \quad \text{Equation 1}$$

Where,

q = flow rate (ft³/s)

h = head on weir (ft)

b = width of weir (ft)

Design flow per cell = 3333 m³/hr [14,675 gpm]

Therefore, design flow per side = 3,333/2 = 1666.5 m³/hr [7,337.5 gpm]

After a couple of iterations to get a set of values that would be easy to fabricate values of b and h were found as:

b = 305mm [12inch] and h = 152mm [6inch], value of q = 1.06 ft³/s = 476 gpm was calculated.

Number of weir notches = 7337.5/476 = 15.4 ≈ 15 or 5 weir notches per 4.26m [14ft] trough.

Then, the center of each 305mm [12in]-wide notch was spaced 853.5mm [33.6in] apart, starting 432mm [17in] away from each end. Thus: (853.5 x 4) + (2 x 432) = 4.26m [14ft].

Hence, a total of six troughs (three per half-cell) each measuring 4.26m [14ft] and containing five rectangular weir notches of 152mm [6inch] deep and 305mm [12inch] wide was used as intermediate basin (refer figure 5: Dimension of water trough).

Solution to STEP II:

Construction of false floor:

To direct the cold water falling from the fill into the intermediate basin, a false floor of corrugated galvanized steel sheets, galvanized pipes, and clamps and good quality tarpaulins covering the cold-water basin was made. Galvanized materials were used because of its strength and resistance to corrosion. The idea was to run first set of pipes along the edge of the existing beam providing as the base for rest of the scaffolding set-up. Another set of pipes was run perpendicularly to the existing basin beams. The connection between the first and second set of pipes was done using clamps designed for that purpose. The placement of second set of pipes was done at every 20% of the face-to-face distance between the columns.

For example:

Face-to-face distance between the columns = 3962mm [13ft]

Place a rod at every 792mm [31.2inch] of the beam length or 5 pipes placed transversely throughout a horizontal beam of 3962mm [13ft].

After laying down the second set of pipes, galvanized corrugated sheets were laid down covering the entire scaffolding of pipes. Finally, the sheets were covered with tarpaulins to minimize any water leakage in the basin. This system formed a temporary "false floor" on which the cold water flowed into the collection troughs.

Angle of inclination of false floor:

The "floor" was set at a slight slope so that the water falling on the floor moved down the incline; inhibiting the stagnation of water. After trying different angle of inclinations for the set-up it was observed that with an angle of approximately two degrees the water falling from the fill easily cascaded down to the water collection troughs. To create a slope of about two degrees, the vertical distance from the horizontal beams over the cold-water basin to the false floor was calculated to be 314mm [12.36inch] which can be considered as approximately 305mm [12inch].

◆ Refer Figure 06: Calculation of angle of inclination for bed.

$$\tan\theta = \frac{\text{Perpendicular}}{\text{Base}}$$

$$\text{Perpendicular} = \tan\theta \times \text{Base} \quad \text{Equation 2}$$

$$\therefore \text{Perpendicular} = \tan(2) \times 8992\text{mm}$$

$$\text{Perpendicular} = 0.349 \times 8992\text{mm} = 314\text{mm [12.4inch]}$$

To achieve this height, mortar bricks were used.

Hence, a scaffolding using pipes, corrugated steel sheets, clamps and tarpaulins was made at an angle as a floor to direct water into the intermediate cold-water basin (Refer Picture set- 1).

Sample of Data Collection:

In this project – for one cell (having two air inlets) a total number of six troughs (three on each side) were used. Each trough was equipped with two probes. Hence a total number of twelve probes for collecting cold water were used per cell and then the average of all the cold-water probes were taken. (Refer Sheet 1: Sample Data Sheet)

Troubleshooting:

In the first attempt to lay down the scaffolding between the columns with face-to-face distance of 3.35m [11ft.], three pipes were placed equidistant from each other i.e. every 30% of the face-to-face distance between the columns to act as a base for the set-up. After the entire scaffolding was installed, the cell was to be tested the day after. On arriving to the site, the next day, it was observed that because of increase in water flow during night, the set-up was not able to withstand the prolonged load of water, the pipes buckled, and the entire set-up collapsed. (Refer Picture set – 2). In order to rectify the situation and avoid the problem next time, the span for placement of pipes was reduced to existing 20% and the earlier used medium gauge pipes were replaced with heavy gauge pipes. No failure has been observed ever since.

Conclusion:

Engineering is not always just about formulas and calculations it is also about innovation and experiments. The quest to fulfil the customers goal on how to devise a test set-up for an individual cell, challenged Brentwood's team to come-up with a modular, portable, cost effective and rugged test set-up that can be used for all sizes of counter-flow towers with great ease. The test set-up's pragmatic nature helped Brentwood to test several different counter-flow cells of various towers across the country.

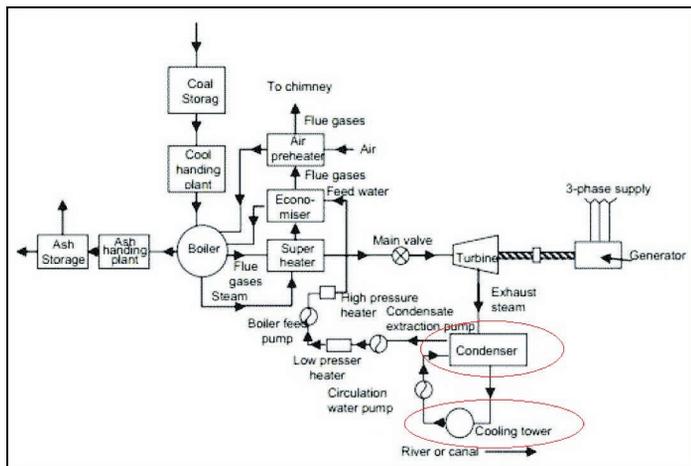


Figure 1: Condenser in a thermal power plant

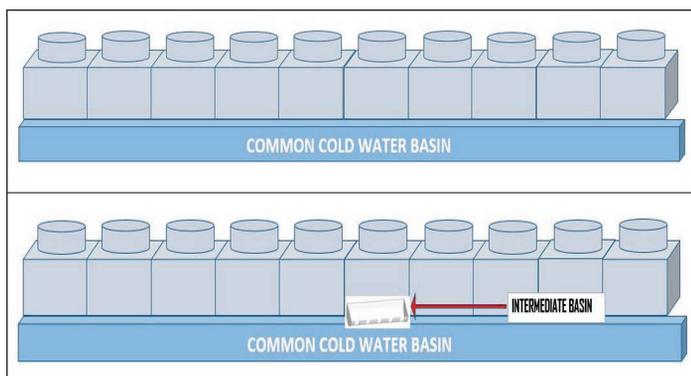


Figure 2: The idea of intermediate basin

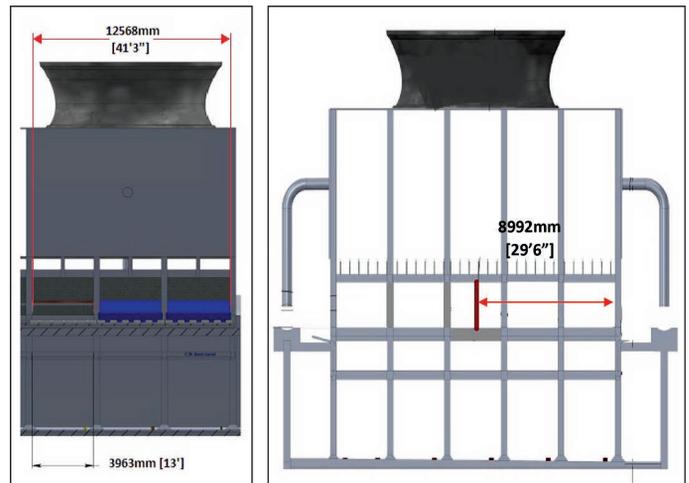


Figure 3: Dimensions of the cell

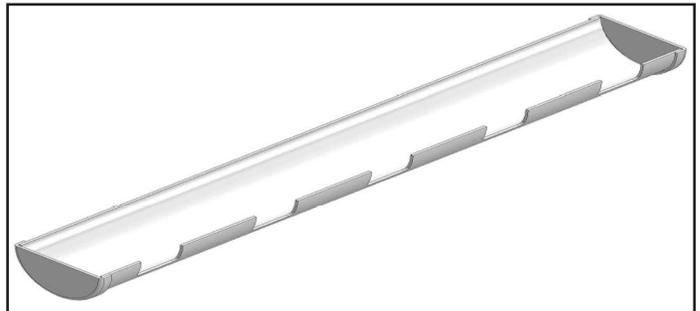


Figure 4: Design of Water Trough used as intermediate basin

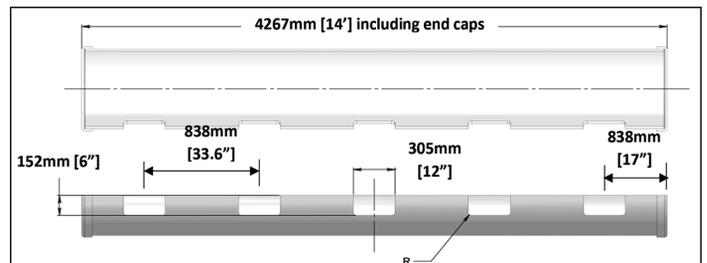


Figure 5: Dimension of water trough

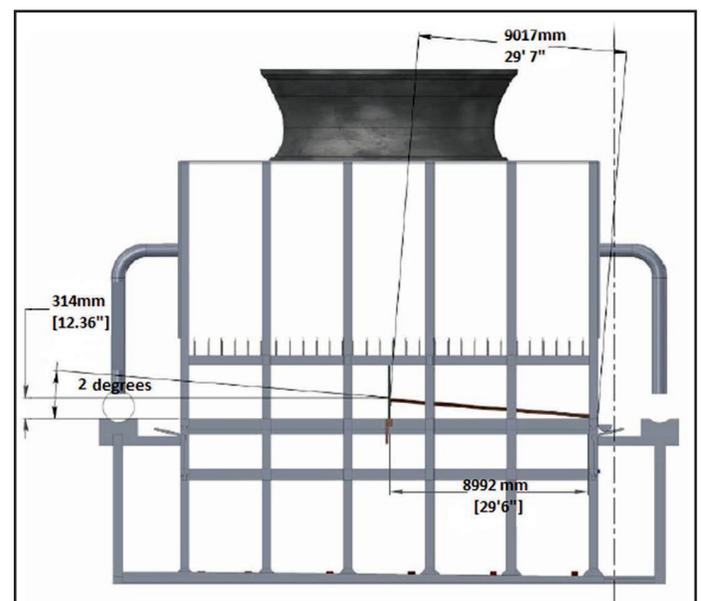
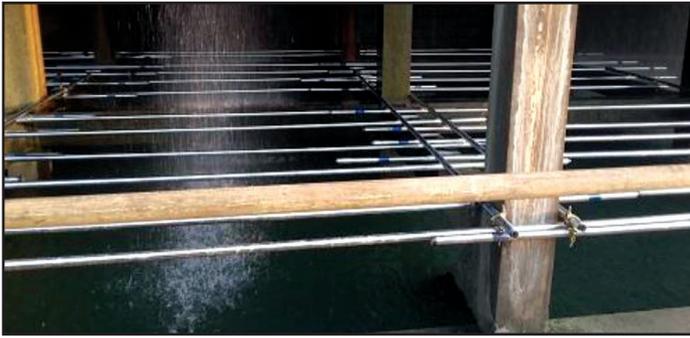


Figure 6: Calculation of angle of inclination of bed



Picture Set 1.1: Layout of the galvanized pipes



Picture Set 1.2: Connection between two pipes using galvanized clamps



Picture Set 1.3: Use of bricks to create inclination



Picture Set 1.4: Placement of corrugated galvanized sheets



Picture Set 1.5: Placement of water collection troughs



Picture Set 1.6: Placement of Tarps



Picture Set 1.7: Placement of corrugated galvanized sheets along the cell boundary



Picture Set 1.8: Placement of temperature probes



Picture Set 1.9: The setup in operation

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	DBT
1	Scan	CWS1	CWS2	CWS3	CWS4	CWS5	CWS6	WHT1	WHT2	CWS1	CWS2	CWS3	CWS4	CWS5	CWS6	WHT	WHT	DBT	
481	480	35.655	36.035	35.521	35.384	34.756	33.987	27.306	45.102	34.3	34.07	36.868	35.626	33.406	32.988	45.128	26.441	36.111	
482	481	35.527	35.85	35.416	35.242	34.648	33.881	27.191	45.079	34.2	33.998	36.789	35.555	33.456	33.021	45.104	26.523	36.108	
483	482	35.154	35.641	35.301	35.182	34.61	33.753	27.188	45.047	34.102	33.945	36.707	35.565	33.444	33.056	45.072	26.574	36.106	
484	483	35.265	35.531	35.278	35.168	34.621	33.686	27.129	45.029	34.213	33.904	36.675	35.672	33.421	33.095	45.038	26.593	36.093	
485	484	35.271	35.512	35.132	35.191	34.567	33.686	27.192	44.964	33.978	33.909	36.756	35.777	33.045	33.124	44.989	26.561	36.161	
486	485	35.302	35.561	35.11	35.146	34.532	33.662	27.24	44.916	34.046	33.976	36.808	35.815	33.48	33.114	44.945	26.509	36.263	
487	486	35.32	35.596	35.055	35.142	34.49	33.642	27.302	44.871	34.094	34.001	36.844	35.779	33.453	33.089	44.905	26.455	36.337	
488	487	35.147	35.618	34.999	35.174	34.459	33.617	27.32	44.833	34.074	33.947	36.786	35.666	33.379	33.039	44.871	26.452	36.368	
489	488	35.156	35.67	34.969	35.152	34.442	33.596	27.363	44.807	34.01	33.87	36.756	35.669	33.327	33.044	44.852	26.488	36.404	
490	489	35.169	35.69	34.942	35.136	34.414	33.584	26.972	44.784	33.998	33.848	36.723	35.586	33.331	32.996	44.835	26.485	36.421	
491	490	35.167	35.742	35.02	35.182	34.362	33.553	27.409	44.784	34.056	33.901	36.668	35.62	33.343	32.973	44.825	26.463	36.441	
492	491	35.627	35.935	35.238	35.302	34.402	33.585	28.082	44.777	34.158	33.978	36.584	35.613	33.308	32.937	44.818	26.397	36.466	
493	492	35.662	36.212	35.304	35.311	34.616	33.693	28.327	44.778	34.251	34.042	36.508	35.57	33.281	32.875	44.814	26.344	36.498	
494	493	36.037	36.597	35.7	35.749	34.878	33.842	28.249	44.776	34.284	34.078	36.531	35.607	33.269	32.829	44.815	26.318	36.503	
495	494	36.076	36.433	35.744	35.897	34.983	34.134	27.949	44.785	34.281	34.061	36.597	35.552	33.246	32.804	44.813	26.35	36.534	
496	495	35.988	36.383	35.672	35.812	34.943	34.212	27.838	44.793	34.271	34.057	36.584	35.526	33.29	32.816	44.829	26.393	36.534	
497	496	35.85	36.29	35.614	35.688	34.85	34.183	27.344	44.8	34.21	34.083	36.67	35.533	33.361	32.861	44.838	26.513	36.534	
498	Average	CWT1	CWT2	CWT3	CWT4	CWT5	CWT6	WBT1	WBT2	CWT7	CWT8	CWT9	CWT10	CWT11	CWT12	WBT3	WBT2	DBT	
499		34.9056603	34.9097121	34.9087944	35.0056111	34.8791612	34.8811794	27.4482278	44.7942616	34.4641151	34.4396491	36.1663004	36.1604395	34.0109217	33.8429385	44.8307768	27.2893065	35.2470048	
500		CWT AVERAGE													34.8098915				
501		WBT AVERAGE													44.8154113				
502		WBT AVERAGE													27.4827871				
503		DBT													35.2470048				

Sheet 1: Sample Data Sheet



Picture Set - 2.1: Failure of set-up



Picture Set - 2.3: Deficient number of pipes



Picture Set - 2.2: Bent Pipes

References:

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2. CTI ATC-105 - Acceptance Test Code for Water Cooling Towers
3. CTI Cooling Tower Manual, Chapter 5, Cooling Tower Field Test Handbook



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Life-Cycle Cost Analysis For Concrete Cooling Towers

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Abstract

The deterioration of concrete cooling towers and the cost of repairing, rehabilitating, or replacing deteriorated tower structures is a major issue for tower owners and operators. This paper explores the application of a Life-Cycle Cost Analysis (LCCA) as a useful tool to predict and schedule maintenance and repair tasks for concrete cooling towers. Factors that affect the durability of concrete cooling tower structures, including concrete cover to reinforcement, type of reinforcement, concrete material properties, admixtures, concrete surface treatments, and environmental exposure, are discussed as input parameters to concrete service life prediction models.

Introduction To Life-Cycle Cost Analysis

Various parameters that are used in the design of structural systems for a wide variety of structures ranging from low-rise to high-rise buildings, stadiums and arenas, infrastructures like bridges, roads and pavements, water treatment plants, cooling towers ranging from modest rooftop units to industrial units and power plants all have significant impact on initial construction cost as well as the long-term maintenance cost. In the case of structures exposed to the environment such as bridges, open air stadiums, parking garages and cooling towers, structural engineers designing such facilities usually need to have extensive experience not only in design principles and codes, but also in the performance and limitations of various materials used in construction. This expertise enables the engineers to evaluate the structural performance under various environmental conditions keeping durability as an important factor in design.

In existing structures when repairs are required, it is also imperative that methods and procedures used by engineers keep in view long-term performance of repairs and structural durability.

A valuable tool that has become available to engineers is the Life-Cycle Cost Analysis (LCCA) to provide an actionable Capital Asset Management Plan (CAMP) for the long-term care of assets. Basically, for concrete structures, LCCA includes a detailed review of key factors that may cause premature deterioration initiated by cracking, water intrusion, carbonation and presence of deleterious materials leading to corrosion of embedded reinforcing bars that can potentially impact service life. Projected costs are based on assumed rates of inflation and time-value of money (interest rates) to provide a detailed financial outlook for assets. The reader is encouraged to find additional information about LCCA referenced in this paper.

Throughout their service life, cooling tower structures are exposed to harsh conditions due to moisture and environmental extremes such as freezing temperatures, high wind, and seismic forces. In many instances, cooling towers are located in coastal regions or ad-



Mark E. Williams

acent to large bodies of water that increase the risk of exposure to harmful chlorides. Where owners of such facilities do not have in-house engineering staff, specialized consultants are generally retained by the management to assist them in identifying, prioritizing, and addressing ongoing maintenance and repair needs to preserve asset value, functionality, and public safety. Where the maintenance may require a large capital outlay, it may also become necessary at times to develop a CAMP to spread the available maintenance funds over a specified period of years.

Advantages Of A Life-Cycle Cost Analysis

Basically, LCCA can be defined as a method for assessing the total cost of a facility ownership starting from construction to obsolescence. In the case of buildings, it has been assessed that “over a 30 year period, initial building costs accounts for approximately just 2% of the total, while operations and maintenance costs equal 6%, and personnel costs equal 92%”. (See Figure 1, Reference 1).



Figure 1: 30 Year Cost of Building (From Reference 1)

Another reference (Reference 2) indicates that “85% of the facility’s total cost is in operations and maintenance”.

Thus in order to minimize the overall cost of keeping an asset operational for the expected life of the facility, it becomes important to base the design using materials that will be durable and provide long-term serviceability with minimum downtime and operational cost.

Design professionals in all disciplines of a structure or infrastructure design are aware that there is no one solution that meets the design goals. Several options are available to the designers to meet both the goals of the owners and design professionals who are obligated to conform to the applicable codes and work within the standard of care for the project undertaken. Even though budgets and availability of funds drive the project, fairly quick economic evaluations can be made by conducting a LCCA. This would necessarily involve multi-criteria analysis, cost-benefit analysis and risk-benefit analysis (Reference 3). As described in Reference 3, “At one extreme lies the purely multi-criteria analysis, which employs weights from a variety of sources that contain a large degree of subjective as-

assessment. At the other extreme lies the purely cost-benefit analysis that exclusively employs monetary valuation and has generally more explicitly defined criteria.”

In researching published literature, it became apparent that no information is available on LCCA for any type of cooling towers. Reference 1 discusses LCCA of building related projects with an example of Heating, Ventilating, and Air Conditioning (HVAC). Reference 2 is a brief general presentation on LCCA. Reference 3 describes LCCA of pavement design.

From a historic perspective, it is also interesting to note, that LCCA has been around probably since 1978 when in November 1978, National Energy Conservation Policy mandated that all new federal buildings be evaluated using LCCA. (Reference 4). Section 545 of the Public Law 95-619, 95th Congress states:

Sec. 545. Establishment And Use Of Life Cycle Cost Methods.

42 USC 8255.

ESTABLISHMENT OF LIFE CYCLE COST METHODS.— The Secretary, in consultation with the Director of the Office of Management and Budget, the Director of the National Bureau of Standards, and the Administrator of the General Services Administration, shall— (1) establish practical and effective methods for estimating and comparing life cycle costs for Federal buildings; and (2) develop and prescribe the procedures to be followed in applying and implementing the methods so established and in conducting preliminary energy audits required by section 547.

USE OF LIFE CYCLE COSTS.— All new Federal buildings shall be life cycle cost effective as determined in accordance with the methods established under subsection (a). In the design of new Federal buildings, cost evaluation shall be made on the basis of life cycle cost rather than initial cost.

USE IN NON-FEDERAL STRUCTURES.— The Secretary shall make available to the public information on the use of life cycle cost methods in the construction of buildings, structures, and facilities in all segments of the economy.

From the above it appears that it is befitting for the engineers involved with the design and operations of the cooling towers to also make an attempt to incorporate LCCA in their holistic view of long-term performance of such facilities. One such model developed for a municipal infrastructure in Reference 5 can be also used to show the phases from cradle to grave for a cooling tower as well.



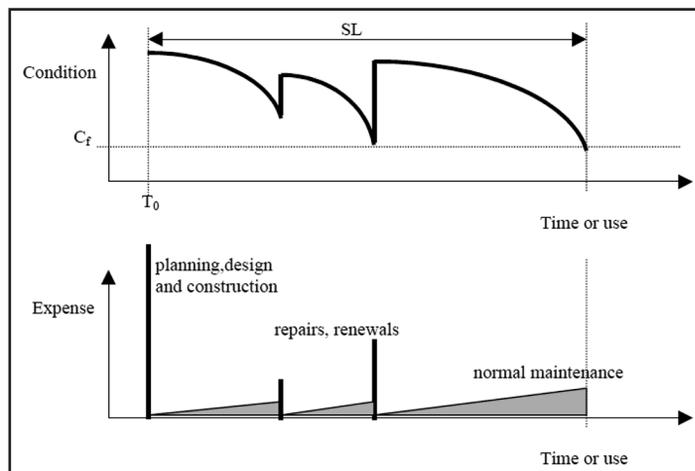
Figure 2: Life Cycle Phases for Cooling Towers (From Reference 5)

It is indeed fortunate that at this juncture, the cooling tower industry does not have to reinvent the whole process of developing LCCA for cooling towers. Fairly extensive studies have been done and published in matters pertaining to bridges, exterior structures that have similar environmental exposure to cooling towers. A noteworthy reference is National Cooperative Highway Research Program (NCHRP) Report 483 (Reference 6). As stated in the document referenced above, “The underlying motivation for using LCCA in bridge management is an understanding that tradeoffs are possible, e.g., spending to install more durable coatings of steel elements during initial construction in order to reduce the anticipated frequency of future repainting, or adopting a somewhat more costly design detail to make future maintenance easier and less costly.” The same opportunity exists for cooling towers also. Even though the serviceable life span of bridges are generally con-

sidered to be 30 to 50 years, changes in traffic pattern and need to upgrade load ratings may compel some bridges to fall in a state of obsolescence much earlier. Sometimes the lack of maintenance makes the rehabilitation uneconomical to the extent that demolition and rebuilding becomes the sensible option.

NCHRP has developed a conceptual “life-cycle activity profile” that graphically depicts expenditures over a certain time period as shown in Figure 2 (Figure 2.3 from Reference 6). This graphical description of expenditure related to life cycle is sometimes referred as “cash-flow diagram” which may also be termed as Capital Asset Management Plan (CAMP)

The same conceptual model shown in Figure 3 is also applicable to cooling towers. Even though published data is not available, it is suspected that many facilities that have significant cooling towers as assets lack the benefit of developing CAMP using LCCA. A lesson that has been often learned is that when maintenance is deferred, the resulting costs are much higher than that incurred in a methodical planned manner (Reference 7).



SL: Service Life
T0: Time Structure placed in Service
Cf: Threshold of Acceptable Functionality of Structure

Figure 3: Expenditure Related to Life Cycle

In one recent instance there was a significant capital outlay in upgrading and rehabilitating two concrete hyperbolic tower in a power plant in Jacksonville, Florida (Reference 8). However, within five years of the completion of the rehabilitation project, the needs of the cooling towers changed dramatically when a switch was made from using coal to natural gas in the power plant and consumer demand dropped significantly due to gains in energy efficiency. As a result, the two concrete hyperbolic cooling towers in the plant were no longer needed and they suddenly fell in a state of obsolescence. The decision was then made to demolish these towers using implosion techniques (Reference 9).

Life-Cycle Cost Analysis Of New Concrete Structures

Prior to completing the design of a new concrete structure, various design and material parameters can be studied to optimize the future performance and service life of a concrete structure. At a minimum, service life modeling for new concrete structures requires a knowledge of the following parameters:

1. Concrete mix design (new)
2. Structure type
3. Expected environmental exposure conditions

Based on the provided input parameters, study alternatives can be generated to look at the sensitivity of each of these parameters

as well as means to improve the overall durability of the concrete tower structure.

In the pre-design phase of a project, there are a number of variables that should be considered in the concrete service life modeling process, such as:

1. The initial cost of corrosion protection systems
2. Time to initiate corrosion of reinforcing steel
3. Future maintenance costs
4. Future repair cycles and repair costs
5. Anticipate service life of the concrete structure

The optimum service life can best be achieved in close consultation and design iteration between the owner and design professional.

Life-Cycle Cost Analysis Of Existing Cooling Towers

Prior knowledge of service life modeling of new concrete systems can easily be applied to the service life prediction of existing concrete cooling towers. Similar to the modeling parameters for new concrete, service life modeling for existing concrete structures requires a knowledge of the following parameters:

1. Existing concrete mix design and permeability (by concrete coring and laboratory petrographic analysis)
2. Structure type
3. Actual environmental exposure conditions
4. RILEM or similar permeability studies
5. Structural maintenance and repair history as well as costs for concrete repairs, waterproofing, etc.

Based on the determined input parameters, study alternatives can be generated to look at the sensitivity of each of these parameters as well as means to improve the overall durability of the existing concrete tower structure. Information obtained from the service life modeling will then inform the development of a CAMP so that owners can effectively forecast and budget for on-going maintenance and repair.

Case Histories

While there are published research studies and guidelines on LCCA for exposed concrete structures in USA (Reference 6) and Canada (Reference 5), there appears to be a lack of published or documented information on LCCA of either new or existing concrete cooling towers.

Since there are a large number of variables involved in performing LCCA of structures, it is appropriate to select the right software for the kind of structure under study. Several software packages are currently available in the industry. Some are very specific to a particular industry like the programs developed by Federal Highway Administration (FHWA) for performing the life cycle cost analysis of pavements (Reference 12). Some software packages may be termed as general purpose or standalone or not specific to a certain industry. Examples of these are:

1. D-LCC: Developed by SoHAR Incorporated - <http://www.sohar.com/reliability-software/d-lcc.html>
2. LccWare: Developed by Isograph Inc. - <https://www.isograph.com/software/availability-workbench/life-cycle-cost-analysis/>
3. Life-365: Developed by Consortium III – <http://www.life-365.org/consortium.html>
4. STADIUM (Software for Transport and Degradation in Unsaturated Materials): Developed by SIMCO - <https://www.simcotechnologies.com/what-we-do/service-life-durability-design-engineering/>

References to some other LCCA software packages and handbooks are listed in Reference 5.

After reviewing several software packages, the authors consider Life-365 Service Life Prediction Model™ to be an appropriate software for conducting LCCA on the nature of projects worked by them. These primarily involve a wide range of facilities where various types of concrete structures are exposed to aggressive environments.

Three case histories are selected which are described briefly below followed by a brief commentary on the applicability of the LCCA for concrete cooling towers. The first two cases studies present LCCA applications to new concrete structures with exposures similar to cooling towers and the third case study presents a LCCA for an existing concrete cooling tower. In all cases, Life-365 software was utilized to estimate the service life and life-cycle costs by changing various parameters pertaining to concrete construction (Reference 10). As discussed by the consortium involved with the development of the program, Life-365 follows ASTM E917-05, “Standard Practice for Measuring Life-Cycle Costs of Building and Building Systems” to estimate life-cycle costs (Reference 11).

Case History 1: New Medical Center Parking Garage

When the eight level Migo Garage in the Buffalo Niagara Medical Campus (Figure 4) was planned in 2011, the desire of the facilities management group was to have a post-tensioned concrete parking garage with built-in durability keeping in view a service life of at least 50 years.



Figure 4: Buffalo Niagara Medical Center Parking Garage

The Base Case parameters selected for the project were as follows:

1. High strength concrete: 5,000 psi
2. Water/cementitious ratio: 0.40
3. Fly ash: 20% cement replacement
4. Increased concrete cover: 2"
5. Epoxy coated reinforcing bars (top level slab only)
6. Silane sealer on all levels of slabs

Variables considered in the study were:

For Concrete:

1. Fly ash (Base Case)
2. Silica fume supplementary cementitious material as alternate to fly ash
3. Inhibiting crystalline waterproofing admixtures in concrete for slabs in all levels (Option 1, Table 1)

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- Corrosion inhibiting crystalline waterproofing admixtures in concrete for slabs in all levels (Option 2, Table 1)

For Reinforcing Steel:

- Higher concrete cover than that specified in ACI 318-14 (Reference 13). This is the Base Case reference cover of 2"
- Epoxy Coated reinforcing bars (all levels)

For Waterproofing:

- Silane sealer at slab edges in all levels
- Membrane waterproofing
- Joint sealants

A study on the initial cost of enhancements was done which is shown in Table 1.

Enhancement Description	Option 1 Major Enhancements	Option 2 Moderate Enhancements	Option 3 Minor Enhancements
Silica Fume	\$350,000	\$350,000	\$350,000
Corrosion Inhibitor	\$525,000	\$350,000	\$0
Additional Epoxy Bars	\$125,000	\$125,000	\$0
Sealant at joints	\$65,000	\$65,000	\$65,000
Membrane at Top Level	\$295,000	\$0	\$0
Membrane at Lobbies	\$50,000	\$50,000	\$10,000
Sealer at Slab Edges	\$15,000	\$15,000	\$15,000
Miscellaneous Details	\$150,000	\$150,000	\$150,000
TOTAL	\$1,575,000	\$1,105,000	\$590,000

Table 1: Initial Cost of Enhancements

Once the cost implications were determined for various enhancements, service life modeling was done for this garage.

In using the Life-365 software, the following parameters were input for the garage located in Buffalo, NY where it was known that sodium chloride (NaCl) would be used as deicing agent in winter:

- Location: Buffalo, NY
- Type of element: Deck Slab
- Exposure condition top of deck: Exposed to weather
- Temperature mean value and amplitude: 55.4° F and 20.7° F
- Humidity mean value and amplitude: 67.5% and 0%
- Exposure type: NaCl = 700 ppm
- Exposure duration: 10 days

Life-365 gave some valuable information about the initiation of corrosion in the garage. Repair costs using the three options detailed in Table 1 were studied for 50, 60 and 70 year service life spans. The results are summarized in Figure 5 for understanding the potential savings in money on repairs and maintenance over the service life desired.

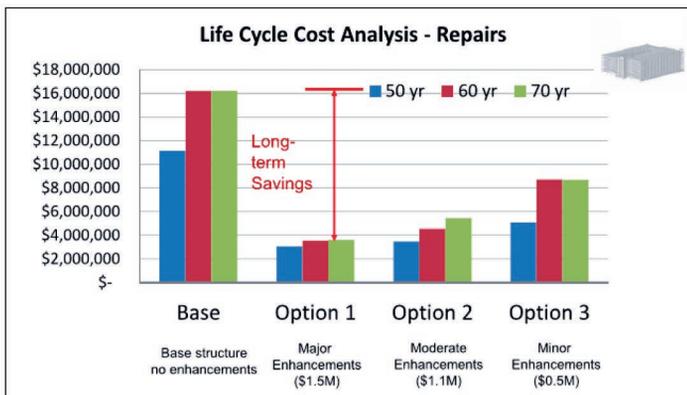


Figure 5: Repair Cost Saving for 50, 60, and 70 Year Service Life with Enhancements

By using LCCA, the concrete construction parameters for this cast-in-place garage structure were carefully reviewed to formulate a durable structure for the harsh winter weather in upstate New York.

Commentary on Cooling Tower Application:

Cooling towers in power plants and industrial complexes are largely concrete structures. Important parameters for durability involving concrete mix design such as water-cement ratio and use of supplementary cementitious materials like fly ash and silica fume are common to all types of concrete construction. So also are types of reinforcing bars such as epoxy coated, galvanized, or regular uncoated bars. Other durability factors include cover of concrete to reinforcing bars and use of sealers and treatment of construction joints in concrete. The case history of LCCA of garage is easily adaptable to any cooling tower as well.

Case History 2: El Paso 375 Loop - Service Life Study of New Bridge

In 2014, a major highway construction project was undertaken in west Texas. In addition to the miles of concrete roadway, the project also contained a number of concrete bridges that would be exposed to a wide range of temperatures from below freezing to 110oF. The owning agency for the new project wished to evaluate and forecast the

durability of the concrete and potential for corrosion in the uncoated reinforcing steel over the entire 100-year service life of the bridge.



Figure 6. El Paso 375 Loop Bridge Under Construction

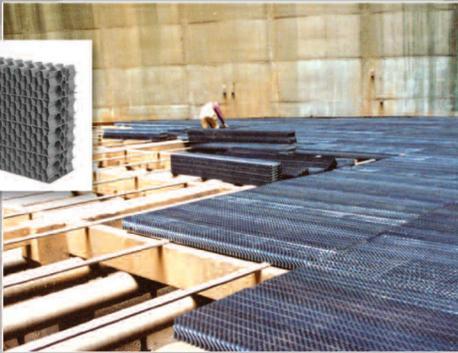
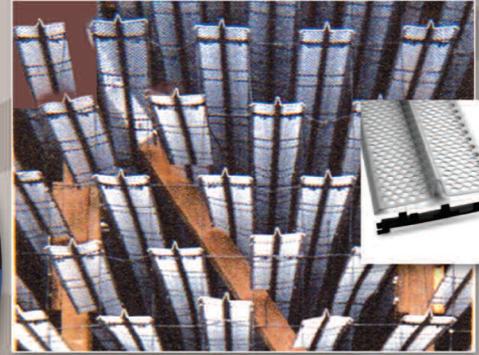
Once again, Life-365 software was used for performing LCCA for this bridge similar to what was done for the garage in Buffalo, NY.

Input parameters were as follows:

- Location: El Paso, Texas
- Bridge deck slab thickness: 8.5"
- Clear cover to reinforcement: 2.5"
- Exposure: NaCl (roadway deicing salts)
- Water/Cementitious ratio: 0.45 (For high-performance concrete)
- Fly ash: 20% cement replacement
- Reinforcement: Black or uncoated bars

Chloride concentration and temperature information are given in Figure 7.

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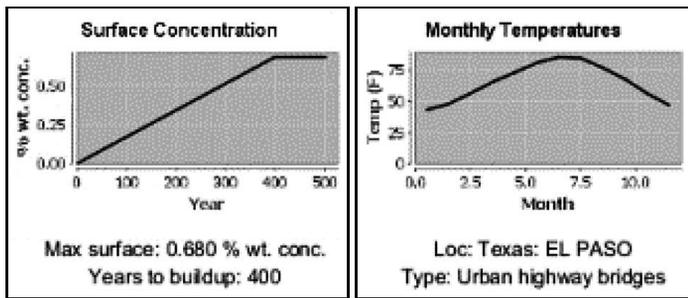


Figure 7: Chloride Concentration and Monthly Temperature Variation for Bridge

LCCA indicated that the service life of the selected bridge using concrete with parameters listed above with uncoated reinforcing bars was approximately 104.4 years. This satisfied the desired life of 100 years specified in the project specifications.

Commentary on Cooling Tower Application:

Parallels can be drawn between the bridge project discussed above and cooling towers. Both are continuously subjected to the changes in weather from hot to cold and dry conditions to humid environment. The usage of the facilities may be different, but both are in aggressive environments. Both rely on the durability of concrete used for the desired service life.

Case History 3: Existing Hyperbolic Cooling Tower (2010)

Two concrete hyperbolic cooling towers were constructed in Jacksonville, FL in the early 1980s to support power production for the greater Jacksonville area (Figure 8)



Figure 8: Hyperbolic Cooling Towers, Jacksonville, Florida

Although located approximately 6 miles from the coast, salt water infiltration through underground wells affected the concentration of chlorides in the makeup water for the cooling towers and subsequent chloride concentrations in the cold water basin. While likely unforeseen at the time, the chloride concentration in the makeup water created exposure condition comparable to marine exposure with splash zones. This case history retroactively evaluates the known concrete design parameters and environmental exposure conditions to correlate site deterioration conditions. It is our understanding, based on a review of historic data, that corrosion-related

deterioration initiated less than 10 years into the service life of the cooling tower structures. It is further our understanding that the as-constructed towers did not have supplemental corrosion protection measures.

Service life modeling was conducted using existing concrete design parameters determined from excising concrete cores and subsequent laboratory (petrographic) testing of the concrete veil structure. The existing construction drawings were also reviewed to obtain the dimensions of the structure and placement of reinforcing steel. The following primarily input parameters were considered in the service life modeling:

- Concrete water/cement ratio (i.e. permeability)
- Veil thickness of 8.5" and reinforcing steel cover of 1.5"
- Wall type structure (veil)
- Marine exposure conditions in Jacksonville, FL
- Previous maintenance and repair schedule

The Life-365 program was utilized to predict the initiation of corrosion, the anticipated service life of the structure, and periodic maintenance and repair costs. Design alternatives were also studied to understand the benefits of protective sealer and coating applications with respect to extending the service life of a new structure. Key information obtained from the service life modeling is provided in Table 2.

Case	Time to initiate corrosion (years)	Estimated service life (years)
Veil Base Study	4.2	10.2
Veil + Sealer	6.4	12.4
Veil + Coating	10.8	16.8

Table 2: Service Life Model Prediction

The results of the service life modeling study in Table 3 correlate well with anecdotal observations of corrosion initiation and concrete deterioration. The results also clearly show the value of applying protective measures to reinforced concrete structures. In this case, if a coating had been applied to the exterior surface of the veil during initial construction, the service life would have been extended by an additional 6 years. It's also worth noting that the reapplications of sealers or coatings would have extended the service life even further.

Commentary:

This retroactive case study demonstrates how LCCA can be applied to both the design of new concrete cooling towers as well as the evaluation of existing concrete cooling towers for budgeting for repair.

Conclusions

The concept of LCCA has been around for about 40 years now and there are several papers and scholarly documents that are available some of which are referenced herein. Most of these deal with infrastructure facilities which are publicly funded. The designers of such facilities are generally obligated to use LCCA to address not only the initial cost of the project but also to advise on allocation of future resources for repair and maintenance.

The same issues also exist in the corporate world. Based on the pressure by facility owners to develop new facilities with minimum initial cost along with minimal maintenance and labor costs over the service life of the facility, designers have started taking a look

at LCCA to meet the current expectations. With the availability of user friendly software packages, sensitivity analyses can be done fairly quickly,

The authors are of the opinion that concrete cooling towers are well suited to take advantage of the modern LCCA tools for sensitivity analyses that involve:

1. Studies on how various parameters in the concrete mix design affect the initial cost and long-term durability.
2. Rapid evaluation and resolution to “what if” scenarios and come to rational and informed decisions about the most expedient way to achieve durability goals for the concrete elements of the cooling towers.
3. Methodical isolation of the effect of one variable while holding the other parameters constant to see what yields the greatest economic benefit over the service life of the cooling tower under study.

In order to accomplish these goals, the industry has to have a mindset to change its attitude and embrace the modern tools of LCCA available to us.

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Profiling, Diagnostics and Evaluation of Cooling Towers

Jure Smrekar; JS Energy Ltd
Marko Hoceval; University Of Ljubljana

Abstract

In the natural-draft cooling tower (NDCT) market, there is no service that can estimate the impact of component problems inside NDCTs on power production, financial losses and emissions. Due to the slow pace of degradation of NDCTs, their large size and the complexity of heat and mass transfer processes, NDCTs' performance degradation is in many cases unnoticed and unattended. In this paper, the solution for profiling, diagnostics and evaluation of natural-draft cooling towers is presented.

It consists of:

1. A high-resolution mobile-based measuring system for the detection of component problems inside NDCTs,
2. NDCT and power plant modeling, and
3. Cost-benefit analysis.

Based on high-resolution measurements, the impact of the degradation, damage or design issues of the tower's components on power generation, emissions and financials is evaluated. The paper includes 10 months of operational data from a 345-MWe power plant with NDCT. An area with degraded fills inside the NDCT is analyzed and the results are reported.

Keywords: Profiling, Diagnostics, Exit Air Mapping, Performance Evaluation, Natural draft, Cooling tower, Power plant, Real-life Application

Introduction

Power plants are amongst the largest sources of emissions and, as such, are receiving a great deal of attention from politicians, end-users and researchers. As a result, increasingly stringent regulations on exhaust gas emissions are being introduced worldwide. The operators are thus looking for new solutions that can improve system efficiency and emissions, while remaining on the profitable side.

Fossil-fuel fired boilers have the largest direct impact on the environment via exhaust gas emissions. Power plants using fossil fuels have been applying so-called primary measures or combustion-zone treatment technologies, which directly target plants' emissions and efficiency. The positive side of the primary measures is that they are profitable. However, even after applying the primary measures, most of the power plants still do not meet the emission limitations, obliging them to apply so-called secondary measures or post-combustion-zone treatment techniques, which are no longer profitable. Power plant operators have, thus, been looking for new potentials to improve their plant's efficiency, to reduce the operational costs of the plant as well as of the secondary systems for emissions mitigation.

Many large power plants use natural-draft cooling towers (NDCTs), which constitute one of the major components in processing huge energy flows. The cooling towers have been neglected in many power plants, undergoing no proper maintenance or overhauls. The



Jure Smrekar

problems arising are the slow pace of degradation, the large size and the complex processes of heat and mass transfer, rendering the problem in NDCTs unnoticed and, in many cases, unattended. Broken and clogged fills, clogged water sprayers, fouling, broken drift eliminators, etc. [1]-[4] are some of the common issues that are slowly but steadily appearing in the process of NDCT aging. In addition, as these issues do not directly affect the plant's production, it is hard for them to be detected at the events when they occur. As the plan area of an NDCT is huge, the local irregularities can significantly affect the NDCT and, hence, the system's performance.

Cooling towers (CTs) remain widely used in power-producing industries for the cooling of process water [5], [6]. Approximately half of the energy delivered by fuel is rejected via a cooling system. Due to the low temperature levels, the energy is low with exergy. In this regard, an explanation of the CT performance from an exergy point of view and its trends for optimization can be found in [7], [8]. This necessitates both a better understanding of the CTs' operation and the optimization of their design parameters [9]-[11]. Nevertheless, a small percentage increase in a cooling system's efficiency represents significant savings in fuel, as well as a reduction in emissions. Increasing fuel prices, CO₂ credits and NO_x emissions regulations are additional reasons that the focus on regular cooling tower maintenance is economically justified. Furthermore, increasing energy demands and the extensive use of natural waters are further reasons that cooling towers are continually being built and hence need continuous design improvements.

Limited maintenance of the CTs is reflected in the CTs' local problems and decreased heat and mass transfer rates. These have an impact on the CT's efficiency and, hence, on the efficiency of the energy system. Willa [12] summarized a history of CTs in the 20th century. Zelek's paper [13] traces the history of fill designs, while providing guidelines as to the proper fill selection. In the past 50 years, considerable improvements have been reported [14], [15], through the introduction of the film type fills, resulting in higher heat and mass transfer rates. Besides higher efficiencies, lower capital and operational costs have been achieved, which have led to smaller CT constructions. The main factors for choosing certain types of fills are the effectiveness of the heat and mass transfer, the quality of cooling water, the pressure losses, the costs and the lifetime of the packing [16].

Water entering the CT is sprayed over the packing by means of nozzles. The spray zone can account for up to 25% of the total heat and mass transfer [17]. It is important that water is sprayed equally across the plan area of the packing. Inappropriate water distribution by the nozzles is often cited as a problem, which decreases the CT's performance [18], [19]. Mohiuddin and Kant [16] summarized different types of nozzles used for the spraying of water. Above the spray zone, drift eliminators are installed to prevent excessive water loss from the CT. There are different types of eliminators [20], which, unavoidably, contribute to the pressure losses. To achieve optimal performance of the CT, it is necessary to also minimize

the pressure losses of the eliminators [21]. From the packing, water flows into the rain zone, where a significant heat and mass transfer rate can be noted [22]. A study of the heat, mass and momentum transfer in the rain zone of the counter-flow CTs was carried out by de Villers and Kröger [23].

Proceeding to the local scale of the CT, optimal water distribution across the CT's plan area, with respect to the air flow, was analyzed in [24]. The same group developed the Cooling Tower Profiler (CT-Profiler) measuring and evaluation techniques for diagnostics of NDCT performance [25]-[29], as a part of the methodology presented in this paper. It is based on a mobile unit measuring the moist-air properties across the plan area of NDCTs. The origin of the technology for exit air mapping goes back in 80's [30],[31].

Although CTs are rather simple devices, their mathematical modeling is a challenging task. The basis for the CT analysis was produced by Merkel [30] in 1925. His model is based on several critical assumptions, which make the model easy to use in a simple by-hand calculation. Several versions of e-NTU methods followed [33]-[38]. In the early 1970s, Poppe and Rögener developed a new method for CT analysis [39], which avoids all the critical assumptions of Merkel's model. In the Poppe model, the Lewis factor is not equal to one; instead, it is determined according to an empirical equation produced by Bošnjaković [40]. Comparison of the models (Merkel, e-NTU and Poppe) for the CT analysis, the influence of the Lewis factor on performance prediction of wet-cooling towers and transparent derivation of the Poppe model were subjects of studies carried out by Kloppers and Kröger [41]-[43]. Rigorous mathematical models of the heat and mass transfer in the spray zone and in the packing were also made by Fisenko [44],[45].

In this paper, the application of technology for profiling, diagnostics and evaluation of cooling towers is demonstrated in a real-life case with degraded fills inside an NDCT. The technology is briefly presented, including its main parts, i.e. (1) High-resolution mobile-based measuring system for the detection of component problems inside the NDCT, (2) NDCT and power plant modeling, and (3) Cost-benefit analysis. The measured region with fill issues within the NDCT is evaluated in terms of power generation, emissions and financials. The results are reported, based on 10 months of power plant's real operational data and measured profiles by the technology in the corresponding NDCT.

Motivation For Development Of The Technology For Profiling, Diagnostics And Evaluation

The motivation for the development of the technology for profiling, diagnostics and evaluation was to be able to identify and evaluate component problems inside NDCTs, in terms of power production, emissions and financials, considering long-term operation. Such a solution gives operators the opportunity to obtain a complete evaluation of an NDCT's state, also considering the specifics of the power plant operation and ambient conditions. Based on the profiling, diagnostics and evaluation results, optimal CT maintenance, considering operational conditions, budget and time, can be selected. In addition, many countries' security regulations prohibit access to NDCTs, while they are in operation. The mobile units for profiling represent autonomous self-driven systems that also overcome this issue.

Technically speaking, NDCTs are huge constructions with a harsh environment; hence, their evaluation is a challenging task, from the measuring as well as the analysis point of view.

The NDCT's size and construction make it practically impossible to directly measure properties of the tower's components, especially in its concealed parts, i.e. water nozzles, fills and water distribution system. In this regard, the technology must meet several technical requirements:

- Measurements must be of high resolution (~1 m (3.3 ft) scale), to pinpoint and identify the problems with components inside an NDCT.
- Short profiling time inside NDCTs. As the performance of an NDCT significantly depends on weather conditions, it is highly important that measurements in a CT are conducted in a few hours rather than in several days. This necessitates the technology being highly automated, with little or no human intervention inside the tower.
- Nonintrusive measuring technology. The technology for profiling must be lightweight and nonintrusive, without influencing the measured parameters.
- Thermodynamic-based evaluation. The component issues must be detected from moist-air measurements rather than from characteristic changes of components, which are infeasible to measure.
- The application requires highly accurate models for NDCT and power plant modeling, which enables analyses of the impact of the tower's component issues, as well as its repairs or upgrades.
- Cost-benefit analysis must take into account the impact of the tower's problems on power production and emissions, considering plant's long-term operation and ambient conditions.
- Secure technology. The technology must ensure that no human presence is required inside the cooling towers during profiling, minimizing the health risks.

The above mentioned requirements have been considered during the technology development and integrated in the service for profiling, diagnostics and evaluation. It represents a highly automated and accurate approach for NDCTs' evaluation that is based on measurements of the characteristics of the power plant and the cooling tower.

System Description

The real-life case involves an NDCT, which is part of a 345-MW_e power plant. The operational data of 10 months, covering a broad range of the plant's operational as well as ambient conditions, were used. The NDCT is a wet type natural-draft cooling tower of 94 m (308 ft) height, 80 m (262 ft) diameter at the base and 54.4 m (178 ft) diameter at the top. The main cooling system contains decarbonized water flowing from a condenser to the NDCT by means of two pumps with nominal mass flow rates of 19250 t/h (21220 sh.t/h) each. The drift eliminators are installed 17.2 m (56.4 ft) above the base of the NDCT. The NDCT was designed for uniform water distribution, which is achieved by nozzles of one type installed across the tower's plan area. The water is sprayed over the film type packing of 2.5 m (8.2 ft) height and flows to the water basin, which is 2 m (6.6 ft) below the fills' outlet.

The NDCT had degraded fills and non-optimal design, which can be noticed as the non-homogenous areas in Fig. 1. The air velocity and temperature profiles measured above the drift eliminators were acquired by the mobile units, described in the **Cost-benefit Analysis** portion of the **Technology For The Profiling, Diagnostics And Evaluation Of Cooling Towers** section. The profiles represented the basis for the NDCT's problem detection, diagnostics and evaluation.

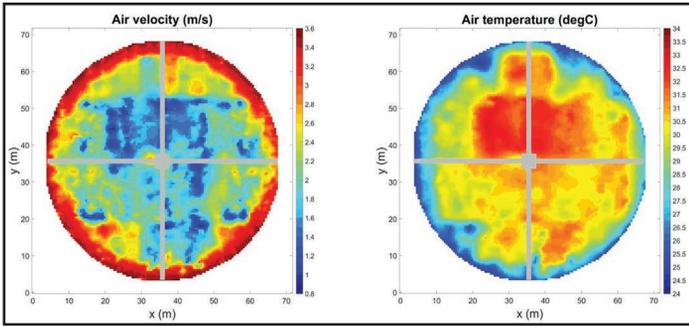


Fig. 1. Air velocity and temperature profiles measured above the drift eliminators in the NDCT.

The plant uses a once-through boiler using brown coal with the elementary component analysis shown in Table 1. Nominal fresh steam properties delivered by the boiler are 540 °C at 185 bar (1004 °F at 2683 psi) and 1050 t/h (1157 sh.t/h) mass flow. Steam expands through the high-pressure turbine and, after the second superheater, it reaches 545 °C at 41 bar (1013 °F at 595 psi). The mass flow rate of reheated steam is 935 t/h (1030 sh.t/h) at maximal pressure of 65 bar (943 psi).

Parameters	Values
Moist	32.4%
Ash	19.1%
Carbon	32.6%
Hydrogen	2.7%
Nitrogen	0.7%
Oxygen	10.5%
Sulphur	1.8%

Table 1: Elementary analysis of brown coal.

Technology For The Profiling, Diagnostics And Evaluation Of Cooling Towers

For the complete evaluation of an NDCT, reliable and detailed measurements related to the cooling tower and the power plant's operation are essential. The measurements inside a cooling tower provide important information about the tower's state and components' conditions. In addition, the data can be used for the long-term evaluation of CT operation. Power plant measurements provide a basis for the evaluation of the damage, repairs or upgrades of an NDCT, in terms of power production, emissions and financials. In this section, the technology for the profiling, diagnostics and evaluation is briefly presented in three parts:

1. High-resolution mobile-based measuring system,
2. NDCT and power plant models, and
3. Cost-benefit analysis.

High-resolution mobile-based measuring system

NDCTs are many times not inspected periodically, leading to long-term and gradual degradation, which goes often unnoticed and unattended. In most cases, degradation is localized and usually not visible from above the surface of drift eliminators. Degradation includes damage and anomalies, among them clogged fills, damaged sprayers, moved packing, fouling, etc. Localized degradation may also affect large surfaces, for instance along the circumference of the NDCT. Besides local degradation, some NDCTs may show problems in operation, originating from their suboptimal design.

The measuring part of the technology consists of a fleet of mobile units to address such problems in NDCT components. They drive above the drift eliminators across the plan area of an NDCT. The mobile units are autonomous and self-driven, without the need for human monitoring inside a tower, reducing the safety and health risks. Each mobile unit has four arms, which carry the following sensors: vane anemometers, temperature sensors and hygrometers, for measuring the characteristics of the cooling air, as presented in Fig. 2. The mobile units are also equipped with visual surveillance for drift eliminator inspection and for the purpose of the units' security. The fleet of such mobile units ensures completion of measurements inside an NDCT in a matter of hours. This reduces the time of the required plant's constant load operation. In addition, the accuracy of the profile measurements is highly improved, in comparison to that of several day measurements, with, potentially, great changes in weather conditions.

Airflow properties inside cooling tower require use of large anemometers of 200 mm (7.87 in) diameter. Four custom designed measurement units are arranged as housing in the form of a rim, containing a vane anemometer, temperature and humidity sensors as shown in Fig. 2. Accuracy of airflow velocity measurements is less than ± 0.2 m/s (± 0.66 ft/s), temperature less than ± 0.5 °C (± 0.9 °F) and humidity less than $\pm 3\%$. Anemometer vanes feature appropriate blade angle such that they are suitable for low airflow velocities below 5 m/s (16.5 ft/s) usually present in natural-draft cooling towers. For low energy consumption, an 8-bit microcontroller with 16-bit A/D converter and wireless module is used for data acquisition and communication with process computer outside the NDCT. The measuring results of the air velocity and temperature profiles that were used in the demonstration of the methodology are presented in Fig. 1. In this case, the issue was degraded fills. In the figure, the corresponding non-homogenous areas in the NDCT operation can be noted. It is obvious that non-homogeneities in the temperature profile are highly correlated with those in the velocity profile. The areas with distinctive non-homogeneity were examined and analyzed, in terms of power plant efficiency, emissions and financials.

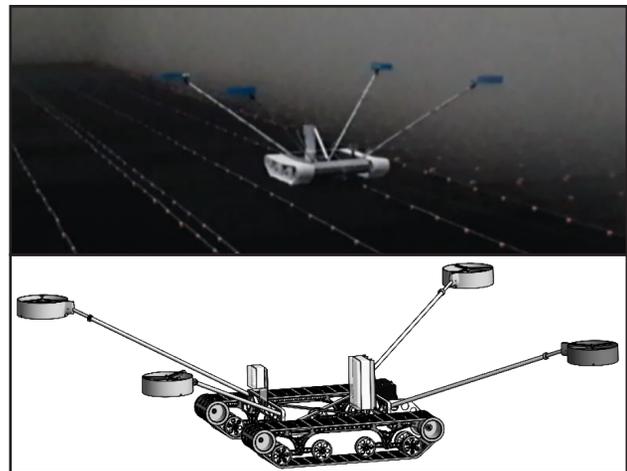


Fig. 2. Autonomous self-driven mobile unit for profiling of NDCT characteristics; top: mobile unit in an NDCT; bottom: CAD figure of the mobile unit.

In some cases, cooling tower operators perform a visual inspection of the NDCT state, especially eliminators and water sprayers, when the NDCT is not in operation. Aside from that, it is hard to visually assess the state of fills, which are one of the main components accounting for over 50% of the heat and mass transfer processes. On

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the other hand, the profiling measurements aim to capture the deep information of all essential NDCT components while in operation, to evaluate their actual thermal performance.

NDCT and power plant modeling

The cooling air flowing across the rain zone, fills, spray zone and drift eliminators provides information about the conditions of the NDCT's components. This information is captured in the moist-air measurements, such as velocity and temperature, which are sufficient for the evaluation of an NDCT [26],[46]. To transform this information into power production, emissions and financials, NDCT and power plant modeling must be performed.

NDCT modeling

NDCT modeling has reached a high level of accuracy in recent decades. Currently, the Poppe model [39] is considered one of the most rigorous models that does not apply several critical simplifications, in comparison to the pioneer Merkel's model [30]. It has been used for different applications; hence, several variations of the model can be found in today's literature [28],[47]. The described technology uses several different models that consider NDCT on an integral as well as a local basis. The local one for thermodynamic evaluation of NDCTs components is based on the Poppe model, which is briefly described in the following.

The Poppe model

The profiling measurements provide the data, based on which the water temperature at the fills' outlet can be calculated on the local scale. The Poppe equations are used to calculate the air humidity and the water temperature, based on the air temperature. Hence, the air humidity and the water temperature are expressed as functions of the air temperature, i.e. dw/dT_a and dT_w/dT_a , as presented in the following.

Governing equations for heat and mass transfer in CT for unsaturated air

Based on the Poppe model, the modified governing equations, expressed as functions of air temperature, for the unsaturated air are:

$$\frac{dw}{dT_a} = c_{pma} \left\{ \frac{[Le_f (i_{masw} - i_{ma}) + (1 - Le_f) i_v (w_{sw} - w)]}{(w_{sw} - w)} - (i_{fgwo} + c_{pv} T_a) \right\}^{-1} \quad (1)$$

$$\frac{dT_w}{dT_a} = \left[c_{pma} - (c_{pw} T_w - i_{fgwo} - c_{pv} T_a) \left(\frac{dw}{dT_a} \right) \right] \left(\frac{m_a}{m_w c_{pw}} \right) \quad (2)$$

where i_{fgwo} is latent heat at 273.15 K, w air humidity ratio, T_a local air temperature, c_p specific heat at constant pressure, c_v specific heat at constant volume, Le_f Lewis factor, i specific enthalpy of air and m mass flow. Subscriptions refer to as follows: ma is moist air, a dry air, w water, s saturation and i local measurement.

To integrate Eq. (2), it is necessary to substitute the differential (dw/dT_a) for the right-hand side of Eq. (1). Lewis factor Le_f denotes relative rates between heat and mass transfer in the evaporative process. Bošnjaković [40] developed an empirical equation to determine the Lewis factor, which was employed by Poppe in his model [39]:

$$Le_f = 0.865^{0.667} \frac{\left(\frac{w_{sw} + 0.622}{w + 0.622} - 1 \right)}{\ln \left(\frac{w_{sw} + 0.622}{w + 0.622} \right)} \quad (3)$$

In the governing equations, the ratio of water-to-air mass flow rates (m_w/m_a) changes across the packing, due to the water evaporation, according to the following equation:

$$\frac{m_w}{m_a} = \frac{m_{wi}}{m_a} \left(1 - \frac{m_a}{m_{wi}} (w_o - w) \right) \quad (4)$$

From Eqs. (1), (2), (3) and (4), the outlet water temperature and the outlet absolute humidity of air can be determined on the basis of the inlet air properties (T_a, T_{wb}) , inlet water temperature, inlet water mass flow rate, outlet air temperature and mass flow rate of air. With the described technology, all these parameters are measured.

The Merkel number Me for the unsaturated air, expressed as a function of air temperature, is:

$$\frac{dMe}{dT_a} = \frac{m_a}{m_w (w_{sw} - w)} \left(\frac{dw}{dT_a} \right) \quad (5)$$

Governing equations for heat and mass transfer in CT for supersaturated air

In the supersaturated state, the mass transfer from water to air is present if the air temperature is lower than the water temperature. This corresponds to the difference in partial pressures of vapor between the water-to-air boundary layer and the cooling air.

Based on the Poppe model, the modified governing equations, expressed as functions of air temperature, for the supersaturated air are:

$$\frac{dw}{dT_a} = \left[c_{pass} + \frac{\partial w_{sa}}{\partial T_a} (i_{fgwo} + T_a (c_{pv} - c_{pva})) \right] \cdot \left[\frac{[Le_f \{ i_{masw} - i_{ss} - (w_{sw} - w_{sa}) i_v + (w - w_{sa}) c_{pw} T_w \} + (w_{sw} - w_{sa}) i_v]}{w_{sw} - w_{sa}} - c_{pva} T_a \right]^{-1} \quad (6)$$

$$\frac{dT_w}{dT_a} = \frac{m_a}{m_w c_{pva}} \left\{ \left[c_{pass} + \frac{\partial w_{sa}}{\partial T_a} (i_{fgwo} + T_a (c_{pv} - c_{pva})) \right] + c_{pva} (T_a - T_w) \left(\frac{dw}{dT_a} \right) \right\} \quad (7)$$

where the specific heat of supersaturated air c_{pmas} is $c_{pmas} + w_{sa} c_{pva}$ and the Lewis factor for the supersaturated air is calculated according to Bošnjaković [40]:

$$Le_f = 0.865^{0.667} \frac{\left(\frac{w_{sw} + 0.622}{w_{sa} + 0.622} - 1 \right)}{\ln \left(\frac{w_{sw} + 0.622}{w_{sa} + 0.622} \right)} \quad (8)$$

To integrate Eq. (7), it is necessary to substitute (dw/dT_a) for the right-hand side of Eq. (6). Differential $(\partial w_{sa}/\partial T_a)$ cannot be expressed analytically. It can be determined by knowing the ambient pressure and the saturation pressure of vapor. The latter parameter can be expressed based on equations of state, i.e. approximation polynomials. From Eqs. (4), (8), (6) and (7), the outlet water temperature and the outlet absolute humidity of the air can be calculated on the basis of inlet air properties (T_a, T_{wb}) , inlet water temperature, inlet water mass flow rate, outlet air temperature and mass flow rate of air.

The Merkel number Me for the supersaturated air, expressed as a function of air temperature, is:

$$\frac{dMe}{dT_a} = \frac{m_a}{m_w (x_{sw} - x_{sa})} \left(\frac{dw}{dT_a} \right) \quad (9)$$

Local water temperatures at the fills' outlet are calculated. Due to unknown air properties entering the packing across the plan area of the CT, ambient conditions are assumed. To complete the calculation, the energy and mass balance equations of the NDCT at its integral level must be applied, to calculate the outlet water temperature from the tower.

Power plant modeling

To evaluate NDCT performance in terms of power production, emissions and financials, modeling of the power plant must be performed. The power plant can be operated through numerous sets of parameters. By modeling the plant, the influence of the tower's issues, as well as improvements, can be analyzed in depth, while also considering plant operation and seasons.

Mathematical modeling of the power plant was conducted by a tool, developed in-house, which is based on commercial software for power plant modeling. There are several commercial software packages on the market that can be used for this purpose [48]-[52]. The extensive libraries of contemporary commercial software with many ready-made components can simulate a real-life system with high accuracy. The power plant models can be developed, based on measured characteristics of the plant's components. The models can be tuned on measured nominal values, where off-design operation can also be simulated. The model validation must be performed on a separated test data set, which is not used during the model development or tuning. The intention of the modeling is to provide the connection between a CT and power plant operation, based on which the impact of CT issues, as well as upgrades, can be investigated, in terms of power production, emissions and financials.

The basic scheme of the plant is presented in Fig. 3. The turbine is modeled with eight "sub-turbines" with the measured efficiencies. The values were acquired, based on the power plant's unit measurements. The efficiencies of the boiler and the pump were set to 0.89 and 0.85, respectively, and were kept constant throughout the calculations.

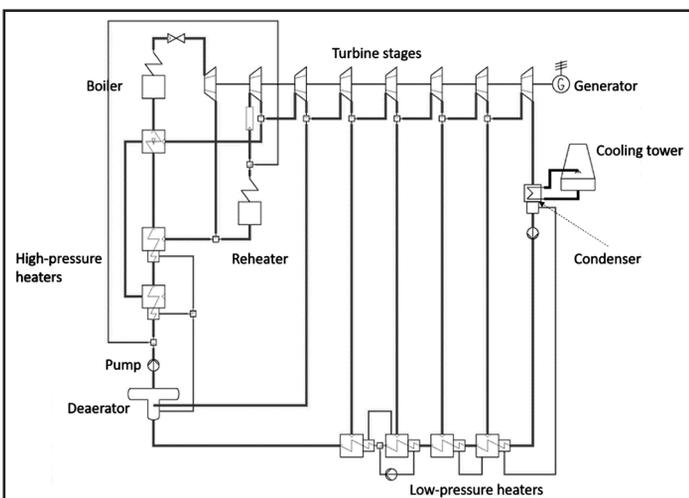


Fig. 3. Scheme of the power plant model.

Validation of the empirical model

The validation of the model was made with the "unseen" data of one month, which were not used during the model development. Commonly, the measured data are examined and filtered for outliers (inconsistent recordings) before the validation of the empirical model is conducted. Fig. 4 presents the results of the validation of the power plant model.

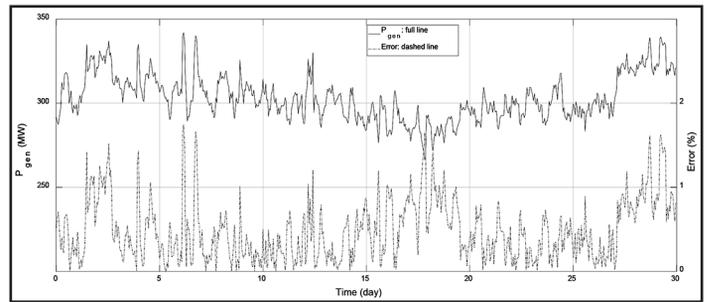


Fig. 4. Validation of the power plant model with "unseen" data.

The full line in Fig. 4 represents the measured power output, and the dashed line is the relative error of the power output predicted by the model. The left-hand axis corresponds to the power output, while the right-hand axis contains the relative error of the power plant model. The average error of predicted values over one month is 0.56%. The main reason for deviation in error is that most of the time the power plant was not operating at nominal point and there were other unmeasured disturbances, such as coal quality, fluid friction, etc. Moreover, the correlation coefficient between the measured and predicted values is 0.995. Due to the small relative error and high correlation between predicted and measured values, the use of the model was confirmed.

Cost-benefit analysis

Cost-benefit analysis is based on NDCT and power plant models that are fitted to operational data. The plant model enables the estimation of losses and improvements made at the NDCT. The increase in the tower's efficiency has a positive effect on fuel savings, CO₂ emissions and NO_x emissions or ammonia water consumption, if SCR/SNCR is installed. The first two benefits which were present in this case are briefly discussed in the following.

Fuel savings

The NDCT improvements result in an increase in the power plant's efficiency, which means fuel savings for the same power production. If the same power production P_{gen} is considered, then, at the increased power plant's efficiency $\Delta\eta_{pp}$, the fuel savings Δm_{fuel} can be calculated with the following rule of thumb equation:

$$\Delta m_{fuel} = P_{gen} / (\Delta\eta_{pp} \cdot H_i) \cdot D \quad (10)$$

where Δm_{fuel} represents annual fuel savings, P_{gen} average power generation, $\Delta\eta_{pp}$ average increase of the power plant efficiency, H_i average calorific value of the fuel, and D number of operational hours per year. Multiplying the fuel savings with the cost of the coal gives us the fuel savings in the desired currency.

The fuel's calorific value significantly influences the fuel consumption. Usually, power plants have daily recordings of the fuel's calorific value (which are often average values over several samples taken from conveyor belts) and other daily varying parameters, which can further improve the accuracy of the fuel savings calculation.

CO₂ savings

Financial savings from CO₂ are related to the CO₂ credits that power plants buy for their production. To calculate the financial savings from CO₂ credits, the fuel savings and the elementary analysis of the fuel are required. In the paragraph above, the fuel savings per year Δm_{fuel} can be calculated, based on the increase in the power plant's efficiency $\Delta\eta_{pp}$. The elementary analysis of the fuel is presented in Table 1. The following is a rule of thumb equation for the calculation of the amount of CO₂ produced by burning the coal

$$\Delta m_{CO_2} = \Delta m_{fuel} \cdot 44/12 \cdot (C_{coal} - \sum C_{loss}) [53]. \quad (11)$$

where Δm_{CO_2} represents saved CO₂ emissions from coal combustion, Δm_{fuel} coal savings, C_{coal} average of carbon content in coal and $\sum C_{loss}$ total carbon not completely burned, including carbon in fly ash and ash slag. Multiplying the CO₂ savings with the cost of the CO₂ credit gives us the savings from the reduction in CO₂ in the desired currency. Daily recordings of the fuel's elementary analysis and other parameters can further improve the accuracy of the CO₂ savings' calculation.

Results Of The NDCT Analysis

The results are reported, based on the power plant's operational data of 10 months and profiling measurements from the NDCT, described in the **System Description** section. The data were examined and pre-processed, by which means the measured data deviating from the normal operation were eliminated from the database. For the analysis of the performance, 15-min average values were used. For each operational point, the modeling and analysis were conducted, which represented a heavy computational load.

The left plot in Fig. 5 represents the original NDCT state, showing the selected area with the issues. High air temperatures and low air velocities can be noticed in the analyzed region as shown in Fig. 1. Low velocities indicate high pressure losses, which generally emerge due to damaged packing and/or eliminators. The mobile units are also equipped with visual surveillance, confirming that drift eliminators were in good condition. It turned out that the fills' degradation was the main issue. The degraded area represented about 530 m² (5705 ft²) of the effective plan area, which is 20.2% of the NDCT's total plan area. The right-hand plot in Fig. 5 represents the NDCT with the modeled newly replaced fills. The low-fouling fill for slightly to medium polluted water, with a specific surface area of 150 m²/m³ (1615 ft²/ft³), was used in the same way as when it was originally installed, and the operation with the new fills was predicted. The characteristics, such as transfer and loss coefficients, for fills, nozzles and drift eliminators were known and used in the calculations.

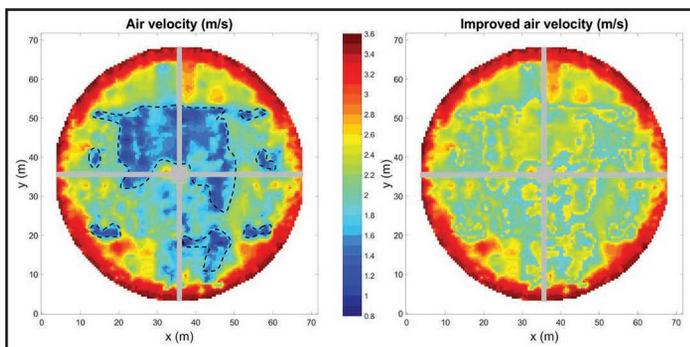


Fig. 5. Before (left) and after (right) conditions related to fill replacements.

The predicted repaired state of the NDCT shown in the above figure (right) represents the new boundary conditions in the NDCT model. The result of the model is outlet temperature from the tower, which is then fed into the power plant model. Based on the NDCT model, its increase in efficiency is estimated. Based on the power plant model, the power generation and emissions are calculated.

The predicted power output and the power increase, as the consequence of the rise in NDCT efficiency, are shown in Fig. 6. The average power output in the 10-month period was 303.17 MW, while

the predicted average power increase due to repairs to the region with the fill issues was 1.923 MW. The average power increase is significant, considering also that the modified region comprised only 20.2% of the total effective plan area of the NDCT.

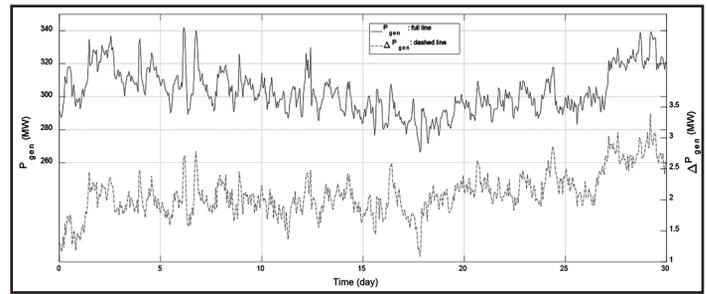


Fig. 6. Operation of the power plant and the predicted power increase due to the replacement of the fills.

Fig. 7 shows power plant efficiency and its increase due to the replacement of the fills. The average thermal power plant efficiency in the 10-month period was 38.31%, and its increase due to the replacement of fills in the tower was 0.246%. The increase in efficiency has turned out to be significant.

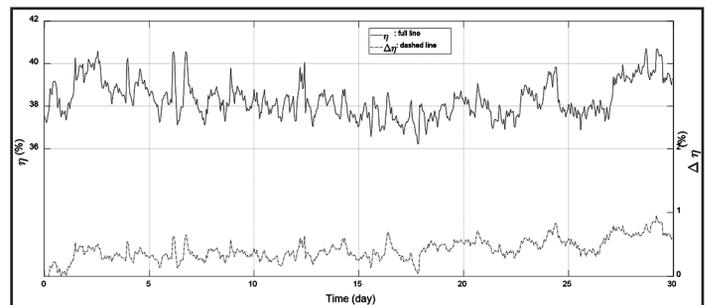


Fig. 7. Power plant efficiency and its predicted increase due to the replacement of the fills.

Cost-benefit analysis

Fuel savings

Using the equations found in the **Costs-benefits analysis** portion of the **Technology For The Profiling, Diagnostics And Evaluation Of Cooling Towers** section, the fuel savings due to the fill replacement were calculated, as a result of the efficiency increase of the power plant. The estimated average increase of the plant over the period of 10 months was 0.246%. This resulted in brown coal savings of 4491.25 tons (4950.75 sh.t.). At the time of writing this paper (September 2018), the brown coal price was 102.4€/ton (117.7\$/ton). Hence, the annual fuel savings over 10-month operation are estimated to be ca. 460k€ (\$530k).

CO₂-credit savings

In the previous paragraph, we showed estimated fuel savings of 4491.25 tons (4950.75 sh. t.) of brown coal in 10 months. At the time of writing (September 2018), the price of CO₂ credits in Europe was 21€/ton (24.5\$/ton). Considering Table 1's elementary coal analysis and the equations in the **Technology For The Profiling, Diagnostics And Evaluation Of Cooling Towers** section, the amount of mitigated CO₂ is 5268.93 tons (5808sh. t.). Multiplying this value with the price of CO₂ credits per ton gives about 110k€ (\$128k) savings.

Summing up the savings from coal and CO₂ credits, the total savings due to the fill replacement were estimated to be ca. 570k€ (\$655k) for the 10-month period. The total cost of measurements,

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analysis and repairs was 380k€ (\$437k). Hence, the payback period was estimated on 0.67 years.

Summary

This paper presents the technology for the profiling, diagnostics and evaluation of cooling towers. The technology can identify problems in tower components and estimate the impact of these problems on power generation, emissions and financials. In the first step, a fleet of mobile units takes the profile measurements of moist-air across the plan area of the cooling tower, through which problems are identified. In the second step, the measured profiles are used as the boundary conditions in the cooling tower and power plant models. These are developed based on measured characteristics of the plant's components and operational data for accurate cooling tower and power plant modeling. Based on the measured parameters, the outlet water temperatures from the tower are calculated. In the third step, the cost-benefit analysis is performed, considering financials from savings of fuel and exhaust gas emissions.

The application of the technology for profiling, diagnostics and evaluation of cooling towers is demonstrated on 10 months of power plant's real operational data and measured profiles by the technology in the corresponding cooling tower. The area with degraded fills, covering 20.2% of the tower's total effective plan area, was analyzed. The investigated region in the cooling tower was predicted by newly replaced fills of the same type. The result of the improved state was increased power production and lower emissions of exhaust gasses. On average, the repaired region yielded a 1.923-MW_e increase in the power output, based on a 10-month operational period, which corresponds to 0.246% average increase in plant efficiency. As a result, 4491 tons (4950 sh. t.) of coal and 5268 tons (5808 sh. t.) of CO₂ were predicted to be saved, yielding about 570k€ (\$655k) in financial savings. The total cost of measurements, analysis and repairs was 380k€ (\$437k) giving the estimated payback period of 0.67 years.

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Cybersecurity And Cooling Technology: What You Need To Know

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Abstract

Cybersecurity risks and data protection vulnerabilities present significant legal, operational and business threats to the cooling technology industry. The relevance of these challenges was highlighted in 2013, when national retailer, Target, was subject to a \$202 million data breach through its HVAC contractor, who had access to the client's server infrastructure. Because of the evolving nature of the threats, cybersecurity remains a high priority issue in cooling technology across all industries including hospitality, healthcare, education and others. In 2018, the American Water Works Association identified cybersecurity as a critically important issue facing the water industry. The failure to adapt to this ongoing threat places the vendor at a competitive disadvantage and their client at risk. Cooling technology providers are challenged to develop sound cybersecurity plans to ensure that both their own internal systems and their clients' systems are protected. This publication addresses general information and considerations that may be explored by cooling technology companies in developing such plans and mitigating against related risks.

Introduction

Cooling technology companies service a wide variety of commercial, residential, industrial, healthcare and government industries. Regardless of the industry setting, cooling technology providers are often engaged in ongoing "partnerships" with their owner and operator clientele to provide the desired environmental control services and to ensure that building water systems achieve the desired level of efficiency and useful life through the avoidance of corrosion, scale and microbiological fouling.

These partnerships have become increasingly technological in a number of aspects ranging from continuous real-time monitoring and equipment control, and to online field service reports to periodic billing and payment. While such continuous connectivity and data exchanges enable rapid responses and seamless payment transactions, such communications and services must be rendered securely and safely, for the benefit of both the customer and the cooling technology company. Connected networks demand close partnering and authentication of access credentials between the cooling technology provider and the customer.

In 2013, retailer Target was the subject of a well-publicized cybersecurity breach. In this instance, an HVAC contractor's computer system which had access to the Target system infrastructure was compromised with malware for the purpose of infiltrating the Target network. The net result was devastating to the customer as Target reportedly incurred expenses exceeding \$290 million as a result of the incident.

The 2013 Target data breach provides a critical lesson in how networked services between cooling technology providers and clients are being targeted by cyber criminals. Since that event, customers are expecting all vendors with whom they interact, including cooling technology providers, to properly secure their computer systems. Deferral of the issue until a crisis arises is no longer an option as wary owners are including cybersecurity policies as part of their due



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diligence procedures when vetting vendors. Those who are unprepared or unwilling to address cybersecurity and data breach preparedness efforts not only are subject to potential lawsuits and regulatory enforcement actions,

but are also at a competitive disadvantage in the cooling technology market. Failure to adequately assess risk and train staff also subjects cooling technology companies to being targeted in email phishing scams whereby fraudulent payments are solicited and often paid.

This paper will provide an overview of cybersecurity matters that should be considered by cooling technology companies in starting to assess both their and their customers' potential cybersecurity vulnerabilities and opportunities.

Terminology 101: ICS, Scada and IOT

Cooling technology providers render services and related products in a wide variety of settings in both the public and private sectors, ranging from residential and commercial buildings to oil refineries, chemical plants, and thermal power stations. Due to this broad applicability across key strategic, industrial, and commercial sectors, cooling technology professionals provide integral support for essential assets that contribute to the orderly functioning of the American society and economy. Because of this integral support, if the risks associated with the growing technological threats are not managed properly and the proper precautions taken, both the cooling technology provider and their clients can be exposed to serious, legal, operational, and business risks. In recognition of these ongoing risks, the American Water Works Association indicated that "Cyber risk is the top threat facing business and critical infrastructure in the United States." Therefore, any vulnerabilities that exist in the systems and technologies implemented by cooling technology providers similarly create potential risk for their clients, and most importantly, critical infrastructure.

Such technologies may include Industrial Control Systems (ICS), which help facilitate operations via a network of modular controllers, field connections, and sensors. Larger HVAC systems may incorporate a Supervisory Control and Data Acquisition System (SCADA), which relies on computers (hardware), networked data communications, software applications, and graphical user interfaces to provide remote access and control large-scale processes over large distances. When such systems were initially implemented, the control systems and devices communicated with each other within an isolated or local network, and had no connection to larger networks. As the Internet grew and large corporate networks were created to share data, once-isolated control networks were connected to larger networks, thereby exposing such networks to a higher risk of cyber-attacks by malicious hackers, cybercriminals, and nation states.

In the meantime, rapidly-evolving and emergent technologies have

resulted in a technological landscape that further enhances connectivity, communications, data collection and transmittal, by converting physical environments into sensor-imbedded interactive devices that are connected to the Internet. The term "Internet of Things" or "IOT," has been coined to describe this growing technological shift, which will affect engineering and network computing services by creating wireless connectivity with billions of devices, ranging from wearable fitness devices to large scale wireless thermostatic systems.

Many such devices will be deployed within "smart" buildings, vehicles, critical infrastructure, and public works. However, each such device provides a potential access point to systems, such as SCADA systems, which were designed with connectivity, and not security, in mind, due to the perceived low risk of access for malicious purposes at the time such systems were implemented. These devices have become more common in the cooling technology industry over time, and because of this the risks associated with them for cooling technology providers, has grown with their increasing prevalence.

However, as of 2010, cybersecurity researchers were alarmed to observe the emergence of the Stuxnet virus, which specifically targeted industrial computer systems and caused significant damage to an Iranian nuclear power plant, by seizing control of nuclear centrifuges and forcing them offline. Specifically, this virus was designed to target Programmable Logic Controllers (PLCs), which control machinery on assembly lines and in HVAC systems. The virus targeted systems using the Microsoft Windows operating system, and sought out Siemens STEP 7 software, which operated such physical devices as the centrifuges in question. While the attack targeted a rogue nation state, it also demonstrated the reality of an industrial-scale cyber warfare attack, which can be adopted by cyber-criminal networks, cyber-terrorists, foreign cyber-military forces, and foreign intelligence organizations. Cooling technology providers and their clients are not immune to such an attack as shown by the attack on Target and its customers in 2013 as discussed more fully below. As an example, the recent Marriott/Starwood data breach has been linked to Chinese intelligence authorities, which are believed to have conducted the attack to collect valuable personal information on individuals and officials.

In light of this heightened risk environment, both government and non-profit entities have sought to develop resources, assessment tools, and educational information to promote and enhance cybersecurity in virtually all industries and settings in the U.S. Because of the technical expertise required to identify and protect against threats in an ever-evolving environment, cybersecurity consulting firms have rapidly grown to meet the growing demand for such services in every critical infrastructure sector.

Unfortunately, cyber threats are projected to increase due to several factors, which are also fueling the expansion of IOT. First, a new internet protocol, known as IPv6, is being implemented worldwide, which will allow essentially any object/device on the planet to have unique internet ID, which, coupled with the continued expansion of broadband internet and dropping prices of "smart" devices, will lead to more devices (and users) being connected to the internet than ever before.

As applied to the cooling industry, the use of sensors has been established in HVAC systems for years, and the enhancement of such sensors by wirelessly connecting them to internet networks will allow for increased data collection, storage, trouble shooting, maintenance, and real-time monitoring. New online management platforms will expand monitoring to ducts to measure such variables as airflow, temperature, and static airflow. The benefits of such technology will not only extend to preventive maintenance, rapid response, and increased energy efficiency, but will provide useful data to improve upon business practices and provide enhanced feedback from customers and clients. However, such enhanced con-

nectivity will also subject HVAC systems and cooling technology providers to cybersecurity risks, which have been crystallized in the well-known case study of the massive Target data breach of 2013.

The Target Data Breach

In 2013, news outlets widely reported Target's unprecedented data breach of over 110 million customers, which included personal information and payment card account information. As a consequence, Target faced an onslaught of lawsuits and regulatory investigations, which ultimately cost the company \$290 million. In the course of such lawsuits and investigations, the details of how the hackers were able to access Target's computer network were revealed, and the cause of the breach was ultimately traced to an unfortunate refrigeration/HVAC company that provided services to several Target locations.

The criminal hackers had deployed a phishing email to Target suppliers and an HVAC employee was deceived into opening one such email, which resulted in a malicious code ("malware") to be downloaded onto the HVAC vendor's computer network, without the employee's knowledge. Unfortunately, the HVAC vendor's computer system did not have adequate security and system protections and did not detect the malware or the intrusion onto the network. The malware ultimately revealed log-on credentials that had allowed the HVAC vendor to communicate with Target's billing system. By using such credentials, the hackers gained access to the Target computer network and were ultimately able to infiltrate a Target customer service database, which contained personal information and payment card account data.

Following the Target data breach, the fact that many companies use Internet-connected HVAC systems, often without adequate cybersecurity controls or policies, became an area of concern, as a potential gateway for hackers to access large corporate systems. Cloud security service provider Qualys reported that its researchers had identified approximately 55,000 HVAC systems that were connected to the Internet, and which were subject to exploitation by hackers. Most significantly, Qualys also reported that it had conducted additional network scanning on Target and had still been able to virtually view Target's HVAC system online, even after disclosure of how the hackers had gained access to the Target system. Thereafter, a remotely-accessible HVAC system at the Sochi Olympic Arena, was determined to have inadequate security, as it lacked authentication requirements to access the HVAC control system, which necessitated a reconfiguration of the system prior to the Olympics and opening ceremonies.

Practical Consequences Of The Target Data Breach

Contracts

In the wake of the Target data breach, businesses have identified vendors and service providers as potential sources of risk, liability, and compliance exposure. As such, contracts with third party service providers and vendors have incorporated cybersecurity provisions, especially where third parties have access to or use of a company's system and data. In light of this, cooling technology vendors may be contractually required to represent and warrant that their access, use, storage, and disposal of client/customer data shall be done in compliance with all applicable federal, state, and foreign data protection laws, and corresponding regulations. Contracts may also require cooling technology vendors to adopt industry-appropriate standards and practices, such as those issued by such organizations as the International Organization for Standardization (ISO) or by U.S. authorities, such as the National Institute of Standards and Technology (NIST), which are also discussed in this paper.

Owner clientele may also impose cybersecurity standards on cool-

ing technology vendors that support such owner's effort to demonstrate due diligence efforts to their own customers or regulators. For example, vendors may be required to submit detailed network infrastructure diagrams as part of this process. Vendors may also be required to consent to cybersecurity audits and may also have to disclose instances of actual or threatened data breaches or similar cybersecurity vulnerabilities. In addition, vendors may be subject to risk assessments, based on their access to critical assets, and, depending on the degree or nature of such access, may be contractually required to maintain acceptable cybersecurity risk programs to address such risks.

Data breach notification requirements may be required pursuant to any applicable state-specific or industry-specific laws or regulations. The vendor may also be contractually required to cooperate in any data breach investigations, including any private investigations that do not involve law enforcement authorities. In addition, the cost of any such breach may be borne exclusively by the vendor, if so required under the contract, and may also be required to indemnify the customer/client for any losses arising out of the data breach.

Contracts may also require that vendors affirm that they themselves have cybersecurity policies in place to address cybersecurity matters and safeguarding of customer/client data and systems. To the extent that vendors outsource or contract management of the entirety or a portion of their own computer infrastructure, vendors may similarly be required to impose downstream cybersecurity requirements on their own vendors and subcontractors.

In the event that the cooling technology vendor will have access to or will be entrusted with highly-sensitive personal information, encryption might be contractually imposed, with potential reference to encryption standards established by NIST's Federal Information Processing Standards (FIPS). Similarly, if the client/customer is sharing credit card payment data with the vendor, the vendor may be required to comply with Payment Card Industry (PCI) data security standards.

Vendors that serve public sector entities must also review their government contracts for similar requirements, and must also assess their compliance requirements with NIST 800-171, which, as of December 31, 2017, imposed specific security standards on vendors that process, store, or transmit information that is deemed "sensitive" but not "classified" for such federal agencies as the Department of Defense, the General Services Administration, and the National Aeronautics and Space Administration. Vendors subject to such requirements must assess and document their level of compliance in handling such information, including configuration of computer networks, access control, incident response policies, and means/methods by which portable computer media are managed.

In summary, contracts executed by cooling technology companies may impose legal requirements that are enforceable under contract law, including the imposition of cybersecurity standards that may otherwise be voluntary (i.e. such as the NIST Framework, discussed below), but which by reference in a contract, convert them into legally enforceable requirements.

Supply Chain Security

Due to complexity of supply chains, which often involve foreign/international participants, cooling technology vendors should better understand their overall supply chain risk management, particularly within their computer and cybersecurity supply chain relationship networks. A key example of the heightened scrutiny on foreign vendors is a new procurement ban against Russian-based cybersecurity firm Kaspersky Labs, which is now barred from contracting with the Pentagon, the General Services Administration, and NASA, out of concerns of reported ties between Kaspersky and the Kremlin. In light of these developments, cooling technology vendors should consider assessing their supply chain risk manage-

ment programs to ensure that they:

1. Determine cybersecurity requirements for suppliers;
2. Impose contractual cybersecurity requirements on their own vendors and suppliers;
3. Communicate to suppliers that such requirements will be verified and validated;
4. Verify that all cybersecurity requirements are met via the appropriate methodologies, and
5. Manage all the above activities.

Such an assessment should be applied to all applicable technologies that are used by the cooling technology vendor, such as information technology, industrial control systems (discussed above), and any IOT devices (also discussed above.)

Legal And Regulatory Requirements

In addition to contractual obligations, cooling technology companies may be subject to both federal and state cybersecurity laws and regulations, which will be determined by such factors as their individual business practices (i.e. types of data collected, stored, or transmitted), technology adopted/implemented (i.e. hardware, software, network configuration, etc.), types of clients/customers served (i.e. businesses, consumers, government entities), and jurisdictions in which they are doing business or intend to do business. While a comprehensive summary of all potentially applicable cybersecurity-related laws and regulations is beyond the scope of this paper, provided below are selected laws/regulations that may be reviewed by cooling technology companies and their counsel.

Federal Laws and Enforcement Actions

At present, there is no single federal data protection or cybersecurity law (or any single enforcement authority) that governs cybersecurity matters/practices by U.S. businesses. Rather, several such laws and regulations are industry-specific. For example, the 1996 Health Insurance Portability and Accountability Act (HIPAA), requires that regulated healthcare organizations take measures to protect their computer systems, networks, and information, while the Gramm-Leach-Bliley Act (GLBA) requires financial institutions to "establish appropriate safeguards" to protect customer personal information "(1) to insure the security and confidentiality of customer records and information; (2) to protect against any anticipated threats or hazards to the security or integrity of such records; and (3) to protect against unauthorized access to or use of such records or information which could result in substantial harm or inconvenience to any customer." The Federal Information Security Management Act (FISMA) applies to all federal government agencies and requires the development and implementation of mandatory policies to address information security. As noted above, such laws, while not necessarily directly applicable to cooling technology companies that do not participate in such industries, may lead private or public customers subject to such laws to contractually impose cybersecurity requirements on cooling technology vendors. For example, a cooling technology vendor servicing a hospital may be contractually obligated to comply with HIPAA, if such vendor potentially has access to protected health information of hospital patients (even if such data is not actually viewed by the vendor).

The Federal Trade Commission (FTC) Act allows the FTC to enforce consumer protections provided in Section 5 of the Act, by bringing enforcement actions against business entities that participate in "unfair or deceptive acts or practices." Under this broad authority, the FTC has brought dozens of cases against companies that have allegedly failed to provide appropriate protections for customer data. The FTC recently approved a final settlement with



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Uber Technologies, over allegations that the company had deceived customers about its privacy and data security practices. Specifically, the FTC alleged that, despite Uber's claim that consumer data was "securely stored within our databases," Uber's security practices failed to provide reasonable security to prevent unauthorized access to consumers' personal information in databases Uber stored with a third-party cloud provider. The FTC also alleged that the company similarly failed to protect Uber driver information. Under the terms of the final settlement, Uber is subject to imposition of civil penalties if it fails to notify the FTC of future data breaches involving customers or drivers, and is also prohibited from making misrepresentations regarding its data security practices. Uber is also required to implement a comprehensive privacy program and has agreed to submit to independent third party assessments of its program for 20 years. Cooling technology vendors should therefore ensure that their public representations regarding the status of their cybersecurity protections (perhaps via advertising materials or on websites) are accurate and do not run afoul of FTC cybersecurity guidance and recommendations.

Publicly traded companies must also consider their compliance posture as to Securities and Exchange Commission (SEC) guidance on cybersecurity risks and incident disclosures. On September 26, 2018, the SEC announced the imposition of a \$ 1,000,000.00 fine with a financial services entity to settle charges arising out of a 2016 cybersecurity incident wherein customer information was compromised. This enforcement action, the first-ever enforcement of the SEC's Identity Theft Red Flags Rule, demonstrates the heightened federal enforcement environment at this time, in regard to cybersecurity practices by regulated companies. Therefore it is necessary for those cooling technology providers that are publicly traded to be aware of these additional requirements.

State Laws

In addition to federal laws and enforcement actions, companies should consider the applicability of state laws that relate to cybersecurity and data breach notification requirements. As of the present time, all fifty U.S. states have imposed data breach notification laws, governing any such incidents that affect residents of the respective states. The legal requirements vary among the states, and several states have now required that regulated companies must take "reasonable measures" to protect and secure data that contains personal information. Although several attempts have been made to implement a single national data protection law, such efforts have thus far been fruitless, and companies are cautioned to determine whether they collect, store, or transmit personal information in specific states or relating to residents of specific states.

Critical Infrastructure Protection Considerations

As referenced above, cooling technology companies interface with many critical infrastructure sectors, in both the private and public sectors, and such companies should therefore be familiar with critical cybersecurity threats that place such sectors (their customers) and themselves at risk. Although multiple cybersecurity standards have been developed over the years by several organizations, groups, and think tanks, a recent study has reported that 70% of surveyed organizations identified the NIST Cybersecurity Framework ("Framework") as the most popular standard. The Framework was developed pursuant to Executive Order 13636, "Improving Critical Infrastructure Cybersecurity," which was issued by President Obama in February 2013, and authorized creation of a voluntary critical infrastructure Cybersecurity Framework to address and manage cybersecurity risk. In 2014, the Cybersecurity Enhancement Act of 2014 (CEA) further updated the role of NIST in identifying and developing cybersecurity risk frameworks for voluntary use by

critical infrastructure owners and operators, such as cooling tower technologies, to help identify, assess, and manage cyber risks.

The latest version of the Framework, issued in April 2018, provides a potential tool for cooling technology companies to:

1. Describe their current cybersecurity posture;
2. Describe their target state for cybersecurity;
3. Identify and prioritize opportunities for improvement within the context of a continuous and repeatable process;
4. Assess progress toward the target state; and
5. Communicate among internal and external stakeholders about cybersecurity risk.

While these five primary functions serve as a useful general framework for analyzing an organization's cybersecurity status, the Framework itself is intended only to complement, rather than replace an organization's risk management, cybersecurity, or compliance programs.

Among the specific measures that may be considered in any such programs, whether based on the Framework or not, are:

1. Developing a formal cybersecurity governance and risk management program, including preparation of formal policies and planning ongoing measures to assess cybersecurity vulnerabilities and maintain inventories of the business technological infrastructure.
2. Creating a Business Continuity and Disaster Recovery Plan to prepare for data breaches, cyber incidents, and similar emergencies/events, and periodically test such plans via drills and staff exercises.
3. Adopt measures to harden critical servers and related hardware, while ensuring that critical software updates are applied on a timely basis.
4. Secure system access by ensuring that physical, administrative, and technical safeguards are in place, such as effective passwords and multi-factor authentication measures.
5. Implement appropriate controls on applications and third party accounts, including separate accounts for administrators and users.
6. Consider encryption of devices where theft or loss is a possibility, such as a laptop, smartphone, or tablet, as well as encryption of communications.
7. Identify and review all customer agreements, vendor agreements, supplier agreements, third party service agreements for compliance with any applicable cybersecurity terms and conditions, and establish procedures for emergency response with such parties in the event of a data breach or similar incident.
8. Initiate a cybersecurity awareness and training program for staff, including on-going training in new risks and potential vulnerabilities
9. Implement a personnel security program to further control access, including periodic background checks and review of the applicable cybersecurity policies.

Additional Cost Considerations Costs of Data Breach

In further assessing the appropriate level of investment to address potential vulnerabilities, cooling technology companies should further familiarize themselves with potential costs of action or inaction. According to the 2018 Ponemon Data Breach Cost Report, the average cost of a data breach per compromised record was \$ 148.00, reflecting a continuing trend of annual increases in total cost, per-capita cost, and average size of data breach (by number of records lost or stolen). The reason for such increasing cost be-

comes apparent when analyzing the multiple and complex measures that must be undertaken by any company seeking to remediate a data breach.

First, affected companies assume breach detection and escalation costs, for such services as forensic and investigative activities, assessment and audit services, crisis management teams, and communications to and with executives and managing boards of directors. Second, notification costs are assumed for creating contact databases, assessing regulatory compliance requirements, engagement of outside experts (including legal counsel), mail expenses, and email and website buildouts for notification. Third, post data breach costs are incurred for help desk set up, follow up investigations, remediation measures (such as credit monitoring and identity theft protection services for affected customers), legal expenses, and regulatory response/defense. Lastly, independent of any lawsuits that may be filed by affected businesses or customers, a data breach may result in loss of business and negative impact on reputation.

Cyber Insurance

Because of the above-described costs, a common component of many cybersecurity programs is securing cybersecurity or data breach insurance, which started being offered by insurance companies in the early 2000s. Such early policies included coverage for business interruption, data asset loss, extortion, crisis management costs, and liability arising out of data breaches. Since that time, as data breach incidents have continued to occur and increase in cost and scope of affected individuals, cyber insurance policies have also been expanded to cover such costs as forensic analysis, privacy or security breach notification and response, and data loss or destruction. Other insurable costs include investigation costs, litigation costs, data restoration, litigation damages, regulatory defense, and penalties.

Among the various types of insurance coverage, first-party cover-

age addresses costs related to activities that the insured has to undertake in response to a data breach, such as hiring of attorneys, public relations firms, crisis management firms, or computer forensics firms. Other immediate costs include notification costs (i.e. printing and mailing costs), credit monitoring services for affected customers, and establishment of call centers to address customer questions and issues.

In addition, coverages may extend to training employees, establishing data breach information portals/websites, creation of cybersecurity incident response templates, compensation for loss of income (i.e. business interruption), and restoring lost data.

Third-party coverage policies protect the insured from liability to affected third parties, and may include coverage of litigation damages, costs of litigation defense, and costs of regulatory fines and defenses of same.

Conclusion

The current state of the legal, regulatory, and threat environment within which cooling technology companies operate mandates thorough, competent, and on-going assessments of their individual cybersecurity vulnerabilities, preparedness, and resiliency. As participants across multiple critical infrastructure sectors, cooling tower companies stand much to lose if appropriate measures are not taken to address the important issue of cybersecurity, but also have much to gain if they avail themselves of the various resources, both public and private, which are available to strengthen their cybersecurity posture.

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Impact Of Legionella Regulations On Water Treatment Programs And Control – An Observational Prospective Survey

Patrick Racine, P.Eng, Cem
Klenzoid Canada – A Dubois Company

Abstract

Implementations of local Legionella regulations bring attention to cooling towers and their perceived Legionella risk. Following the enactment of a local regulation in the Province of Quebec in Canada, an observational prospective survey was undertaken by a leading water treatment firm. A review of a large dataset of Legionella culture results from more than 300 cooling towers with their associated water treatment program control over three years allows to draw important conclusions on the impact of Legionella regulations on water treatment program controls. This paper reviews specifically how the regulation affected the client engagement in their water treatment programs and their associated biocide feed control mechanisms. This led to a significant improvement in overall Legionella results. Conclusions are drawn on the impact of such regulations on the water treatment program, control and the industry.



Patrick Racine

Introduction

A Legionella outbreak linked to a cooling tower in Quebec City in the summer of 2012 (Goupil-Sormany & Huot 2012) caused the provincial regulators to establish a rigid risk management and monitoring program for all cooling towers in the province of Quebec. The Regis du Batiment du Quebec (RBQ) regulation defines cooling towers as all open recirculating cooling systems, including cooling towers, fluid coolers and evaporative condensers. The regulation requires a documented mechanical maintenance program and a documented water treatment program for all cooling towers. Sampling was mandated for all cooling towers on a 30-day interval for Legionella testing by culture. A leading water treatment firm took this opportunity to combine all Legionella culture results with the database of water treatment control parameters collected by their field engineers and chemists.

Miller and Koebel (2006) reviewed the efficacy of different biocides on Legionella control. A limitation has always been the lack of data regarding the level of control of the water treatment program in the field. No study to date has been able to access a large dataset (over 300 cooling towers) over an extended period (3 yrs) to review the impact of the control of the water treatment program on the control of the Legionella bacteria in the system.

Early observations of this Quebec dataset (as seen in Table 1) indicated improvement over time, following the implementation of the sampling requirement in the regulation. This allowed the authors to delve deeper into the factors led to this improvement.

This study reviews the relationship between water treatment program parameters being within control ranges and Legionella positivity. It also reviews the impact of biocide feed automation on Legionella positivity. Also of interest is the relationship between average total bacteria count and average Legionella results across the sample set.

Percentage of Cooling Tower Samples > 10,000 cfu/L over time

(Legionella Pneumophila sg 1 – 14)

Quarter% >	10,000 cfu/L
Q3 2014	20.9%
Q4 2014	14.1%
Q1 2015	11.1%
Q2 2015	12.3%
Q3 2015	14.0%
Q4 2015	11.7%
Q1 2016	8.1%
Q2 2016	10.2 %
Q3 2016	12.1%
Q4 2016	7.6%
Q1 2017	6.2%
Q2 2017	8.4%

Sampling regulation took effect on July 1, 2014

Table 1: Percentage of Cooling Tower Samples > 10,000 cfu/L over time

This study builds on two previous papers on this dataset:

- Key factors in Legionella control and the positive impact of Legionella regulations for water treatment professionals – Racine and Smith (AWT 2018)
- Legionella regulation, cooling tower positivity, and water quality in the Quebec context – Racine, Elliott, Betts – (ASHRAE 2019)

This study reviews the relationship between water treatment program parameters being within control ranges and Legionella positivity. It also reviews the impact of biocide feed automation on Legionella positivity. Also of interest is the relationship between average total bacteria count and average Legionella results across the sample set.

Method

To analyze whether Legionella growth is associated with control of the water treatment program, 323 cooling towers were sampled monthly. The sample period analyzed ranges from July 2014 to June 2017. Not all cooling towers in the dataset are represented in every month in the sample period based on seasonality of the cooling load and type. The dataset has a total of 8936 observations. This observational prospective survey analyzed the results from this dataset.

Sampling technicians were responsible for collecting water samples for Legionella testing by the third-party laboratory. The measure used for this study is Legionella Pneumophila measured in CFU/L. The readings were recorded as falling into a given range (i.e. <10,000) and were categorized and ranked on a log-linear scale for this study, such that readings under 10,000 were recorded as 1; 10,000 to under 100,000 as 2; 100,000 to under 1,000,000 as 3, and over 1,000,000 as 4. Temperature was also measured at the time of sampling and was included in the dataset.

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In parallel, technical representatives were on site at least once per month to measure and record a variety of water quality tests. This was done as part of the water treatment firm's standard service offering. The decoupling of the sampling task from the management of the water treatment program was intentional to increase accountability.

For the first part of this study, the degree of deviation from the control limits of the water treatment parameter was calculated for each category of Legionella results. The water treatment results were evaluated against their associated control parameters to determine whether or not there were any quality exceptions (parameters outside the designed control limits (CL)). The following parameters were reviewed:

- Total hardness above the designed UCL
- pH above or below the CL
- Conductivity above the designed UCL
- Total halogen below the designed LCL
- Free halogen below the designed LCL
- Corrosion/scale inhibitor below the designed LCL

The control limits were established through best practices by the water treatment specialist on site. The control limits are the same for a given water source. All cooling towers in this dataset were running an oxidizing biocide (sodium hypochlorite) and an organic deposit penetrant aid & dispersant (trade product) combined with a halogen stable, multicomponent mixture that combined corrosion inhibitors for ferrous and admiralty metals with polymer technology that stabilizes scale-forming minerals.

To analyze the relationship between system control and Legionella levels, the authors looked at the percentage of water treatment parameters within the designed control ranges (or percent in control, PIC hereafter). The PIC was calculated for three time periods: in the month prior to the Legionella sampling (T-1); two months prior (T-2); and three months prior (T-3). The differences in average PIC by group of Legionella Pneumophila positivity levels were calculated (<10,000, 10,000 – 1,000,000 and >1,000,000 cfu/L). Test statistics were computed using the pooled sample variance method to test for statistical significance in the difference in average PIC between cooling towers grouped by Legionella rankings.

In the second part of the study, Legionella positivity over time was compared to the percentage of cooling systems that were using ORP control to feed the oxidizing biocide. The conversion to ORP-based halogen injection significantly improved free halogen control. This change in control method is also used as a proxy for the clients' engagement in continuous improvement of their systems.

Finally, a review of total bacteria count (TBC) performed by the technical representatives was compared to Legionella results within the same quarter. Though past studies have shown no correlation between the two measurements on a given system, the authors wanted to evaluate if this dataset would show any correlation.

Results

(total CFU/L)	Legionella Pneumophila.			
	Rank	% in Control t-1	% in Control t-2	% in Control t-3
<10,000	1	94%	93%	93%
<100,000	2	91%	92%	92%
<1,000,000	3	92%	93%	92%
>1,000,000	4	90%	91%	91%

Table 2 - Average Cooling Tower Control in Periods Preceding Legionella Reading

Table 2 shows that an increase in the level of control of the water treatment program over time has an impact on the reduction of Legionella levels in these systems. To test whether this observation is statistically significant, Table 3 publishes the test statistics, measuring the statistical significance in the difference in PIC between cooling towers grouped by Legionella ranking.

Rank	% in Control t-1	% in Control t-2	% in Control t-3
1-4	2.29	1.61	1.80
1-3	2.18	0.74	1.36

BOLD = Significant at the 95% confidence level

Table 3 - Tests for significant difference in % in control between Legionella groups, across time lags

The first row of Table 3 tests whether, from Table 2, the PIC for Rank 1 is significantly greater than for Rank 4, variance and sample size considered. Rank 1 minus Rank 3 is also considered in the second row to check for how robust the results are, given that Legionella readings over 1,000,000 are very uncommon in the dataset.

Given that the pooled standard deviation is equal to 1.3%, Table 3 confirms the statistical significance of higher PIC levels in cooling systems that have lower presence of Legionella. This demonstrates that water quality is of statistical significance in controlling for Legionella Pneumophila levels.

When looking at the adoption rate of ORP controllers in our dataset, we can see from Figure 1 and Figure 2 below that the greater the adoption rate of such control, the greater the control on Legionella positivity over time.

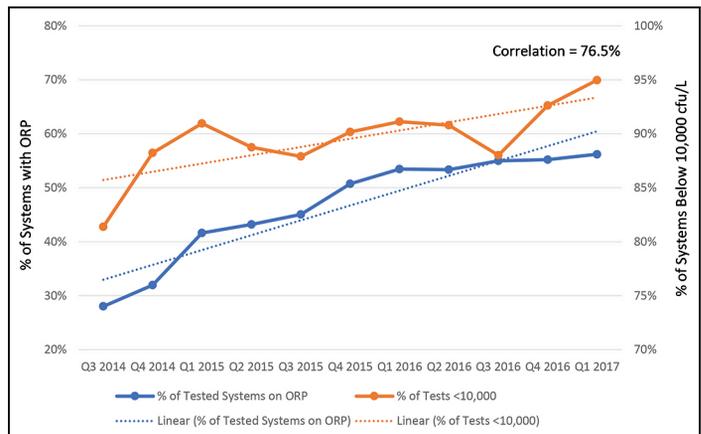


Figure 1 – Percentage of systems over time, with ORP control and % of systems with Legionella results below 10,000cfu/L

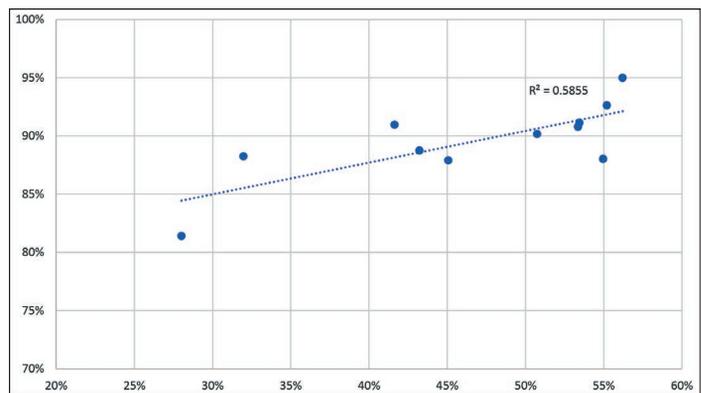


Figure 2 – Percentages of systems with ORP control vs. percentages of systems with Legionella less than 10,000cfu/L

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Total bacteria counts were taken on 4,454 of the observations over the three-year period. Table 4 below shows the distribution of these results in log intervals.

Log intervals of TBC results – cfu/L	% of Samples
<1000	74.3%
1,001 - 10,000	19.7%
10,001 - 100,000	5.5%
100,001 to 1,000,000	0.4%

Table 4 - Percentage in log intervals of total bacteria counts

The log interval results were compared to the cooling systems' Legionella results in Table 5 below. These observations show a very low correlation of 3.9%.

Total bacteria count (TBC)	Legionella (cfu/L)		
	< 10,000	10,001 to 100,000	100,001 to 1,000,000
<1,000	75%	69%	73%
1,001 to 10,000	19%	23%	26%
10,001 to 100,000	5%	8%	1%
100,001 to 1,000,000	0%	0%	0%

Table 5 - Percentage of each log interval observations of TBC in each log interval of Legionella counts

Discussion

The analysis of this dataset confirms that consistent control of water treatment parameters over time is a critical component of a Legionella risk mitigation strategy. Stronger program automation is shown to have a positive impact on water treatment control, leading to reductions in Legionella presence in cooling systems. The results confirm the conclusion of past studies that total bacteria count should not be used as a proxy for Legionella control in cooling towers. The data from Table 1 show a consistent improvement on the level of Legionella control following the implementation of the Legionella sampling requirement in the regulation.

The strength of the control of the water treatment program over time is shown to be statistically significant. Table 2 and Table 3 show this, including in highly controlled programs. All of the aggregate data show program control above 90% in each category in Table 2. This creates a limitation to this dataset, where the average client in this study had already chosen to work with a leading water treatment firm and that the programs were already well-controlled.

Many other factors create limitations to this study, such as non-water treatment factors which have an impact on Legionella results. System design, dead-legs, type of system sumps, filtration, incoming raw water source, and exposure to sunlight and bio-nutrient are all factors that can affect the presence and level of Legionella in a given cooling system. These factors are outside of the scope of this data review but cannot be ignored by cooling system owners and operators.

The authors assert that one of the key driving forces to the improvement in the level of control of the cooling systems over time was the mandate to sample for Legionella. The awareness of these results combined with the regulatory requirement to react to such results was the catalyst for systems improvement.

The authors reviewed the adoption of ORP control in this study, knowing that this technology is designed to increase the degree of control of an oxidizing program on a cooling system. The authors also believed this to be a strong proxy for a client's engagement in the improvement of the site's water treatment programs. Installing

an ORP control system is a measurable indication of continuous improvement of the program and is rarely done as the only change in the program. It would be ill-advised to use these results to claim that implementing an ORP control strategy alone is a solution towards risk mitigation. Rather, the study indicates that a regular review of the water treatment program and its associated results (including Legionella sampling) leads to a willingness to implement continuous improvement measures of the programs. Continuous improvement measures must include chemistry, but also equipment, control schemes and data management as part of a complete bundle of services. The authors believe this to be a change that occurs both in the water treater's and the client's mindset.

Of importance in the results is the confirmation through this dataset of the lack of correlation between total bacteria count and Legionella counts. Control of total bacteria count is an important part of a strong water management program. Efforts should be made to ensure that this is achieved. Using total bacteria count as an indicator of Legionella risk mitigation would not be correct.

Conclusion

Our data suggest that the introduction of the Quebec regulations raised the level of awareness and accountability in the management of cooling water treatment programs. This led to a reduction in levels and incidences of Legionella positivity. The data also suggest that the Legionella sampling requirement was a primary driver to this improvement. The adage that "you can't manage what you don't measure" applies here. Our observations through the last three years indicate that measuring the performance of the water treatment programs through Legionella sampling created a willingness to improve these programs. The Quebec regulation forced program assessment through legislated sampling requirements. This created a sense of awareness and accountability from the cooling tower owners. Actions were followed-through, and the impact of these actions was acknowledged through re-sampling.

Regulators should consider taking a common-sense approach when establishing guidelines and regulations. Clear and simple regulations can have a major impact on the risk associated with the presence of higher levels of Legionella in cooling water systems.

The industry, including water treatment firms and cooling equipment manufacturers, is often wary of the introduction of new regulations. Our data indicate that regulations can improve how water treatment programs are controlled, leading to reduction in levels and incidences of Legionella positivity. This confirmed our strongly-held belief that improving the consistency of the water treatment program not only has a positive impact on operating costs but can also reduce exposure risk by reducing the level and presence of Legionella in a cooling system.

Acknowledgments

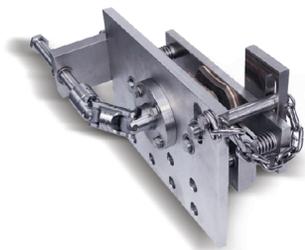
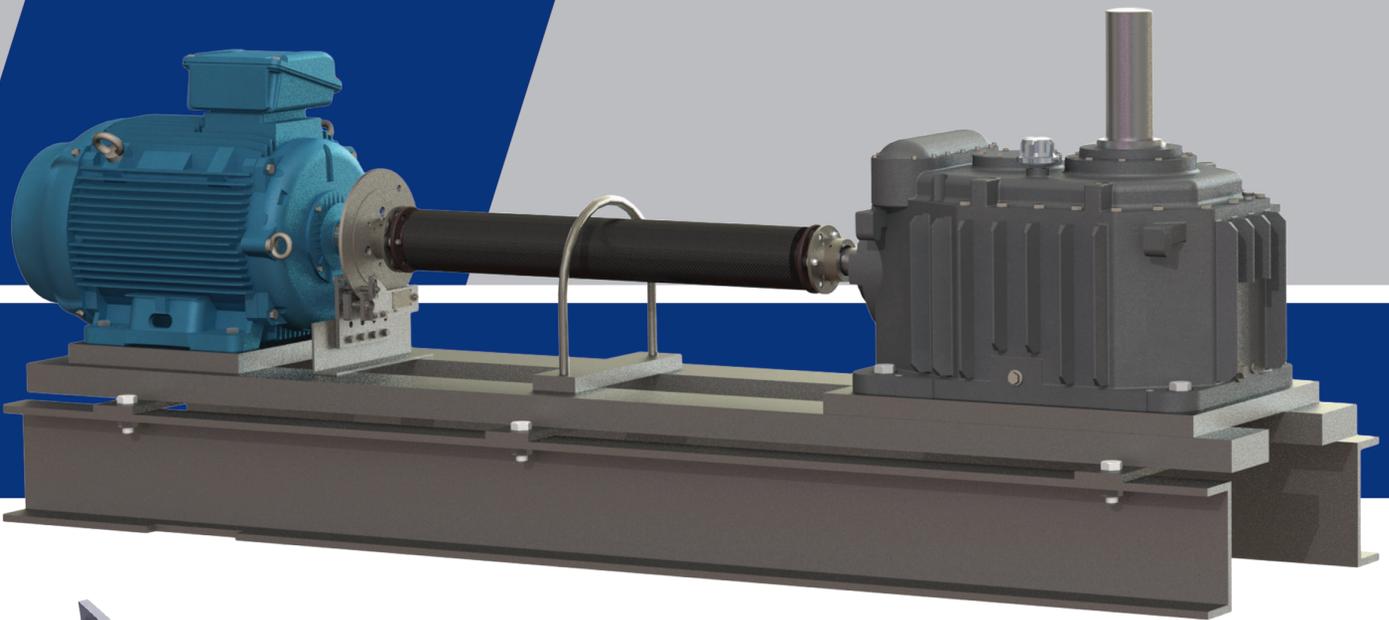
The author would like to acknowledge the following people for their support in collecting the data and reviewing the paper:

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Using Experience And Six Sigma To Optimize Water Treatment

David W. Anton, Ascend Performance Materials
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Abstract

Coagulation and flocculation are basic process steps to providing the quality of water required at many industrial and commercial sites. Water clarification and lime softening depend on the correct application of these processes. Surface water clarification is the first water treatment step for many sites. The process involves taking turbid river or raw water that contains both settleable solids and dispersed solids and producing clean water for direct use and/or downstream processes. The dispersed solids tend to be colloidal and require treatment to assist the settling process. While the clarification process is well understood, the application of chemistry in many instances does not achieve the desired results. Statistical analysis and the use of the Six Sigma Process was used at one site with significant success. This paper details the process used to obtain the improved results and provides a path to make the chemistry component of the water treatment process function more effectively. First, an entire process is covered – improving the clarification process using Six Sigma Analysis.

The paper does not focus on all the technical aspects of clarification and/or water treatment process since these areas are both well documented and can be unique for specific sites. It is however a good roadmap toward improving current operations and providing a focus that is often ignored. It is hoped that individual sites can use this study to prove their data and develop a plan to improve and control their processes.

The process worked so well that it was used on other parts of the water treatment program to improve results. This is the second part of the paper – using Six Sigma tools to improve water treatment. Specifically the Measurement System Analysis (MSA) was used to determine if the measurement of key parameters was sufficiently accurate and precise to predict outcomes for the process. We base decisions on data that in many cases is not accurate or precise.

Introduction

The water treatment program efficacy relies on stability. Water Sources can be completely different for two sites, even those located 20 miles apart. Combine this with differences in process demands, e.g. tube wall temperature, metallurgy, exchanger design, etc., and the complete solutions to problems can be more complex than we realize. There are tools and processes that will uncover undetected solutions and opportunities. The process that was used in this case first focused on the science and the process before utilizing the math. The Six Sigma Process was the roadmap here.

The Six Sigma Process is a disciplined, data-driven approach and methodology for eliminating defects (driving toward six standard deviations between the mean and the nearest specification limit) in any process. Six Sigma's focus is on eliminating defects and reducing variability. Six Sigma utilizes many established quality-management



David W. Anton

tools that are also used outside Six Sigma. It was introduced by engineer Bill Smith while working at Motorola in 1986. Jack Welch made it central to his business strategy at General Electric in 1995. ^[1]

Six Sigma doctrine asserts ^[2] :

- Continuous efforts to achieve stable and predictable process results (e.g. by reducing process variation) are of vital importance to business success.
- Manufacturing and business processes have characteristics that can be defined, measured, analyzed, improved, and controlled.

- Achieving sustained quality improvement requires commitment from the entire organization, particularly from top-level management.

Features that set Six Sigma apart from previous quality-improvement initiatives include:

- A clear focus on achieving measurable and quantifiable financial returns from any Six Sigma project.
- An increased emphasis on strong and passionate management leadership and support.
- A clear commitment to making decisions on the basis of verifiable data and statistical methods, rather than assumptions and guesswork.

The **DMAIC** project methodology has five phases ^[3] :

Define the system, the voice of the customer and their requirements, and the project goals, specifically. This is an important step that is too often quickly done to fulfill the process.

Measure key aspects of the current process and collect relevant data; calculate the 'as-is' Process Capability. Review the measurement parameters and the impact on the process. How well can we trust our measurement systems? In this case, the MSA provided the path to success.

Analyze the data to investigate and verify cause-and-effect relationships. Determine what the relationships are, and attempt to ensure that all factors have been considered. Seek out root cause of the **defect under investigation**.

Improve or optimize the current process based upon data analysis using techniques such as design of experiments, failure modes and effects analysis (FMEA), mistake proofing, and brainstorming. If you know the solution before the DMAIC process, you probably did a poor job and wasted a lot of time.

Control the future state process to ensure that any deviations from the target are corrected before they result in defects. Implement control plans, checklists, troubleshooting guides and systems such as advanced process control, production boards, visual workplaces, and continuously monitor the process. This Control Process should be periodically reviewed for effectiveness and capability so that the desired quality level is maintained.

Two adages to follow with any Six Sigma Study are:

1. Science before Math.
2. Challenge your paradigms, don't equate an improvement with a solution.

The Science of Clarification

Jumping to jar testing and/or trialing different polymers can result in an incremental improvement but it does not result in a robust and stable process. Finding improvements should never be equated with finding the solution. With that said let's look at the science of clarification.

The particle removal process for groundwater is accomplished during the slow movement of water thru the earth layers of sand, rock, and clay. Groundwater characteristics tend to be very stable which simplifies the treatment process. Surface water is much more variable as it is impacted by sudden storms, seasonal variations, and multi-decade cycles of drought and high rainfall. This can swing the physical and chemical characteristics of the water source and make the pretreatment process more difficult.

The processes of coagulation and flocculation are used to enhance and/or facilitate the natural process of settling so that a clarifier can function effectively.^[4] Raw water clarification is the first step in the water purification process unless a site has a pretreatment settling pond and/or reservoir. The purpose of a clarifier is to reduce the biological activity and organic matter to an acceptable level in the water, decrease the suspended solids typically measured by turbidity (**NOTE:** clarifiers should not be the sole filtration step), and remove about 60% of the water hardness (cold lime softening clarifiers only) so water can be conserved.

This is accomplished by pretreating the raw water feed with bleach and polymer and then mixing a lime slurry with the incoming raw water to cause the calcium and magnesium hardness (carbonate forms) to precipitate out of the water. The process is then enhanced with the addition of ferric sulfate to improve clarification and prevent operational issues (i.e. lime floc becomes too compacted). The clarifier in this study uses the cold lime method of clarification which has five basic steps:

1. Disinfection of organic matter
2. Hardness Reduction by Lime Softening
3. Coagulation
4. Flocculation
5. Sedimentation

Although many clarifiers do not use lime the optimization process used here is not dependent on which water chemistry treatment program is chosen. For more details on coagulation and flocculation, refer to the NALCO Water Handbook as a start. It provides a good review of colloidal materials and the coagulation process. The Betz and Drew Handbooks provide further details and give more details on the process itself. What is not stressed enough in any of these texts is the importance of flow control and pH control.

Proper control of a Clarifier Operation involves maintaining constant and consistent conditions. The saying "Don't stir up muddy waters" is relevant to this process. Process stability and its impact are not areas that the textbooks stress but as this study will show the impact is significant. The following parameters and control variation are key:

1. Clarifier Flow between 3400 and 7500 gpm (50% / 110% of design)

2. Clarifier flow variation of no more than $\pm 10\%$ per hour.
3. Flow proportioned control for feed of coagulants, polymers, and bleach.
4. Flow adjusted blowdown control as per manufacturer design.
5. Clarifier pH swings kept to a minimum and above 10.0 pH units.

Disinfection of Organic Matter

Bleach is added to the raw water supplying the clarifier as a source of free chlorine. The free chlorine reacts with the organic matter and microorganisms, e.g. algae, dead plant and animal matter, viruses, and bacteria. Bleach will also destabilize some of the colloidal material which improves solids settling. This aspect of the biocide addition is often overlooked. Another variable is the seasonal impacts of the hydrophilic colloidal matter which provides color to the water and increase the chlorine demand.

Hardness Reduction by Lime Softening

Hardness reduction is the removal of calcium and magnesium compounds that are in the carbonate form from the water. These materials have solubilities that decrease with temperature so they can precipitate out in our heat exchangers and impact performance. We perform partial lime softening in the clarifier by adding a hydrated lime slurry $\text{Ca}(\text{OH})_2$ to the water. It may seem odd that we add a calcium compound to remove calcium but what we want is the hydroxide part (OH^-) of the compound. Raising the pH of the water converts all the CO_2 and HCO_3^- to the carbonate form CO_3^{2-} which is not soluble at the elevated pH present in the clarifier. This causes the calcium carbonate to precipitate out of solution and it is removed with the clarifier blowdown. The softening performance is dependent on the raw water calcium to alkalinity ratio so it may change over time. The performance is controlled by adjusting the clarifier pH to achieve the desired hardness reduction. It is critical to maintain a stable pH between 10.0 and 10.4 to prevent calcium precipitation downstream of the clarifier. Stable pH control also keeps the formation of calcium carbonate to the reaction zone, unstable pH could result in calcium carbonate precipitation outside of the floc generating zone which would negatively impact the settling time. One additional benefit of lime softening is the tendency of the lime to adsorb iron and organic matter as measured by the total organic carbon (TOC) reduction in the clarifier effluent. A clarifier that uses lime and/or ferric sulfate addition will have nice aqua blue water color as a result. The entire process occurs in the center reaction zone and mixing tube of the center well (where the water is highly turbid).

Coagulation

The natural settling time of material suspended in the water can range from 10 seconds (coarse sand) to about 1000 days (colloidal material). Colloidal material is about 0.1 microns in size and a good example of its small size is a smoke particle. This colloidal material will foul the reverse osmosis (RO) membrane so it must be removed. Very small particles will not settle even though its density is much greater than water. Compare an iron cannon ball and some fine iron dust each are made of the same material but the tendency to settle is vastly different. One will sink rapidly while the other will float on the surface of water or remain suspended in solution for a long time.

The purpose of the clarifier is to agglomerate or make these dust-like particles come together so they will sink. What prevents particles from agglomerating is the naturally charged nature of these

particles. Like charges repel one another so the charges must be neutralized first for the process to start. The predominant charge in raw water systems is a negative charge so cationic polymer and/or an inorganic coagulant (ferric sulfate) that will provide a positive charge is used for treating the water.

The thoroughly mixed suspension in the draft tube (mixing section) is where the coagulation process primarily occurs. The mixing energy in the center well assures that the neutralization process is completed. However too much mixing can cause the particles to shear or break apart so we must be careful not to mix too aggressively. The supplied mixing energy is measured by the ratio of volume (V_u) of solids in the upper section of the mixing zone to the volume (V_l) of solids in the lower section of the mixing zone. This is referred to as the V/V test. The difference between the two V's infers how much mixing energy is supplied to the flocculation process. With perfect mixing the two V's would be equal. A good range is a difference of 2 – 3 units dependent on the polymer or coagulant used.

Flocculation

Once neutralized the colloidal particles can agglomerate into larger settleable floc particle. This next step requires that the particles contact one another so they can bind to each other and form the required larger particles. You witness this process when you do the V/V test. Flocculation primarily occurs in the center well reaction zone (outside the mixing tube) where the agitation is gentler and the contact rate of particles is very high. Eventually the water flows out of the center tube and into the settling zone of the clarifier. In this area the rake keeps the bed from settling and the flocculation step is completed. At this point of the process the larger dirt particles help clean the turbid raw water in what is referred to as the “sweep floc mechanism”.

The sweep-floc mechanism can be compared to snowfall on dirty air. As the snow falls, it adsorbs particulates in the air, which coprecipitate. In this manner the snowfall acts to clean the air. The goal is to make particles that are 100 microns or greater (fine sand) so that the settling time is less than 100 seconds. When this is achieved the clarifier has sufficient residence time to produce the desired clear water, this outcome can be verified by the ability to see objects that are at a depth of at least 10 feet. In a properly controlled clarifier, the visual test is probably the best indication of performance and it can be used as a leading indicator.

Sedimentation

As the flocculation process goes to completion the clarifier generates large particles or precipitants that are much heavier than water and fall to the bottom of the clarifier. On the bottom, the precipitants form a sludge bed. The sludge bed is maintained at an optimum level, determined by current operating needs. The lighter particles of this floc are picked up by the recirculator and mixed with the incoming raw water and chemicals and serves as a building block for the formation of heavier floc when it comes into contact with the chemicals and raw water. The heaviest floc will fall to the bottom of the clarifier. Here the slow moving rake acts like a snow plow and eventually moves the dense material to the center discharge cone so it can be removed intermittently by the blowdown process.

Stokes Law

The principle involved in the entire clarification process is the settling velocity of particles. This was studied by George Gabriel Stokes who derived an expression, now known as Stokes law, for the frictional force – also called drag force – exerted on spherical ob-

jects with very small Reynolds numbers in a viscous fluid.^[6] Stokes law is derived by solving the Stokes flow limit for small Reynolds numbers of the Navier–Stokes equations.

At terminal (or settling) velocity, the excess force F_g due to the difference between the weight and buoyancy of the sphere (both caused by gravity) is given by:

$$w = \frac{2(\rho_p - \rho_f)gr^2}{9\mu}$$

g is the gravitational acceleration (m/s²)

R is the radius of the spherical particle.

ρ_p is the mass density of the particles (kg/m³)

ρ_f is the mass density of the fluid (kg/m³)

For dilute suspensions, Stokes' law predicts the settling velocity of small spheres in fluid, either air or water. This originates due to the strength of viscous forces at the surface of the particle providing the majority of the retarding force.

$$F_g = (\rho_p - \rho_f) g \frac{4}{3} \pi R^3$$

Where w is the settling velocity, ρ is density (the subscripts p and f indicate particle and fluid respectively), g is the acceleration due to gravity, r is the radius of the particle and μ is the dynamic viscosity of the fluid.

Thus the floc particle size (function of chemistry and mixing), upward velocity (determined by clarifier flow), and water temperature (impacts fluid viscosity) are the key parameters. Understanding the science behind the process allows one to rate the impacts properly.

Desirable Floc Characteristics

1. Firm and compact at least the size of a pin head.
2. Water that is clear between floc particles → indicates removal of colloidal materials.
3. Floc particles that appear to settle in slow motion (suspended particles → chemistry or mixing issues)

Once there is a clear understanding of the science, the next step is the Define and Measure Phases of the DMAIC process.

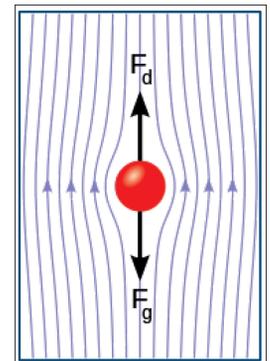
Define Phase – Define the system, the voice of the customer and their requirements, and the project goals, specifically.

What are we trying to accomplish?

- Assure Clarifier & Downstream Equipment meet the feed requirements for the Reverse Osmosis (RO) Process. (Critical)
- Optimizing the clarification process has the potential to significantly reduce the Silt Density Index (SDI) and Turbidity without impacting the lime softening process.

Problem & Goal Statements

- Weather and Process Variability have impacted the quality of the feed (SDI) to the RO Process which increases costs and reduces RO Effluent output.
- This project will impact the Strategic Goal of “Utility Operations” by assuring the availability and a reduced cost for the key component of the site steam system.



Settling floc particle in the upward flow of clarifier water (streamlines), drag force F_d and force by gravity F_g determine particle direction.

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Voice of the Customer/Project Goals

#	Customer	VOC	Key Issue	Requirement
1	Unit Manager	Do not restrict or impact the supply of water for the Site.	Utility systems must reliably meet the customer needs.	Maintain adequate supply with stable quality parameters at the end of the project.
2	Process Specialist	Do not exceed SDI Limit so there are no surcharges associated with process.	Extended periods of time (> 1 day) above 4.0 SDI will have an impact on both cost and membrane life.	Minimize the impact on production. The unit maintains normal operation after project is implemented.
3	Process Specialist	Operation of the clarification and downstream processes should be "stable."	Apprehension of the processors about losing stability in an effort to improve SDI.	The unit will operate with controls which do not impact the overall process stability.
4	RO Water Provider	Provide lower SDI if possible.	When changes are made SDI can go beyond the contract limits.	Maintain or improve SDI compliance at the end of the project.
5	RO Water Provider	Do not impact other water parameters such as hardness, free chlorine, TOC.	The current process is stable and RO Water Provider can handle the SDI swings.	Overall product quality should be optimized at the end of the project, while still maintaining unit efficiency.
6	Site Energy Lead	Maintain the SDI at or below what other Evoqua Customers do with Brazos River Water.	SDI swings impact membrane life and Unit OEE.	Membrane Replacement need to be on a 2 year cycle minimum, this requires maintaining SDI < 4.
7	Process Control Lead	Improvements should be limited to non-capital automation solutions, using existing systems.	Automation improvements that involve capital may delay implementation.	Limit the scope of solutions to those that do not require capital.

Parameter	Baseline	Goal	Entitlement	Units
Silt Density Index (SDI)	3.75	< 3.0	< 2.0	SDI
SDI Excursions	24	< 3	0	NTUs
Chemical Usage (Y-Counter)	\$XXX	\$XX	\$X	\$

Why is this important? You need time, money and resources to accomplish the task. The project when completed should address all the customer concerns. Getting input from others assures that your project will be successful. It's also an opportunity to educate others on the current state of the process and what can be accomplished.

Project Timeline/Scope

Project Timeline	End Date	In Scope:
Define	3/01/16	Flow Balancing, Instrument maintenance and/or replacement, Sand Filter Repairs, Automation improvements including control logic.
Measure	4/01/16	
Analyze	7/01/16	Out of Scope:
Improve	10/01/16	Significant process control, process design changes, new equipment and/or significant process modifications.
Control	12/01/16	

You now commit to target dates and what areas may need money and/or other people's time.

The DEFINE Phase ends with a Project Charter which is approved and signed by Site Leadership. Why is this important? People remember and support things that they signed off on.

Measure Phase - Measure key aspects of the current process and collect relevant data; calculate the 'as-is' Process Capability. Review the measurement parameters and the impact on the process. How well can we trust our measurement systems? In this case, the MSA provided the path to success.

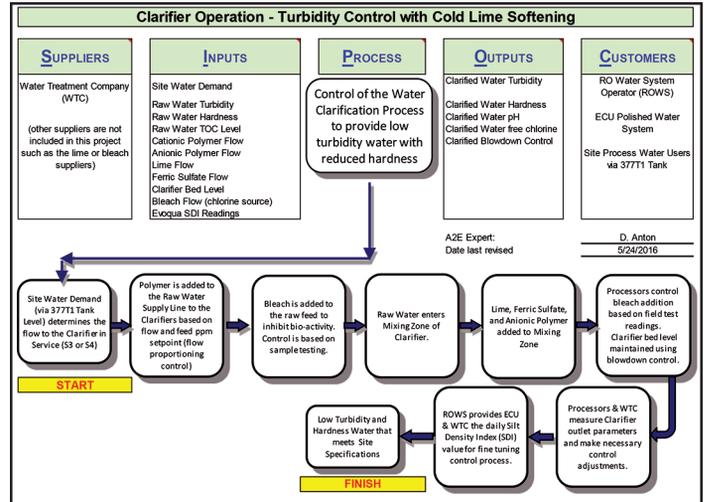
SIPOC/Process Map/C&E Matrix:

The first step was to develop a SIPOC for the process. SIPOC is an acronym based on the Suppliers, Inputs, Processes, Outputs and Customers for the process being analyzed. It is a toll that displays the cross-functional set of activities in a simple map or diagram. This will help one identify both the process inputs (Xs) and outputs (Ys), process owner, all the customers & suppliers as well as the scope or boundaries of the process.

The five key elements of SIPOC are [7]:

- Supplier – Whoever provides the input to your process
- Input – The product or data that a process does something to or with to deliver the required output
- Process – The activities you must perform to satisfy your customer's requirements and deliver the output
- Output – The product or data that results from the successful operation of a process
- Customer – Whoever receives the output of your process

This is a critical step to the entire process, it is the roadmap that will be followed and built upon. The project was now over one week old and no changes, measurements or improvements were made. Most sites would run a few jar tests get some improvement and call it a success. The process is much more involved than simple chemical changes, in fact the simple process of clarification is much more involved when the process steps are detailed as seen in the SIPOC. The SIPOC becomes the foundation of the entire process moving forward.



From this point we develop the Process Map which defines the inputs and outputs for each individual step in the process and whether they are controllable or uncontrollable. In this case, it is based on the flow chart, understanding of the internal working of the specific clarifier design, and the instrumentation and feedback available. The Process Steps are used to develop a Process Map and Cause & Effect (C&E) Matrix.

Part of the C&E Matrix is shown below. A few things to note here are:

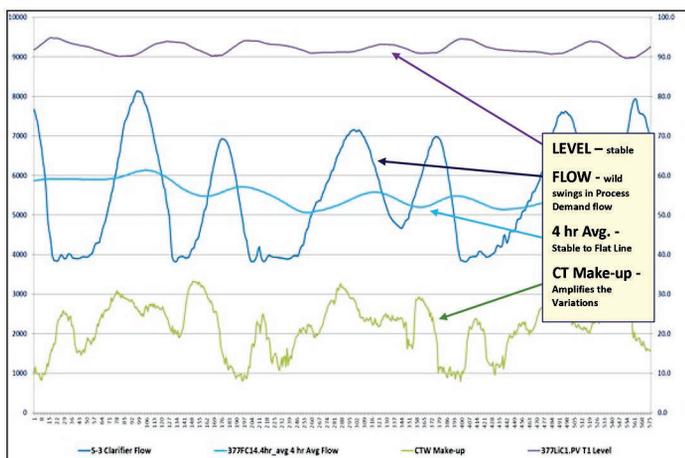
1. The Rating of Importance to Customer – this is aligned with the feedback provided in the Voice of the Customer survey (3/5/9 scale)
2. The Goals in this case are only three. The goals should be kept to only what's truly important to the process.
3. The Process Steps follow the Process Map – at this point the values are not ranked only tabulated based on importance to the customer and overall impact (0/1/3/5/ 9 scale)

You can't fix everything so we now use the Pareto Rule. If we fix 20% of the key issues we should see 80% of the overall benefits.

Cause and Effect Matrix										
		Rating of Importance to Customer								
		1	2	3	4	5	6	7	8	9
	Meet the RO SDI Specification									
	Reduce Clarifier Turbidity (FTI Proc. Cleanup)									
	Reduce Chemical Usage									
NOTE: Only Controllable Inputs were included in this ANALYSIS										
Process Step	Process Input									
1	Clarification - Cold Lime Softening Process	Clarifier pH Reading	5	9	9					117
2	Clarification - Cold Lime Softening Process	Clarifier Mixer Speed	1	5	5					49
3	Clarification - Flocc Generation	Clarifier V/V Readings	3	5	5					67
4	Clarification - Solids Settling	Clarifier Bed Level	9	5	5					121
5	Clarification - Solids Settling	Clarifier Flow Variation	9	9	5					141
6	Clarification - Final Settling / Product	Clarifier Water Turbidity	3	9	9					99
7	Clarification - Final Settling / Product	Clarifier Water Hardness	1	1	9					41
8	Clarification - Final Settling / Product	Clarifier Water TOC Level	5	5	9					97



The C&E Matrix gave three (3) Input Parameters to focus on – Clarifier Flow Variation, Clarifier pH, and Clarifier Bed Level. Now we start looking at our process measurements and process constraints. The top focus was the clarifier flow variation.



The control process does a great job of controlling level but has limitations due to the following issues:

1. **Random discrete events** of different magnitudes limit the effectiveness of PID Control Schemes.
2. **Clarified Water Storage Tank Volume** – also site firewater tank, drastic level swings unacceptable (Requires Tank → at least 50% larger).
3. **Clarifier Limits** – 6800 gpm design flow with ±10% flow change per hour recommended.
4. **Process Swings** → 4,000 to 10,000 gpm range also impacts pH
5. **Single Point Failure** – Numerous Control elements rely on a single flowmeter values (no inherent redundancy).

This is where most improvement processes fail. The control loop is slowed to dampen the swings but it cannot correct the problem due the aforementioned limitations. The fundamental flaw in the process is how the flow control is set-up on a clarifier. We want to control the flow with the feedback being the change in level. Let's look at the limitations first and then how this process used some simple techniques to correct the problem.

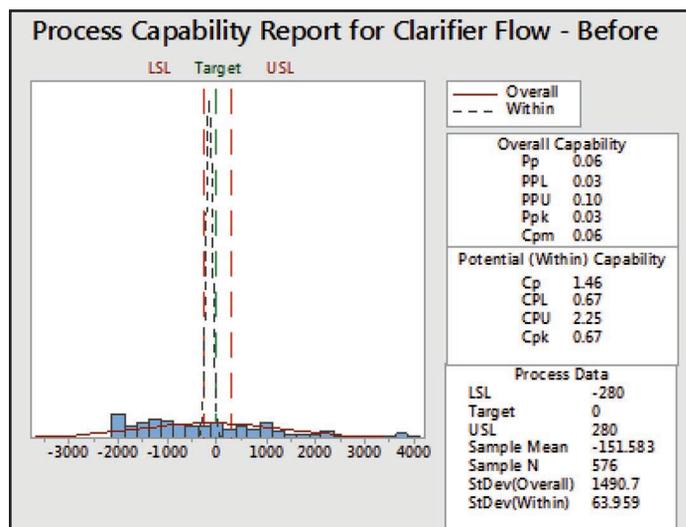
PID Control Limitation [8] – While proportional–integral–derivative (PID) controllers are applicable to many control problems, and often perform satisfactorily without any improvements or only coarse tuning, they can perform poorly in some applications, and do not in general provide optimal control. The fundamental difficulty with PID control is that it is a feedback control system (tank level in this case), with constant parameters (doesn't account for weather or production rates), and no direct knowledge of the process (cooling

tower demand and other discrete flow changes), and thus overall performance is reactive and a compromise. While PID control is the best controller in an observer without a model of the process, better performance can be obtained by overtly modeling the actor of the process without resorting to an observer.

PID controllers, when used alone, can give poor performance when the PID loop gains must be reduced so that the control system does not overshoot, oscillate or hunt about the control setpoint value. They also have difficulties in the presence of nonlinearities, may trade-off regulation versus response time, do not react to changing process behavior (say, the process changes after it has warmed up), and have lag in responding to large disturbances.

The most significant improvement is to incorporate feed-forward control with knowledge about the system, and using the PID only to control error. Alternatively, PIDs can be modified in more minor ways, such as by changing the parameters (either gain scheduling in different use cases or adaptively modifying them based on performance), improving measurement (higher sampling rate, precision, and accuracy, and low-pass filtering if necessary), or cascading multiple PID controllers.

Flow Analysis–Process Capability



The process capability as expected was extremely poor initially. Target for Flow Variance is a Ppk > 0.5 which would result in good clarifier data.

Flow Analysis–Improvement Control Plan

STEP 1 – Analyze numerous random days to determine the natural oscillations in the process. It was found that the swings could effectively last a period of 4 hours. Check for seasonal variations.

STEP 2 – Use the determined oscillation period to develop a parameter to control. In this case the 4 hour running average of clarifier flow was used as the basis.

STEP 3 – Use the parameter to adjust the level control output to the cooling tower make-up valves. Another option could have been to adjust the clarified water tank level setpoint.

STEP 4 – Test the new control scheme.

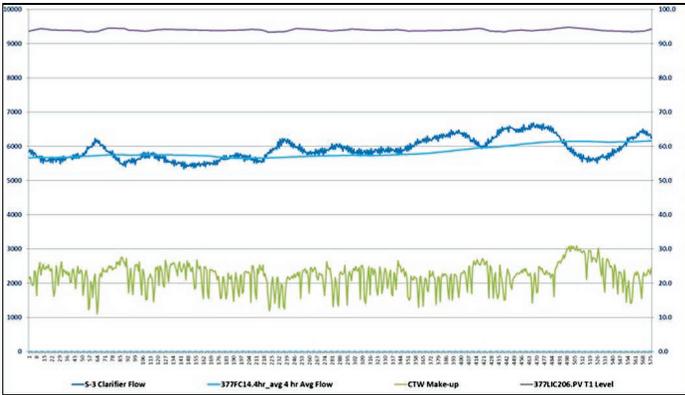
Control Logic – Used to Normalize Flow over a 4 hr. Period

Example CT-6 Lower Limit

= 24+0.125*MAX (WB Temp-34,5)-MAX(CT6 Level PV – CT6 Level - 2,0)*5+ (S3 Clarifier 4hr Flow Avg – Current Clarifier Flow)/25

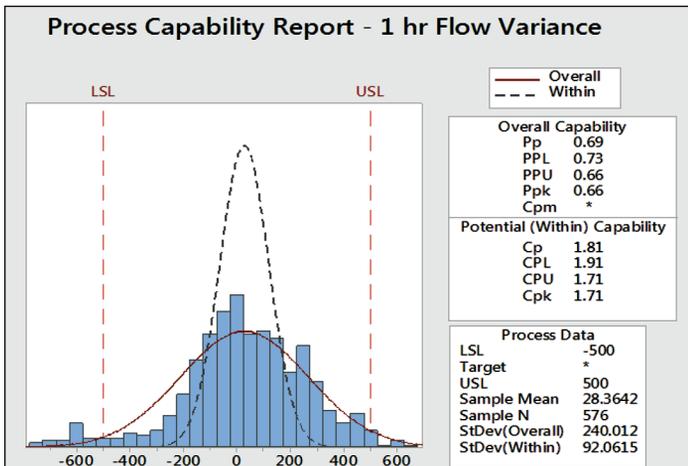
Mean Position Wet Bulb Impact Level Protection Variance from 4 hr. Avg.

The output to the cooling tower make-up valve was limited by the difference in the clarifier current flow to the 4 hour running average. This acted like the counterweight used to dampen the swing tendency of high rise building with different wind loads. When the clarifier flow dropped the cooling towers would make up more to compensate for the lost demand. The net result was a much more stable flow. The cooling tower level control was not impacted by this process which is key.

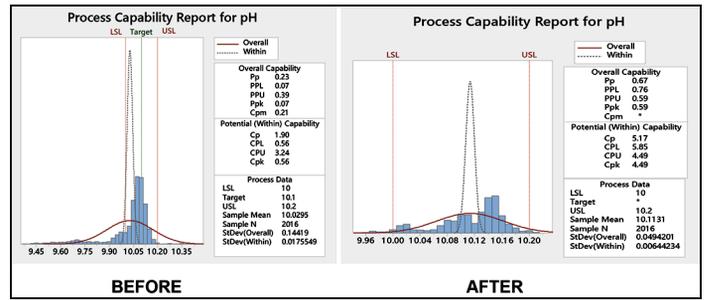


Initial result showed great improvement in the control as the wild swings were eliminated. As expected the level control also improved. The cooling tower level variance did not deviate from setpoint significantly based on the standard deviation before and after the change (Std Dev was less than 0.7% typically). The process level control was essentially the same. The make-up to the cooling towers had become more continuous as a result as the valve open time increased over 50%. Cooling Tower make-up level control was on/off control in this case.

NOTE: The output limits also included control to account for seasonal variations (used wet bulb temperature) and process demand swings (over 2% level deviation from setpoint is corrected for so that level control is not sacrificed).



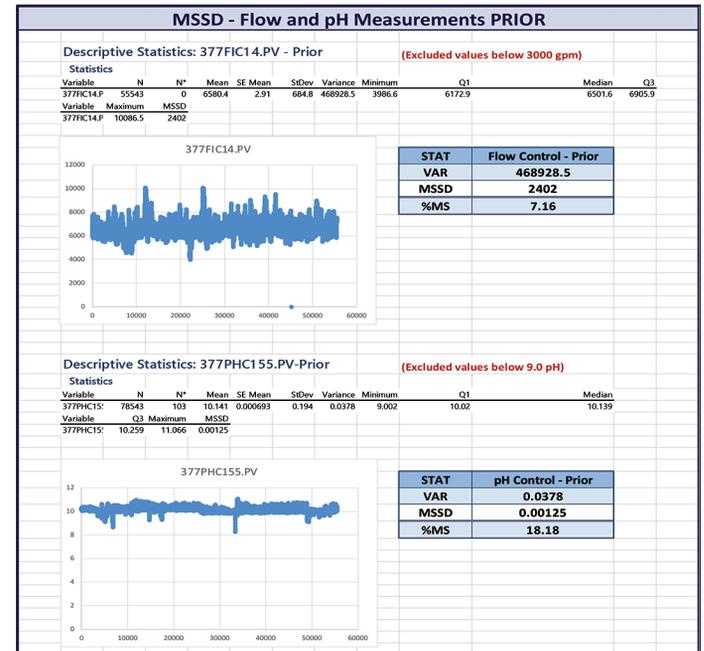
The flow variation is more critical than the flow if the actual flow is within the design operating limits of the clarifier. Flow and pH are not parameters we want to vary. The goal is to make them so stable that they are statistically irrelevant to the results. The pH control was also improved with the more stable flow.



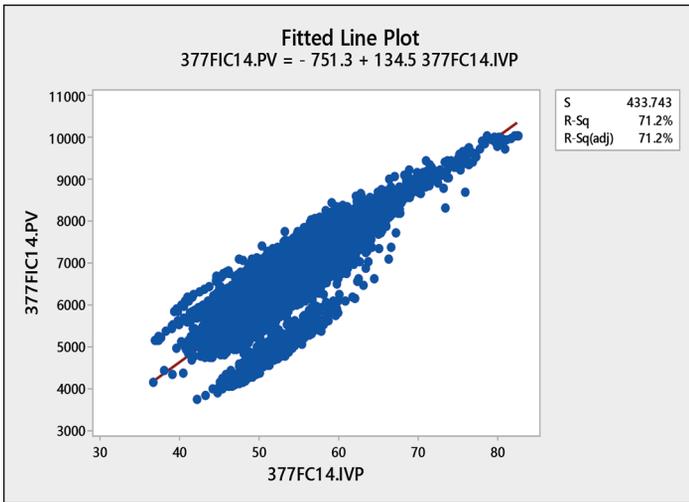
The improvement obtained on the pH control was a result of an FMEA completed on this process. Eductor replacement, specific control parameters for the motive fluid, supply line replaced to the clarifier, detailed PM program for pH probe, were some of the improvements identified.

Since flow and pH were key parameters a MSA was performed on each parameter. The purpose is to determine if the data is precise enough so that control changes can be measured with a high degree of confidence. Mean Squared Successive Difference (MSSD) Analysis is analogous to standard Gage R&R. Variance represents an estimate of long-term variability.

MSSD represents short-term variability, which in essence is the measurement variability $\%StudyVar = 100\% * \text{Sqrt} (MSSD / \text{Variance})$. If the calculated $\%StudyVar$ is less than 30%, we may conclude that the measurement system is acceptable. The MSSD was excellent for Flow and Good for pH Probe prior to any significant changes. After the flow and pH were improved, the MSA remained acceptable so the study results should be valid.



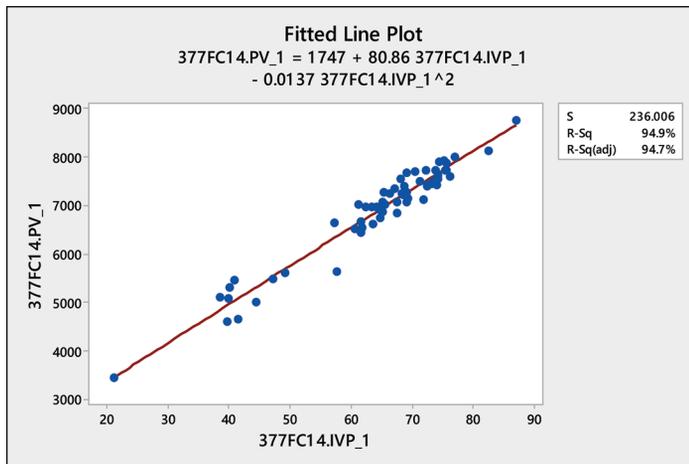
377F14 – Clarifier Flow Controller/377PHC115 – Clarifier pH Controller
Heteroscedasticity (condition where the variability of a variable is unequal across the range of values of a second variable that predicts the output) was observed over a long time period for the system control. Flow is a critical value since it impacts polymer and coagulant feed (automated flow proportioned control), the clarifier slowdown. Feeding insufficient polymer and coagulant aid allowing the bed level to vary due higher flow than calculated makes the entire process less stable. The MSA & FMEA processes helped point out these issues.



Y Axis – Clarifier Flow Controller (gpm)

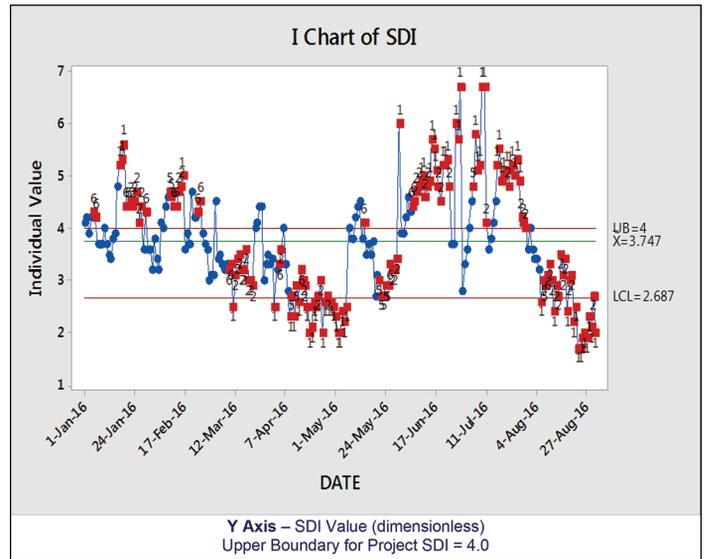
X Axis Clarifier Flow Controller Valve Position (% Open)

The root cause was traced to seasonal variation in the incoming TOC and a flowmeter that measures the raw water prior to any bleach addition but downstream of the polymer addition point. Since both a stable flow and an accurate value is critical to the operation a regression analysis of the flow versus valve position at stable supply pump pressure was completed. This allowed the site to add a virtual flowmeter to improve reliability.



Baseline capability for Silt Density Index (SDI) varies greatly from being in good control to totally out of control. Silt is composed by suspended particulates of all types that accumulate on the RO membrane surface. Sources of silt are primarily organic colloids, biological materials including algae, and fine particular matter. Silt Density Index testing is the widely accepted method for estimating the rate at which colloidal and particle fouling will occur on reverse osmosis membranes. The SDI measurement is a dimensionless number. It's not a particle count analysis or a turbidity which is a measurement of the amount of suspended solids. These parameters are not the same and there is no direct correlation between them. However, for low fouling potential the turbidity must be < 0.5 NTUs and the SDI less than 5.

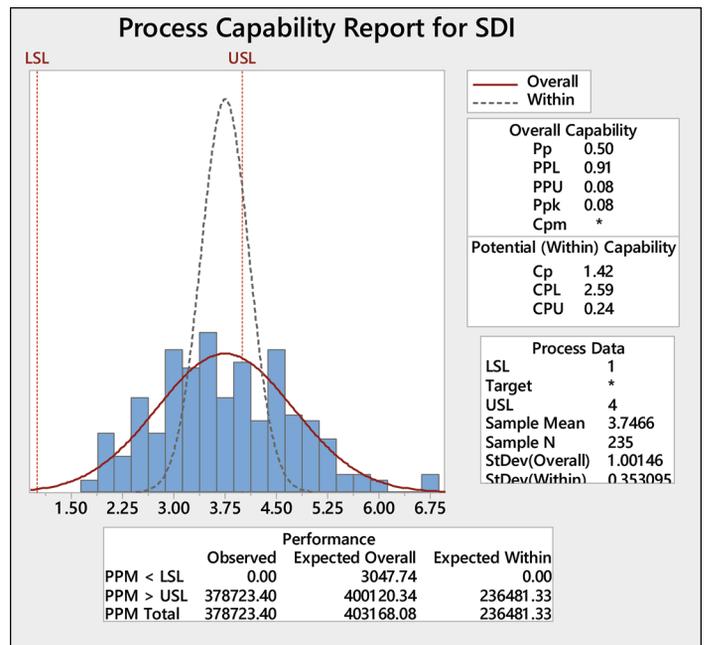
The Project will determine the factors that cause a stable process to dramatically change over time through statistical analysis and the scientific understanding of clarification and filtration.



Y Axis – SDI Value (dimensionless)
Upper Boundary for Project SDI = 4.0

The process went from improved control (thru May 2016) to loss of control of control (summer of 2016) and back in control when the project was started (August 2016). The data shows that good results are achievable and the factors that cause variation must be defined.

The baseline process capability for SDI was very poor with much of the data outside the upper limit of 4.0, a Ppk of 0.08 indicates an out of control process.



Analyze Phase – Analyze the data to investigate and verify cause-and-effect relationships. Determine what the relationships are, and attempt to ensure that all factors have been considered. Seek out root cause of the defect under investigation.

Essentially we determine what factors caused the variations in the data set. The factors that were looked at were as follows:

1. Raw Water Turbidity	1. Clarifier Flow Variation
2. Raw Water TOC	2. Clarifier Bed Level
3. Ambient Conditions (water temp swings)	3. Clarifier Effluent Turbidity
4. Clarifier Polymer Feed	4. Clarifier Effluent TOC level
5. Clarifier Coagulant Feed	5. Sand Filter Turbidity
6. Free Chlorine Level (Clarifier)	6. Filtered Water Free Chlorine
7. Clarifier pH	7. RO Feed Turbidity
8. Clarifier Water Flow	

Results of Multi-Variate Analysis

Regression Analysis: RO SDI versus 377S3Turbidity.fld,, etc.
Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	116.154	19.3591	188.10	0.000
377S3Turbidity.fld	1	2.033	2.0335	19.76	0.000
377S3BedLevel.fld	1	12.052	12.0518	117.10	0.000
Clarifier Effluent TOC (ppmw)	1	2.558	2.5579	24.85	0.000
S3 Inlet Coagulant	1	5.723	5.7229	55.61	0.000
S3 Inlet Polymer	1	3.598	3.5983	34.96	0.000
RO Feed NTU	1	24.659	24.6587	239.60	0.000
Error	340	34.992	0.1029		
Total	346	151.146			

Model Summary

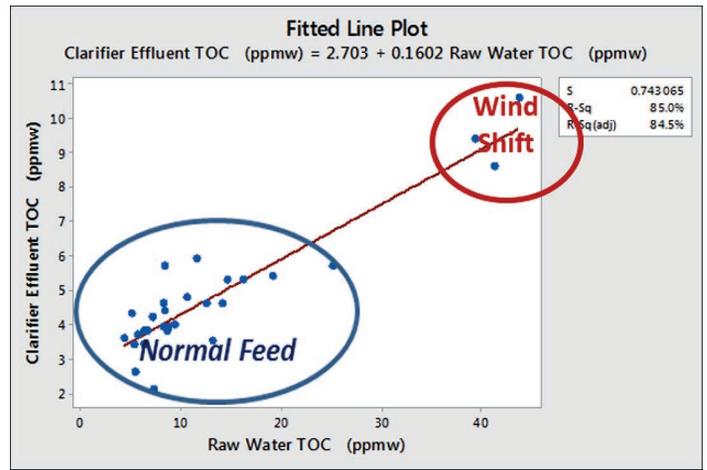
S	R-sq	R-sq(adj)	R-sq(pred)
0.320807	76.85%	76.44%	76.01%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-3.210	0.243	-13.21	0.000	
377S3Turbidity.fld	-0.0673	0.0151	-4.45	0.000	1.10
377S3BedLevel.fld	0.2795	0.0258	10.82	0.000	1.10
Clarifier Effluent TOC (ppmw)	0.0676	0.0136	4.99	0.000	1.11
S3 Inlet Coagulant	0.2474	0.0332	7.46	0.000	1.90
S3 Inlet Polymer	-0.0768	0.0130	-5.91	0.000	1.36
RO Feed NTU	41.67	2.69	15.48	0.000	1.65

Regression Equation

$$\text{RO SDI} = -3.210 - 0.0673 \text{ 377S3Turbidity.fld} + 0.2795 \text{ 377S3BedLevel.fld} + 0.0676 \text{ Clarifier Effluent TOC (ppmw)} + 0.2474 \text{ S3 Inlet Coagulant} - 0.0768 \text{ S3 Inlet Polymer} + 41.67 \text{ RO Feed NTU}$$



The following page shows the control of process capability of all the key parameters and the impact on the RO SDI value.

Variable (U=Uncontrollable / C=Controllable)	PpK		DMAIC		Status
	2017	Current	Phase		
RO SDI					
Y1:RO Feed SDI	0.77	1.91	CONTROL	1.5-3.5	Regression Equation SDI = -3.210 - 0.0673 Clarifier Turbidity + 0.2795 Clarifier Bed Level + 0.0676 Clarifier Effluent TOC + 0.2474 Coagulant - 0.0768 Polymer + 41.67 RO Feed NTU
x1:Raw Water Turbidity-U			CONTROL	Monitor	Minimal Impact on System Performance
x2:Raw Water TOC Level-U			CONTROL	Monitor	Minimal Impact on System Performance
x3:Ambient Conditions-U			CONTROL	NA	With Reservoir not enough difference to be significant
x4:Polymer Feed Rates-C	0.25	1.04	CONTROL	6-10 ppm	More polymer improves SDI
x5:Coagulant Feed Rate-C	0.53	0.66	CONTROL	4-8 ppm	Data shows negative impact so we will minimize and watch
x6:Free Chlorine Level-C	0.27	0.60	CONTROL	.75-1.00 ppm	Higher level match expected performance Clarifier Effluent TOC = 2.661 + 0.2281 Clarifier NTU + 0.1961 Raw Water TOC + 0.00276 Raw Water Turbidity - 0.0593 Clarifier Sd DFH + 0.1525 Clarifier Bed Level - 0.284 Clarifier Free Cl.
x7:Clarifier pH-C	-0.01	2.20	CONTROL	10.0-10.2	Factor in Hardness Removal and RO SDI (Very Critical to downstream precipitation)
x8:Clarified Water Flow-C			CONTROL	<8500 peak	Stable Operation has made this no longer significant (use design limits)
x9:Clarifier Water Flow Variation-C			CONTROL	<10% change/hr	Stable Operation has made this no longer significant
x10:Clarifier Bed Level-C	0.01	0.83	CONTROL	<1ft	Kept in despite higher P value (measurement variation)
x11:Clarifier Effluent Turbidity-C	0.11	0.63	CONTROL	1.5-2.0	High Turbidity improves sand filter performance
x12:Clarifier Effluent TOC Level-C	0.57	0.61	CONTROL	<6.2	High TOC Levels indicate a potential SDI Problem
x13:Filter Water Turbidity-C			CONTROL	Monitor	Minimal Impact on System Performance - Monitor for Sand Filter Issues
x14:Filter Water Free Chlorine-C			CONTROL	Monitor	Higher level match expected performance
x15:RO Feed Turbidity-C	0.56	0.64	CONTROL	<0.11	Indicator of Upstream Issues & performance

Improve Phase – Improve or optimize the current process based upon data analysis using techniques such as design of experiments, failure modes and effects analysis (FMEA), mistake proofing, and brainstorming.

Brainstorming Improvement Ideas

With the process map as a guide for the key parameters the next step is to brainstorm ideas to improve the process control. The team ranked the ideas as follows; ideas are either difficult (Ease – 1) or have a low probability of success (Impact – 1). **High Score → Get it Done!**

Dark Green-Completed Light Green-In Progress or Planned
Pink-On Hold Red-Rejected

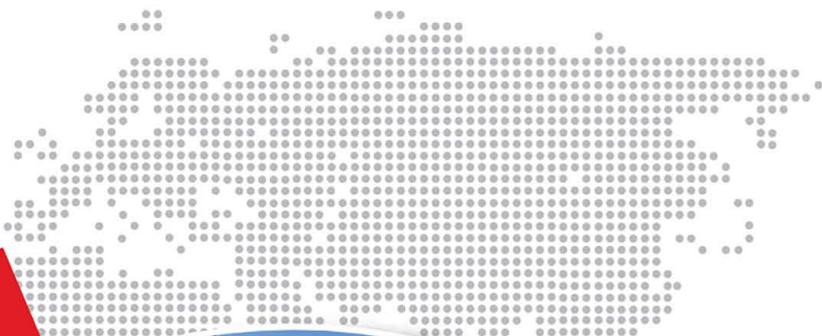
#	Potential Solution	Ease	Impact
1	Control Flow Changes to Clarifier (< 1000 gpm per hr.)	9	9
2	Control Clarifier Blowdown Process (Constant Duration)	9	6
3	Control Clarifier pH within 0.1 pH Units	9	6
4	Lower Clarifier V/V Setpoints	9	6
5	Lower Clarifier Bed Level Setpoints	9	6
6	Change Addition Point for Bleach Feed	6	6
7	Install Blower on Sand Filters	9	3
8	Trial New Lime Slurry - Process Stability	6	3
9	Change Agitation Speed on Clarifier	9	1
10	Replace 1ft of Sand Filter Anthracite with 6 inches of Sand	3	3
11	Trial Anionic Polymer	3	3
12	Increase Water Storage Capacity	1	3

Discussion of Regression Results

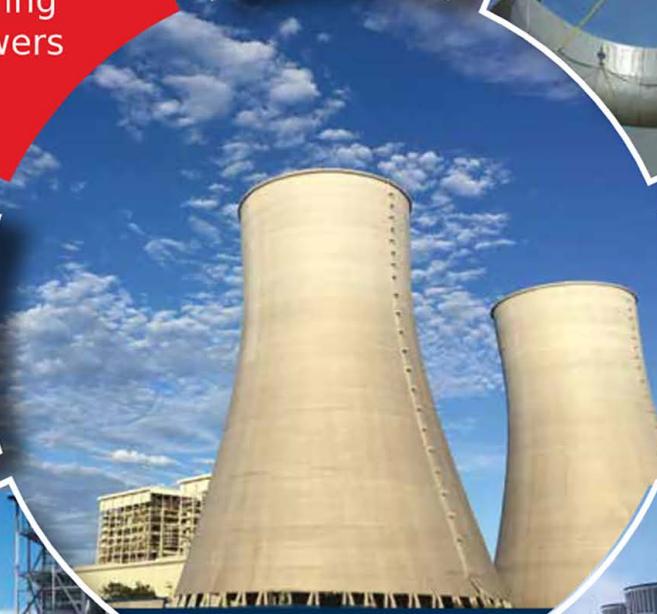
- Started with 15 parameters → 6 Made it to the Regression Equation (77% fit)
- Three Chemistry Controllable Factors → Clarifier TOC (bleach) / Coagulant (Ferric Sulfate) / Polymer (cationic coagulant aid)
- One Process Control Factor → Bed Level which the Processor Measures / MSA Issue due to subjective nature & span) Controlled) – **Process also now follows Manufacturer Guidelines (C&E Matrix & FMEA impacts)**
- Two Process Outputs → Clarifier & RO Feed Turbidity indicates when there are sand filter / softener issues

Uncontrolled Factors

The colloidal material varies with weather conditions and seasonal changes. Ambient temperature and swings had significant impacts but were removed since we don't have the ability to heat or cool the water. Even though they were found to somewhat statistically significant at this time the practical significance is low. One seasonal variation that can be addressed was when the wind directional shift caused a turnover of the site raw water reservoir.



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Implementation Plan Highlights

- Once you have the improvement ideas, a good implementation plan will assure your success.
- Multiple Trials of Clarifier Flow Control Logic were done to define a control scheme that would work under various conditions and not impact cooling tower operations.
- Key Improvements Ideas worked simultaneously – One team member focused on pH Control, one team member worked clarifier parameters, and one team member worked chemical feed reliability issues and step changes in chemistry for themy regression analysis.
- MOC's, testing and commissioning completed with the assistance of Operations.
- Long Periods for the testing identified process dynamic and steady-state response since Unit water demands varied during the entire process.
- Minimal Impact on RO Production Process was critical to the Test Plan and implementation of any improvements or changes.

FMEA

The FMEA provided a roadmap for control of the critical steps of the operation as defined by the Process Map. A high RPN (Risk Potential Number > 100) is not acceptable so plans were required with a timeline to close these gaps. A sample of the FMEA Process follows.

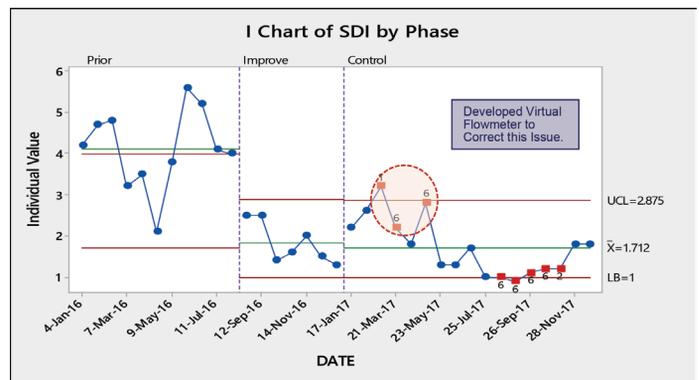
Process Product Name:	RO Feed Quality - SDI	Prepared by:	David Anton	Page:	1 of 1													
Responsible:	EDI Water Treatment	FMEA Date (Orig. / Rev. / Date):																
Process Step	Key Process Input	Potential Failure Mode	Potential Failure Effect	S E V	Potential Causes	O C C	Current Controls	D E T	R P T	Actions Recommended	Resp.	Actions Taken	S E V	D E T	R P T			
What is the process step?	What is the Key Input Variable?	In what ways does the Key Input go wrong?	What is the impact on the Key Output Variable? (Customer or internal requirements?)	How severe is the impact on the Key Output Variable?	What causes the Key Input to go wrong?	What are the existing controls and procedures (specification and test) that prevent either the cause or the failure mode? Should include an SOP number.	What are the actions for reducing the occurrence of the cause or preventing detection? Should have actions only on high RPNs or easy fixes.	What is responsible for the recommended action?	What are the completed actions taken with the established RPN? Be sure to include completion month/year.									
Clarification - Cold Line Softening Process	3779C04.PV Clarifier pH Reading	Low pH	Failure to remove hardness	5	Line Feed Issues / Extractor Problems / Valve Problems	1	2 Week PM Program	3	15	None required.		Process Steward	Lowered the feed line / Properly sized extract / Control of make water pressure	Completed 8/16	5	3	3	45
		High pH	High pH Feed to Downstream Processes	5	Line Feed Issues / Extractor Problems / Valve Problems	1	2 Week PM Program	3	15	None required.		Process Steward	Lowered the feed line / Properly sized extract / Control of make water pressure	Completed 8/16	5	3	3	45
Clarification - Fine Oxidation	3779C04.PV Clarifier Flow Reading - Control Input for Chemical Feeds	Low polymer / Inlet feed	Failure to complete flocculation process	7	Low Flow Reading	5	None	8	28	Redundant Flow Measurement	David Anton	Used Valve position as an alternative means of measuring flow	Completed 8/16	2	2	2	8	
		Waste of Chemicals / Potential to Exceed Downstream Feeding	High polymer / Inlet feed	3	High Flow Reading	3	None	8	22	None required.		ASME Pump Status Indication / Processor Tuning	Completed 8/16	3	3	3	27	
		Chemical Feed Pump Failure		3	Chemical Feed Pump Failure	1	1 Week PM Program	8	24	None required.								

Control Phase – Control the future state process to ensure that any deviations from the target are corrected before they result in defects. Implement control plans, checklists, troubleshooting guides and systems such as advanced process control, production boards, visual workplaces, and continuously monitor the process. This Control Process should be periodically reviewed for effectiveness and capability so that the desired quality level is maintained.

The DMAIC Process will help helped me understand the Science associated with this type of Clarification - challenged my paradigms. In an upflow solids contact clarifier the performance improves with higher bed levels while the lime softening process requires less solids contact.

How did we do addressing the Project Concerns and Issues (VOC – Voice of the Customer)?

1. pH Control Issues – Cold Lime Softening requires stable operation to prevent post precipitation from occurring in downstream vessels and piping. *Straight Line for pH Control / Stable Process - TARGET MET*
2. Poor Flow Control – Random discrete events of different magnitudes limit the effectiveness of PID Control. *Solved using an Intelligent Control Strategy / Minor PID Changes - TARGET MET*
3. Clarified Water Storage Tank Volume – also site firewater tank so drastic level swings are unacceptable. *No Level Issues - TARGET MET*
4. Clarifier Limits – 6800 gpm design flow with $\pm 10\%$ flow change per hour recommended. *Minimal Time above 7000 gpm - TARGET MET*
5. Single Point Failure – Numerous Control elements rely on a single flowmeter values (no inherent redundancy) *Virtual Flowmeter Added (Layers of Protection Analysis - LOPA) - TARGET MET*



Water Treatment Control Plan

1. DEFINITIONS

- a. Target Control Range – desired target for good control, operation may drift out of this range on a short term basis dependent on impact, over control of water processes is to be avoided
- b. Low & High Action Points – Timing for each action may vary depending upon impact of being out of control range on process and reliability goals

PARAMETER	Target Control Range	Controlled By	Control Adjustment Options	Low Action Point / Timing	Recommended Action	High Action Point / Timing	Recommended Action
RO SDI	1.5 – 3.5	WTS / Unit Specialist	Cationic Polymer / Bed Level / Free Chlorine	< 1.5 Based on 5 day average	Reduce clarifier cationic polymer and ferric feed	> 4.0 Based on 2 day average	Check all polymer and ferric pumps / increase cationic polymer and ferric feed / check bed level and increase blowdown if needed
Outlet Turbidity	< 1.5 NTU	WTS / Unit Specialist	Cationic Polymer / Bed Level / Free Chlorine	< 1.0 NTU Based on 5 day average	Reduce clarifier cationic polymer and ferric feed	> 2.2 NTU Based on 2 day average	Clarifier Flow & Lime Controls – Flow swings and loss of lime feed can be factors
Free Chlorine	0.5 - 1.0 ppm	Processor	Bleach Addition (Raw water TOC is a factor)	< 0.3 Based on single verified data point	Increase bleach feed	> 1.2 Based on single verified data point	Reduce bleach feed
Bed Level	-1 to -2 feet	Processor	Blowdown / Ferric Sulfate	< -2 Based on 2 day average	Increase counter for blowdown for less blowdown / Check ferric pump	> -1 Based on 2 day average	Reduce counter for blowdown for more blowdown

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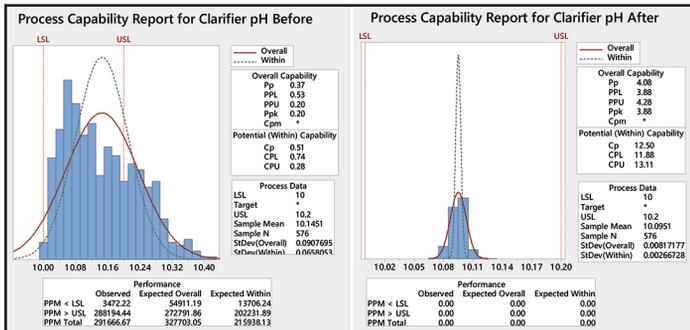


2. CLARIFIER OPERATION

- Operating Control Range – avg flow of 4K to 8K gpm, lower or higher flow may require different actions)
- Chemicals – PC1192 cationic polymer / IC1187 ferric sulfate / AS1001 anionic polymer
- Unit Specialist Role may be filled by shift lead as warranted

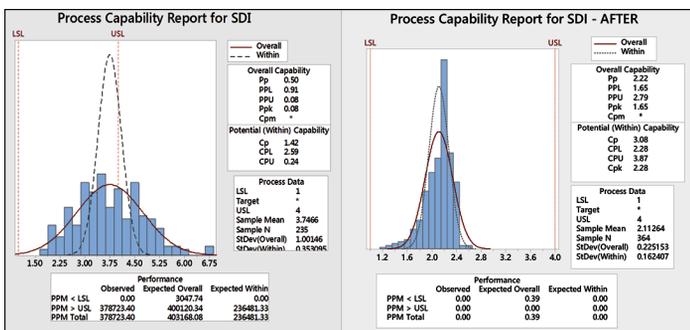
Project Benefits & Stability

- Reduced chemical costs for clarification process thru better process stability. Lower pH saves downstream acid cost. ✓
- Developed method for stabilizing flow to clarifier without impacting cooling towers. ✓
- Developed improvement plan for sand filter and clarifier operation. ✓
- Increased RO capacity by 3% thru improved Overall Equipment Effectiveness (OEE) ✓
- Reduced energy consumption by 36% (lower pump head required). ✓
- Membrane Life extended from 16 months to 28 months (36 to 45 months expectation)
- Lower Risk of Calcium Post Precipitation → Impact on equipment Reliability / Fouling. ✓
- Improved Process Stability as shown below. ✓



BEFORE

AFTER



Summary

Sustainable improvement requires a Control Plan that must be followed and kept evergreen. Knowledge of the process should increase over time and the transfer of knowledge to the processors is critical.

The project provided both significant improvement in quality as the RO SDI improved to what the Site RO Water Provider considers best in class.

The Six Sigma tools helped define the impact of factors not normally considered when trying to improve a clarifier.

The entire process was so productive that other areas used portions of the six sigma process to improve data analysis and control thus providing additional benefits to the site.

Water Treatment Program and Six Sigma

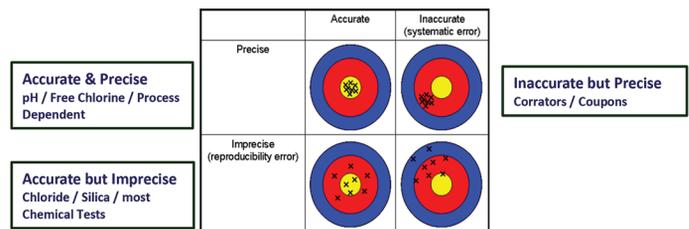
Abstract

The Six Sigma Process is not an all or nothing program. Six Sigma is a set of methods and tools for process improvement and these tools are not unique. Parts of the process can be used when appropriate. The water treatment program for a site relies on instrumentation and measurement systems to determine the appropriate control plans. One gap to this approach is that the measurement system is rarely challenged or reviewed to determine the accuracy and precision of the process.

Introduction - Can You Trust your Measurements?

Key Decisions are made on the assumption of valid measurements. An MSA can help define gaps in the process and a technical review will help define what is important. Some parameters need accuracy while other require precision. The chart helps define the difference along with some common measurements. Measurement system errors are classified into two categories:

- Accuracy—the difference between the part's measured and actual value. Accurate is Correct or Close to real value. Key characteristics include;
 - Bias - difference between average measurement and reference value
 - Linearity - same accuracy across all reference values
 - Stability - change in bias over time
- Precision—the variation when the same part is measured repeatedly with the same device. Precise is Repeating. Key characteristics are;
 - Repeatability - variation same operator
 - Reproducibility - variation different operator



Example 1 – New Hardness Test

The test method used for determining the micro-hardness of zeolite water stream had to be changed for safety concerns with the reagent used in the test. The hardness of the water stream was critical toward determining if the following conditions occurred:

- Resin bed was properly regenerated.
- Regeneration is required.
- Resin performance is stable.

The new test produced lower values and was very stable. A review of the test and its limitations revealed that high concentrations of chlorides and silica would impact the test results. The question for the measurement is whether it requires both accuracy and precision. Since we are not doing a study on the resin bed or system, precision is not the primary concern. However, since poor quality can impact downstream equipment accurate numbers are required.

MSA - Single Sample, 5 tests each method / One Operator

MSA Results - Direction of Interference shown matched Data Sheet



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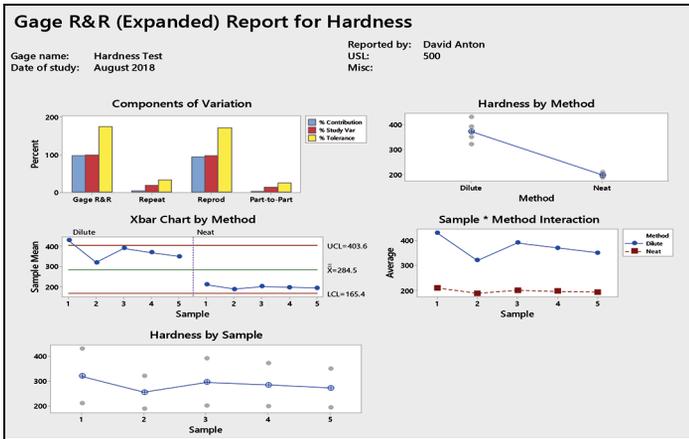
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The test results show that although the simpler neat test had less variability than the diluted test it produced a lower value as expected based on the predicted interference of higher chloride levels. The Dilute Test was chosen with knowledge that there will be significant variation since accuracy was more important than precision.

Sample	Neat #8 NaZ Hardness (ppb)	Diluted #8 NaZ (10:1) Hardness (ppb)
1	209	430
2	187	320
3	200	390
4	196	370
5	193	350
Avg.	197	372
Std. Dev.	8.2	41.5
Condensate	7	---

Chart 1 – MSA Results for Hardness Test

The Gage R&R, which stands for gage repeatability and reproducibility, is a statistical tool that measures the amount of variation in the measurement system arising from the measurement device and the people taking the measurement. The measurements by method were repeatable but not reproducible when the method was varied. Since most of the variation was not Part-to-Part the test methods are not interchangeable.

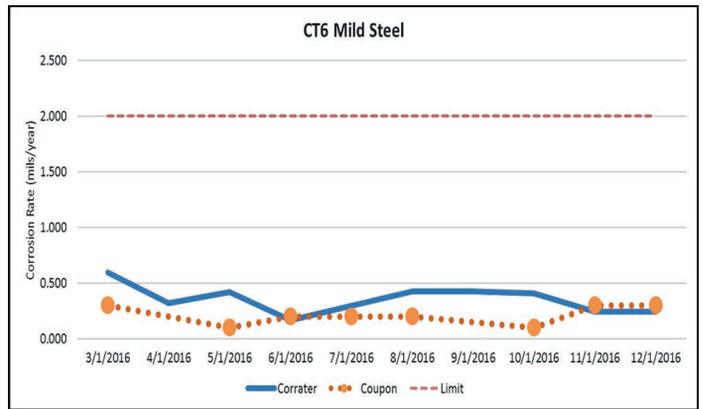
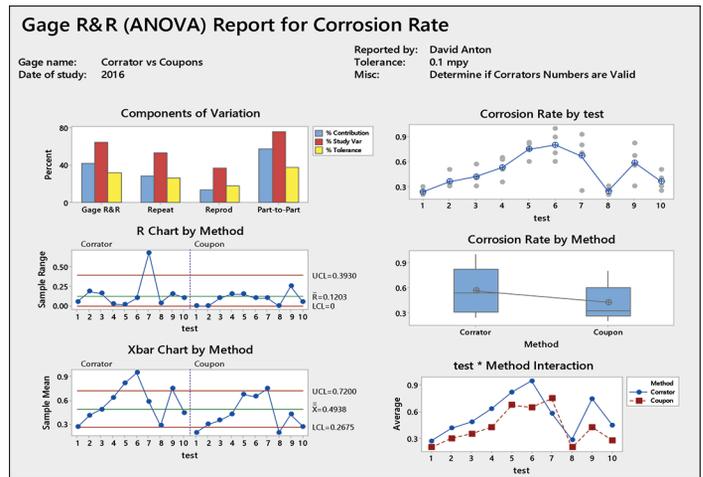


EXAMPLE 2 – Corrotor & Coupon Alignment

If you control the water treatment process by the corrotor readings for specific metallurgies, these measurement values should be validated by coupons (30 day and 90 day). Heat exchanger inspections and wall thickness readings are the accurate measure of the treatment program impact. The variation from corrotor and/or coupon readings is due to velocity, temperature, cycling, and location differences. Since we can't get these values in real time we use the corrotor to provide a directional impact. This by nature implies that precision is a critical parameter.

To evaluate this set of data, a Gage R&R (ANOVA) was done. Minitab uses the analysis of variance (ANOVA) procedure to calculate variance components, and then uses those components to estimate the percent variation due to the measuring system. The percent variation appears in the gage R&R table. In a good measurement system, the largest component of variation is part-to-part

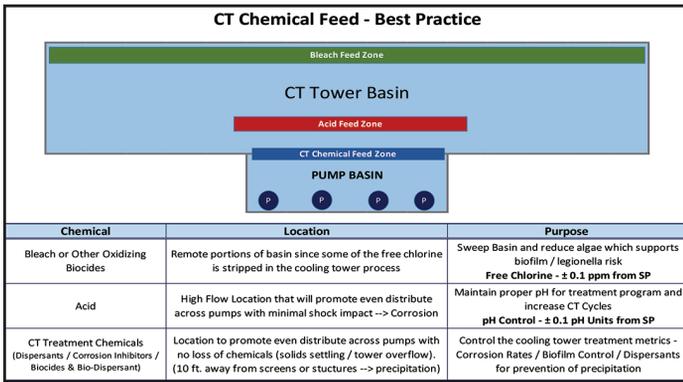
variation. This is the case here but there is still a large variation that can be attributed to the measurement system, so the measurement system may need correcting. Since the corrotor consistently provided a higher value, the process was accepted but further review was planned to validate the analysis.



Can You Trust Your Measurements? – Chemical Feed Locations

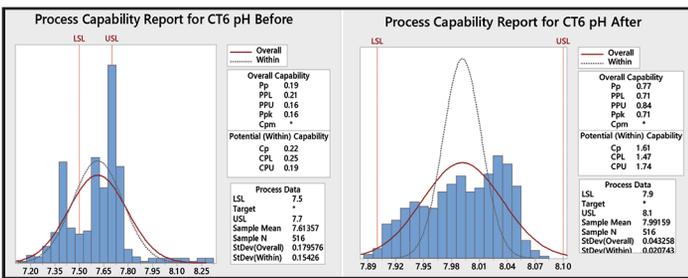
The feed location of chemicals and the sampling points are all part of the MSA. Sampling errors can impact process control decisions. A bad representative sample will result in poor decisions or delayed response to water treatment control issues. Grab sample protocol is well understood and should be part of a site's training program. Continuous sample point validation is a key step in the MSA process, variations in measurements may indicate a potential problem and/or design issue. Is the feed location impacting your pumps and sampling? Proper distribution eliminates errors and issues. The worst case scenario is bidirectional flow from the cooling tower pumps with a single point feed location. This will never supply a uniform product quality to the individual users.

The diagram below details the feed location and distribution plan for cooling water treatment. All feeds system are designed to provide a uniform cooling water quality to the basin pumps. The locations were specifically chosen for a reason and the control system should include an FMEA analysis. With this plan (Design + MSA +FMEA) the site was able to achieve stable and sustainable quality. The PpK improved significantly as shown below.



The chemicals (CT water treatment chemicals / acid / bleach or biocide) should be evenly distributed across their feed zones to assure both good mixing and reduced impact on the basin pumps and piping.

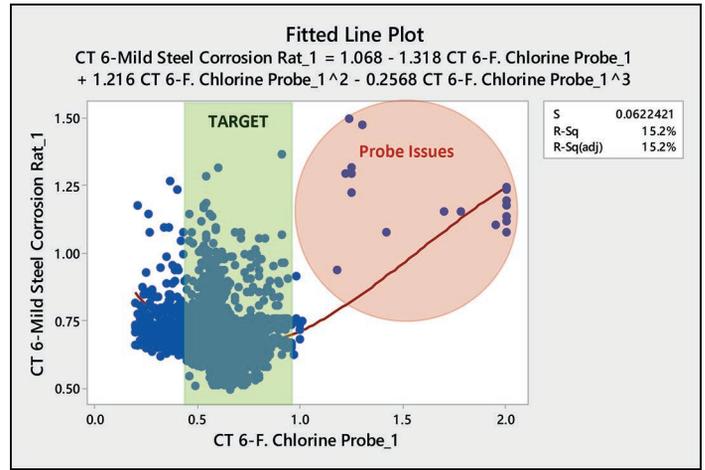
Prior to this study, each chemical was injected at a single point in the cooling tower. For the acid feed the result was unstable control. Installing a distribution header and limiting the acid feed rate improved the overall process stability and assured that each pump sees the same water quality.



Cooling Tower Studies – Some Interesting Data on Phosphate

A study of the water treatment control parameters impact on carbon steel corrosion was done. The findings were that pH / Conductivity / Free Chlorine / Phosphate were significant factors while free chlorine becomes an issue when above target (pH impact as well). The overall program became more stable at higher pH (improved buffering capability) as expected for lime softened water make-up. There is a large variance unaccounted in the process. Suspended Solids and Temperature variation are possible causes as well variation in the metallurgy itself. A Design of Experiments (DOE) may be done to determine the potential causes that can be controlled or improved such as solids level.

First – Determine impact of operating within CTI Guidelines for free chlorine and the impact of operating outside these values (lower and higher). CTI has set a target range of 0.5 to 1.0 ppm of free chlorine. Low data showed slightly more corrosion possibly due to increased biological activity while high free chlorine was a significant contributor to the carbon steel corrosion rate. A target of 0.5 to 0.7 ppm was established due to impact of free chlorine on the heat exchanger with yellow metal construction (brass/copper).



Y Axis – Carbon Steel Corrosion Rate (mils per yr.)
 X Axis CTW Free Chlorine Residual (ppm)

The initial regression fit was very poor but it did point out that the free chlorine probe was a significant impact when it failed. The probe was replaced with a device found to be more reliable. Since the plan was to tighten and lower the free chlorine control the data was removed from the regression equation (Cook's Distance) and the fit improved to 27%.

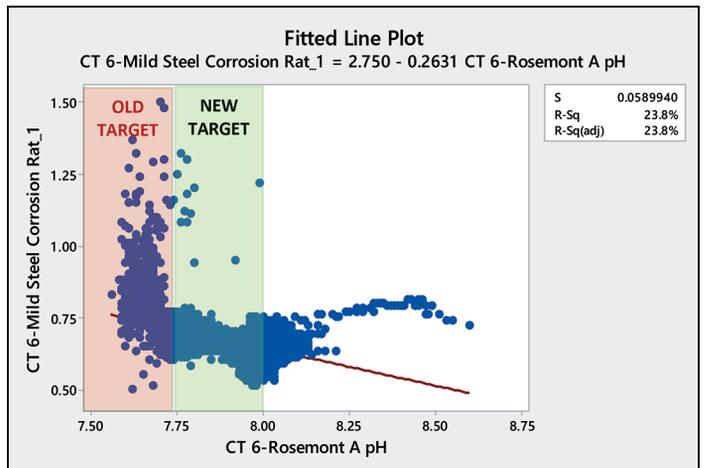
Regression Equation

$$\text{Steel Corrosion} = 2.8053 - 0.003693 \text{ CT 6-Phosphate} - 0.26324 \text{ CT 6-Rosemont A pH}$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0580001	27.11%	27.10%	27.04%

The Water Treatment Provider recommended going to a higher pH for the system control which definitely improved the overall process stability.

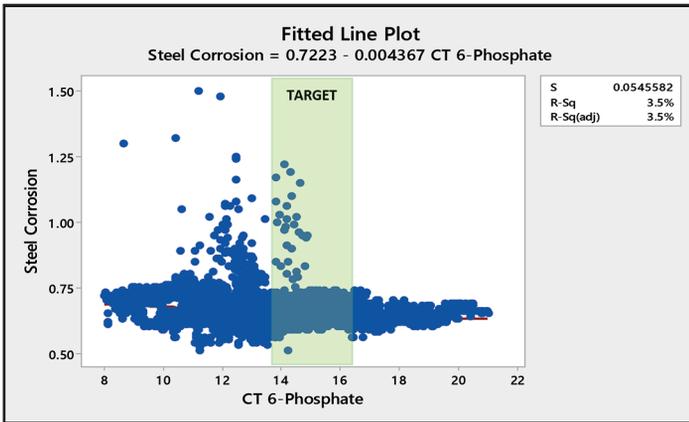


Y Axis – Carbon Steel Corrosion Rate (mils per yr.)
 X Axis CTW Unfiltered Phosphate Level (ppm)

The number of outliers decreases with the higher pH levels. The higher pH values (> 8.1) are indicative of the process running without acid feed. This will happen whenever the pH probes fail, acid pump fails, or the acid delivery is delayed.

The final parameter is the phosphate level in the cooling water. Phosphate is the chemical added to reduce iron corrosion rates so its impact was worth studying. The results were not very dramatic as seen in the following plot. The process however was more stable

at the higher phosphate feed levels. The corrosion process itself is not solely dependent on current phosphate levels. Phosphate inhibits the corrosion mechanism by passivating the metal surface (anodic inhibitor). Passivating (anodic) inhibitors form a protective oxide film on the metal surface. They are the preferred inhibitors because they are economical, form a tenacious film, and rapidly repair when damaged.^[9] The issue is that phosphate can also act like cathodic precipitator and deposit calcium phosphate which reduces the corrosion mechanism but also fouls the heat transfer surface.

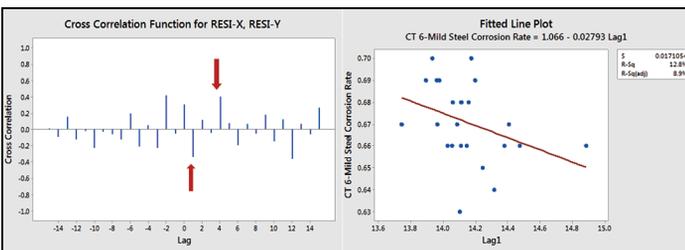


Y Axis – Carbon Steel Corrosion Rate (mils per yr.)
X Axis CTW Unfiltered Phosphate Level (ppm)

Not all factors can be directly regressed to determine if there is a correlation. If there is a suspected time delay in the process the first step is to cross correlate the data and determine the inherent time delay in the process. A time delay for phosphate and corrosion is actually beneficial. The less hypersensitive the process is to subtle changes the better the predicted results for the water treatment program.

Cross Correlation (Corrosion rates to phosphate level) was used to determine if there was a measurable lag between corrosion and phosphate levels. This analysis will define if there is lag for surface passivation after a stress event takes place (e.g. turbuculation breaks free, high solids are circulated, debris is circulated) that impacts the metal surface and initiates the corrosion mechanism.

In the course of time, an event as described above will occur in the cooling water system and this analysis was used to determine how quickly the surface repassivates itself. A lag of 1 to 4 hours between the incident and the completion of the repassivation process was determined. Higher phosphate levels improved the results of this process. This was done by first sorting the data and finding times when both the pH and free chlorine levels were stable to eliminate their potential to define the impact. We have already seen that pH and free chlorine have a much greater impact so that impact would dominate the data and regression fit.



After the time lag of 1 to 4 hours for phosphate impact was added, the regression fit for phosphate impact on mild steel corrosion rate improved by a factor of 4. The actual regression fit is very poor which is actually very desirable. The loss of a phosphate feed pump should not result in rapid corrosion of the cooling water system metallurgy. Directionally it indicates that there are competing processes in the water system – corrosion and passivation. Preparing the metal surface for passivation and then placing a passivation layer on that metal surface allows the process to stay ahead of the corrosion process. All carbon steel heat exchangers should be passivated so we stay ahead of the corrosion mechanism.

Summary

The use of science, process knowledge, and experience when combined with statistical tools can provide benefits to your treatment program. Feeding the proper amount, at the proper location, and properly measuring the amounts and the impacts can prevent surprises and save money today and in the future.

The examples given show how each aspect of the water treatment process was improved without significant capital spends.

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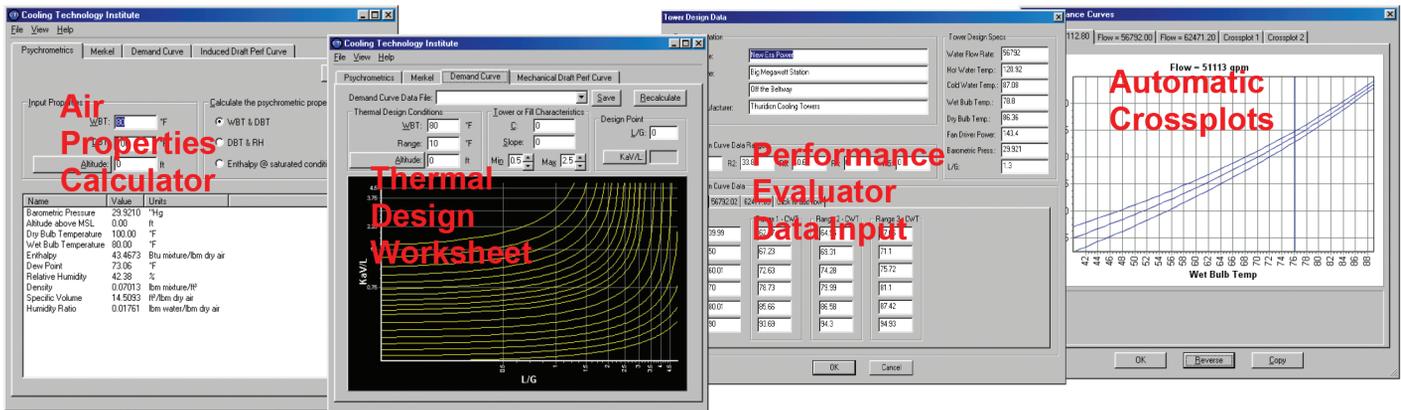


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 Contact: Gabriel Ramos

Cooling Technology Institute Certification Program STD-201 for Thermal Performance



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

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

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

Licensed CTI Thermal Certification Agencies

Agency Name / Address	Contact Person / Website / Email	Telephone / Fax
Clean Air Engineering 7936 Conner Rd Powell, TN 37849	Kenneth (Ken) Hennon www.cleanair.com khennon@cleanair.com	800.208.6162 or 865.938.7555 (F) 865.938.7569
Cooling Tower Test Associates, Inc. 15325 Melrose Dr. Stanley, KS 66221	Thomas E. (Tom) Weast www.cttai.com cttakc@aol.com	913.681.0027 (F) 913.681.0039
Cooling Tower Technologies Pte Ltd 17 Mandai Estate #06-02, Hwa Yew Industrial Bldg SINGAPORE S729934	Johnny Ong johnny@coolingtwrtech.com	+65.98251247
DMT Gmbh & Co. KG Am Technologiepark 1 45307 Essen, Germany	Dr. Ing. Meinolf Gringel www.dmt-group.de meinolf.gringel@dmt-group.de	+49.201.172.1164
McHale Performance 4700 Coster Rd Knoxville, TN 37912	Gabriel Ramos www.mchaleperformance.com ctitestng@mchaleperformance.com	865.588.2654 (F) 865.934.4779



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.



Licensed CTI Thermal Testing Agencies

*License Type A, B**

Clean Air Engineering

7936 Conner Rd, Powell, TN 37849

800.208.6162 or 865.938.7555

Fax 865.938.7569

www.cleanair.com / khennon@cleanair.com

Contact: Kenneth (Ken) Hennon

Cooling Tower Technologies Pte Ltd

17 Mandai Estate #06-02, Hwa Yew Industrial Building
SINGAPORE S729934

+65.98251247

johnny@coolingtwrtech.com

Contact: Johnny Ong

Cooling Tower Test Associates, Inc.

15325 Melrose Dr., Stanley, KS 66221

913.681.0027 / (F) 913.681.0039

www.cttai.com / cttakc@aol.com

Contact: Thomas E. (Tom) West

DMT GmbH & Co. KG

Plant & Product Safety division

Am Technologiepark 1, 45307 Essen, Germany

+49.201.172.1164

www.dmt-group.de / meinolf.gringel@dmt-group.com

Dr. -Ing. Meinolf Gringel

McHale Performance

4700 Coster Rd, Knoxville, TN 37912

856.588.2654 / (F) 865.934.4779

www.mchaleperformance.com

ctitesting@mchaleperformance.com

Contact: Gabriel Ramos

* 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.

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 Drift Testing Agencies

Clean Air Engineering

7936 Conner Rd, Powell, TN 37849

800.208.6162 or 865.938.7555

Fax 865.938.7569

www.cleanair.com / khennon@cleanair.com

Contact: Kenneth (Ken) Hennon

McHale Performance

4700 Coster Rd, Knoxville, TN 37912

856.588.2654 / (F) 865.934.4779

www.mchaleperformance.com

ctitesting@mchaleperformance.com

Contact: Gabriel Ramos



Cooling Towers Certified by CTI Under STD-201

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

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

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



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

The CTI STD-201 Thermal Performance Certification Program has grown rapidly since its inception in 1983 (see graphs that follow). A total of 74 cooling tower manufacturers are currently active in the program. In addition, 16 of the manufacturers also market products as private brands through other companies.

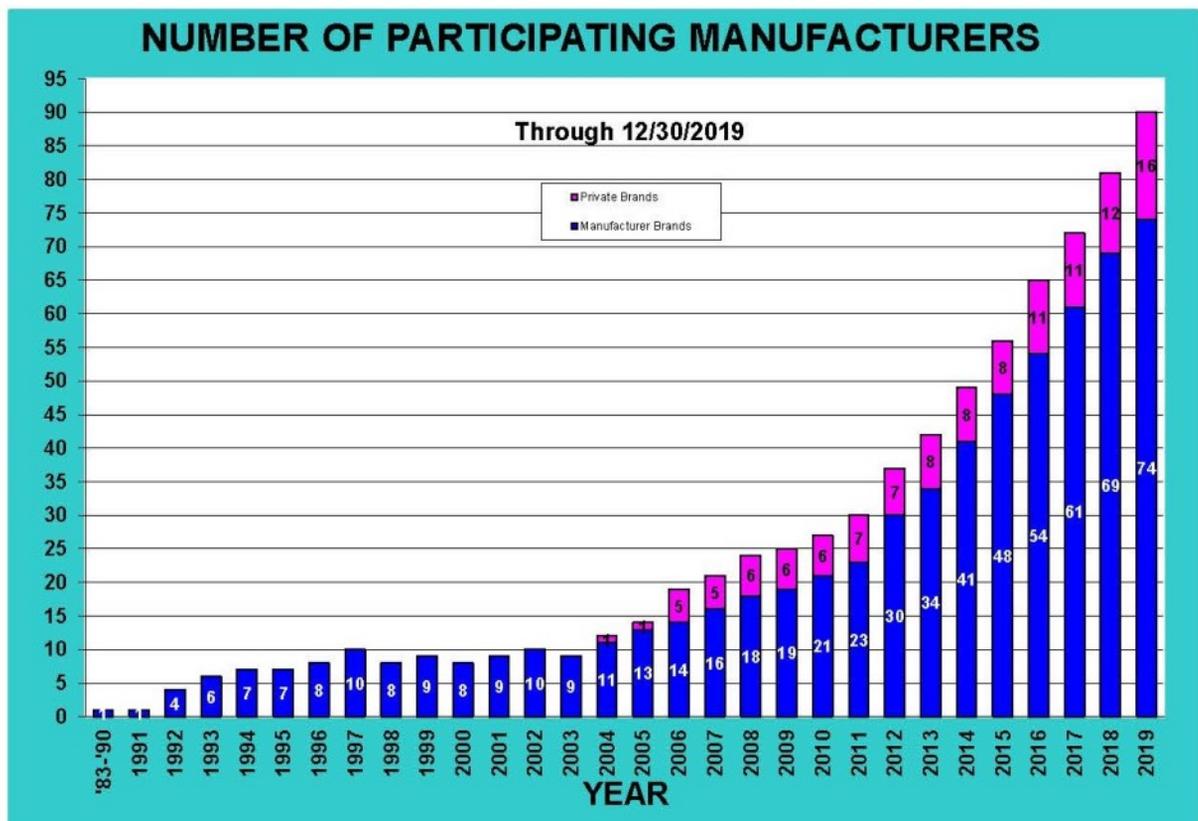
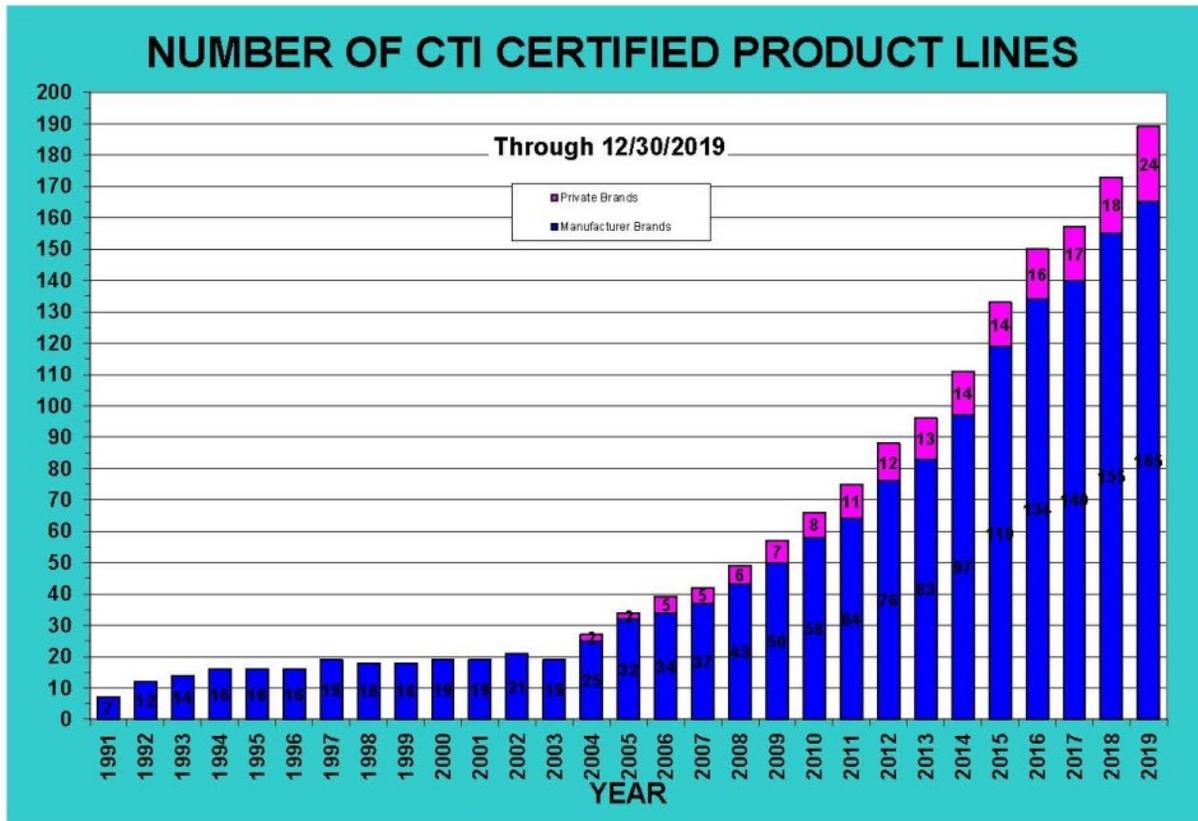
While in competition with each other, these manufacturers benefit from knowing that they each achieve their published performance capability and distinguish themselves by providing the Owner/Operator's required thermal performance. The participating manufacturers currently have 165 certified product lines plus 24 product lines marketed as private brands which result in approximately 46,500 CTI Certified cooling tower models to select from.

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

<https://www.coolingtechnology.org/certified-towers>

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

Thermal Certification Program Participation Through December 30, 2019



Current Program Participants

(as of Dec 30, 2019)

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

<https://www.coolingtechnology.org/certified-towers>

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

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

A

Advance GRP Cooling Towers, Pvt.,Ltd.

Advance 2020 Series A Validation No. C31A-07R03

NTM Line Validation No. C31B-19R00

Aggreko Cooling Tower Services

AG Line Validation No. C34A-08R02

Amcot Cooling Tower Corp.

AST Validation No. C106A-19R00

Series R-LC Validation No. C11E-11R02

American Cooling Tower, Inc.

ACF Series Validation No. C38D-18R00

ACX Series Validation No. C38C-18R00

AONE E&C Corporation, Ltd.

ACT-C Line Validation No. C28B-09R01

ACT-R/ACT-RU Line Validation No. C28A-05R05

Approach Engineering Co., Ltd

NS Line Validation No. C76A-16R01

Axima (China) Energy Technology Co., Ltd.

EWX Line Validation No. C72A-15R03

B

Baltimore Aircoil Company, Inc.

FXT Line Validation No. C11A-92R02

FXV Line Validation No. C11J-98R10

NXF Line Validation No. C11Q-18R01

PF Series Validation No. C11P-12R02

PT2, PTE & PCT Series Validation No. C11L-07R05

Series V Closed Validation No. C11K-00R02

Series V Open Validation No. C11B-92R06

Series S1500 Validation No. C11H-94R09

Series 3000A,C,D,E, Compass & Smart
Validation No. C11F-92R18

Bell Cooling Tower Pvt, Ltd

BCTI Line Validation No. C43A-12R02

C

Cenk Endüstri Tesisleri Imalat Ve Taahüt A.Ş.

LEON Line Validation No. C89A-17R01

LISA Line Validation No. C89B-17R01

ISTANBUL Line Validation No. C89C-19R00

Changzhou Hanf Cooling Equipment Co., Ltd

GTC Series Validation No. C101B-19R01

GTN Series Validation No. C101A-18R01

Chengdu Xingli Refrigeration Equipment Co., Ltd

HBL-HS Series Validation No. C115A-19R00

Chongqing Yinengfu Technology Co., Ltd

YNF Series Validation No. C103A-18R00

Cool Water Technologies

RTAi Line Validation No. C52A-13R03

RTi Line Validation No. C52A-13R02

D

Dalian Spindle Environmental Facilities Co., Ltd

DC Series Validation No. C112A-19R00

DF Series Validation No. C112B-19R00

DX Series Validation No. C112C-19R00

Decsa

TMA-EU Series Validation No. C42C-17R00

Delta Cooling Tower, Inc.

TM Series Validation No. 02-24-01

Delta (India) Cooling Tower Pvt, Ltd

DFC-60UX Line Validation No. C85A-18R00

Dezhou Beitai Refrigeration Equipment Co. Ltd.

DBHZ₂ Validation No. C104A-19R00

Dongguan Ryoden Cooling Equipment Co., Ltd

RT-L&U Series Validation No. C71A-15R03

RTM-L Series Validation No. C71B-15R00

Dunham-Bush (China) Co., Ltd

BHC Series Validation No. C107A-19R00

E

Elendoo Technology (Beijing) Co., Ltd.

EL Line *Validation No. C50C-15R04*
ELOP Line *Validation No. C50B-14R04*

Ebara Refrigeration Equipment & Systems Co.

CDW Line *Validation No. C53A-13R04*
CNW Line *Validation No. C53C-18R00*
CXW Line *Validation No. C53B-14R02*

Evapco, Inc.

AT Series *Validation No. C13A-99R21*
ATWB Series *Validation No. C13F-09R09*
AXS Line *Validation No. C13K-15R03*
ESWA, ESWB, & ESW4 Series *Validation No. C13E-06R11*
L Series Closed *Validation No. C13G-09R04*
L Series Open *Validation No. C13C-05R03*

F

Flow Tech Air Pvt Ltd

FTA Series *Validation No. C69A-16R01*

G

Genius Cooling Tower Sdn Bhd

MK Series *Validation No. C67C-18R00*
MT Series *Validation No. C67A-16R00*
MX Series *Validation No. C67B-16R00*

Guangdong EnZen Energy Saving Technology Co., Ltd

YZC Series *Validation No. C109A-19R00*

Guangdong Green Cooling Equipment Co., Ltd

GLR-E Series *Validation No. C97B-18R00*

Guangdong Zhaorin Industrial Co., Ltd

SRN Series *Validation No. C95A-17R01*

Guangdong Liangken Cooling and Heating Equipment Technology Co., Ltd

LRT Series *Validation No. C66A-15R02*

Guangzhou Goaland Energy Conservation Tech Co., Ltd.

GLH Series *Validation No. C96A-17R01*
GLN Series *Validation No. C96B-17R00*

Guangzhou Laxun Technology Exploit Company, Ltd.

LC Line *Validation No. C45F-16R00*
LMB Line *Validation No. 12-45-02*
PG Line *Validation No. C45G-17R00*
PL Line *Validation No. C45E-16R03*

Guangzhou Single Beam All Steel Cooling Tower Equipment Co., Ltd.

SLH Line *Validation No. C91E-16R02*

H

Hon Ming (Guang Dong) Air Conditioning Equipment Company, Ltd.

MK Series *Validation No. C66A-15R02*

Hunan Yuanheng Technology Company, Ltd.

YCH-F Line *Validation No. C40C-16R02*
YCN-F Line *Validation No. C40D-18R00*
YHD Line *Validation No. C40B-15R00*
YHW Line *Validation No. C40E-18R00*

HVAC/R International, Inc.

Therflow Series TFC *Validation No. C28B-09R01*
Therflow Series TFW *Validation No. C28A-05R05*

J

Jacir

DTC ecoTec *Validation No. C46E-18R00*
KS Line *Validation No. 12-46-01*
S Series *Validation No. C46D-18R00*
VAP Line *Validation No. C46C-16R02*

Jiangsu Dayang Cooling Tower Co., Ltd.

HLT Line *Validation No. C94A-14R03*

Jiangsu Greenland Heat Transfer Technology Co.

GBH-TS Line *Validation No. C87A-18R01*

Jiangsu i-Tower Cooling Technology Co., Ltd.

REH Series *Validation No. C75B-16R01*
TMH Series *Validation No. C75A-16R02*

Jiangsu Ocean Cooling Equipment Co., Ltd.

TKS Series *Validation No. C41D-18R00*

Jiangxi Ark Fluid Science Technology Co., Ltd.

FBFJ Line *Validation No. C83B-18R00*
FKH Line *Validation No. C83A-17R01*

Ji'Nan Chin-Tech Thermal Technology Co., Ltd.

CTHX Line *Validation No. C91E-16R02*

K

Kelvion B.V.

Polacel CF Series *Validation No. C25A-04R02*

KIMCO (Kyung In Machinery Company, Ltd.)

CKL Line *Validation No. C18B-05R04*
Endura Cool Line *Validation No. C18A-93R09*
GX Line *Validation No. C18D-18R01*

King Sun Industry Company, Ltd.

HKB Line *Validation No. C35A-09R05*
HKD Line *Validation No. C35B-09R06*
KC Line *Validation No. C35C-11R02*
KFT Line *Validation No. C35D-16R00*

Korytko Systems, Ltd.

KDI Line *Validation No. C70A-16R02*

KSN Co., Ltd

KSNC Series *Validation No. C44A-12R03*
KSNX Series *Validation No. 12-44-02*
KSNC-C Series *Validation No. C44C-14R01*
KSNX-C Series *Validation No. C44D-14R01*

Kuken Cooling Tower Co.,Ltd.

GXC Series *Validation No. C81B-16R01*
GXE Series *Validation No. C81A-16R01*

L

Liang Chi Industry Company, Ltd.

LCTD Line *Validation No. C20J-18R00*
LCTR Line *Validation No. C20H-17R00*
Series C-LC *Validation No. C20B-09R02*
Series D-LC *Validation No. C20F-14R02*
Series R-LC *Validation No. C11E-11R03*
Series U-LC *Validation No. C20D-10R04*
Series V-LC *Validation No. C20C-10R01*
TLC Line *Validation No. C20G-16R00*

M

Marley (SPX Cooling Technologies)

Aquatower Series *Validation No. 01-14-05*
AV Series *Validation No. C14D-98R03*
DTW Series *Validation No. C14N-16R02*
LW Series *Validation No. C14P-16R01*
MCW Series *Validation No. 06-14-08*
MD and CP Series *Validation No. C14L-08R09*
MHF Series *Validation No. C14G-04R08*
NC Series *Validation No. C14A-92R20*
NX Series *Validation No. C14M-15R01*
Quadraflow Line *Validation No. 92-14-02*

Mesan Cooling Tower, Ltd.

MCC Series *Validation No. C26G-12R03*
MFD Series *Validation No. C26J-16R01*
MXC Series *Validation No. C26H-12R01*
MXR-KM, MXL, MXH Series *Validation No. C26C-08R09*

MITA S.r.l.

PM Series *Validation No. C56B-16R02*

N

NIBA Su Sogutma Kulerleri San, ve Tic, A.S.

HMP-NB Line *Validation No. C55A-14R02*

Nihon Spindle Manufacturing Company, Ltd.

KG Line *Validation No. C33B-12R05*

O

Ocean Cooling Tower Sdn Bhd

OCBSD *Validation No. C86B-19R00*
YC Series *Validation No. C86A-17R00*

OTT Company, Ltd.

OTTC Series *Validation No. C44A-12R03*
OTTX Series *Validation No. 12-44-02*
OTTC-C Series *Validation No. C44C-14R01*
OTTX-C Series *Validation No. C44D-14R01*

P

Paharpur Cooling Tower, Ltd.

CF3 Series *Validation No. C51A-13R03*
OXF-30K Series *Validation No. C51B-14R00*
Series RXF *Validation No. C51C-19R00*

Protec Cooling Towers, Inc.

FRS Series *Validation No. 05-27-03*
FWS Series *Validation No. C27A-04R06*

Q

Qinyang Zhonghe Zhi Da Technology Co., Ltd.

HL-SC Series *Validation No. C99A-18R00*

R

Reymosa Cooling Towers, Inc. (Fabrica Mexicana de Torres, SA de CV)

HFC Line *Validation No. C22F-10R5*
RT & RTM Series *Validation No. C22G-13R07*

Rosemex, Inc.

RC (RCS/D) Series *Validation No. C54A-13R04*
RO (ROS/D) Series *Validation No. C94A-14R03*

RSD Cooling Towers

RSS Series *Validation No. C32A-08R01*

Ryowo (Holding) Company, Ltd.

FDC Series *Validation No. C27E-11R00*
FRS Series *Validation No. 05-27-03*
FVS Series *Validation No. 12-27-06*
FWS and FCS Series *Validation No. C27A-04R06*

S

Shangdong Grad Group Co., Ltd.

GAT Series *Validation No. C88A-17R00*

Shanghai ACE Cooling Refrigeration Technology Col, Ltd.

AC Line *Validation No. C80A-17R01*

Shanghai Baofeng Machinery Manufacturing Co., Ltd.

BTC Line *Validation No. C49A-12R01*

Shanghai Liang Chi Cooling Equipment Co., Ltd.

LCP Line *Validation No. C62D-18R00*
LNCM Line *Validation No. C62B-16R00*
LRS Line *Validation No. C62C-16R00*
LRCM-DD Line *Validation No. C62E-19R00*

Shanghai Tyacht Cooling System Co.,Ltd.

TCT Line *Validation No. C93D-18R00*
TMC Line *Validation No. C93C-18R00*

Shanghai Wanxiang Cooling Equipment Co., Ltd.

FBH/HL Line *Validation No. C54A-13R04*
FKH/FKHL Series *Validation No. C94A-14R03*

Shanghai Zendia Cooling Equipment Co., Ltd.

ZHF-7000 Series *Validation No. C111A-19R00*

Sinro Air-Conditioning (Fogang) Company, Ltd.

CEF-A Line *Validation No. C37B-11R03*
SC-B Series *Validation No. C37C-11R02*
SC-H Series *Validation No. C37A-10R02*

Snowcoil (Shanghai) M&E Engineering Co., Ltd.

SMCC Series *Validation No. C105A-18R00*
SMCR Series *Validation No. C105B-18R00*
SMCT Series *Validation No. C105C-18R00*

Sung Ji Air-Conditioning Technology Co., Ltd.

SJCO Series *Validation No. C74B-16R00*
SJMO Series *Validation No. C74A-16R00*

T

Ta Shin F.R.P. Company, Ltd.

TSS Series *Validation No. C32A-08R01*

The Cooling Tower Company, L.C

TCIA Series *Validation No. C29C-19R00*

Thermal-Cell sdn bhd

THW Line *Validation No. C40E-18R00*

Tower Tech, a div. of CPK Manufacturing, LLC

TTXL Line *Validation No. C17F-08R05*

TTXR Line *Validation No. C17F-15R00*

Truwater Cooling Towers Sdn Bhd

EC-S Series *Validation No. C41A-12R04*

EX-S Series *Validation No. C41B-12R06*

TKS Series *Validation No. C41D-18R00*

VXS Series *Validation No. C41C-13R02*

W

Wuxi Ark Fluid Science Technology Co., Ltd.

FBF Series *Validation C83B-18R00*

Wuxi Fangzhou Water Cooling Equipment Co., Ltd.

FHB Line *Validation C64C-18R00*

Y

YM Tech Co., Ltd.

YFO Line *Validation No. C108A-19R00*

Xsta Line *Validation No. C108B-19R00*

York (By Johnson Controls)

AT Series *Validation No. C13A-99R21*

LSTE Line *Validation No. C13G-09R03*

Z

Zhejiang Dongjie Cooling Tower Co., Ltd.

DHC Line *Validation No. C63B-15R00*

Zhejiang Haicold Cooling Technology Co., Ltd

SF Line *Validation No. C76A-16R00*

Zhejiang Jinling Refrigeration Engineering Co.,Ltd.

JFT Series *Validation No. C28C-16R02*

JNC Series *Validation No. C28B-09R01*

JNT Series *Validation No. C28A-05R05*

Zhejiang Ryoden Cooling Equipment Co., Ltd.

RT/SB Series *Validation No. C102A-18R00*

Zhejiang Shangfeng Cooling Tower Co., Ltd.

SFB Line *Validation No. C73A-15R01*

Zhejiang Wanxiang Science and Technology Company, Ltd.

WBH Line *Validation No. C96A-17R01*

Always Look For the CTI Certified Label with Validation Number on Your Equipment



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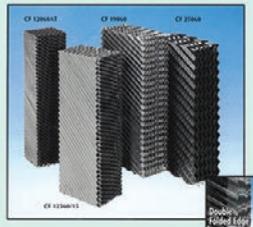
New Cooling Towers:

- Counterflow • Crossflow
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Professional Services Include:

- Cooling Tower Evaluations
- Bid Preparations • Wood Analysis
- Thermal Engineering



Field Services Include:

- Repair & Overhaul
- Scheduled Maintenance
- Inspection & Evaluations
- Emergency Service



Nationwide Service

New Jersey Office:

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 NJ: (973) 966-1116
 NY: (212) 355-0746
 Fax: (973) 966-5122

Arkansas Office:

Ph: (504) 236-3629
 Fax: (870) 862-2810
 E-Mail ctowers@tpila.com

Pennsylvania Office:

Ph: (215) 778-6027
 Fax: (215) 938-8900
smorris@towerperformance.com

E-Mail: stefanguetzov@towerperformance.com

Parts Sales:

Toll Free: (800) 314-1695
 Ph: (970) 593-8637
 Fax: (970) 472-1304
 E-Mail: jfritz@towerperformance.com



Texas Office:

Toll Free: (800) 324-0691
 Ph: (713) 643-0691
 Fax (713) 643-0310
 E-Mail: ctowers@tpitx.com



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info@amarillogear.com

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Company



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*Compared to other factory-assembled, crossflow cooling towers.