COOLING TOWER REPAIRS

Remediating corrosion in hyperbolic towers

Generally, natural-draft (that is, hyperbolic) cooling towers are less expensive to operate and maintain than their mechanical-draft cousins. However, hyperbolics (Figure 1)—which are made of concrete—are vulnerable to corrosion-induced physical damage that can be very costly to repair. Concrete and steel embedded in it will progressively deteriorate when exposed for long periods to a warm, moist environment, carbon dioxide in air, and/or chlorides and scale in cooling water.

Unfortunately, this deterioration often is either ignored or addressed by marginal repairs that perpetuate the "repair of the repair" cycle. Extending the lifespan of a natural-draft cooling tower requires a thorough understanding of both the various mechanisms of the deterioration and effective rehabilitation strategies.

How concrete and steel are attacked

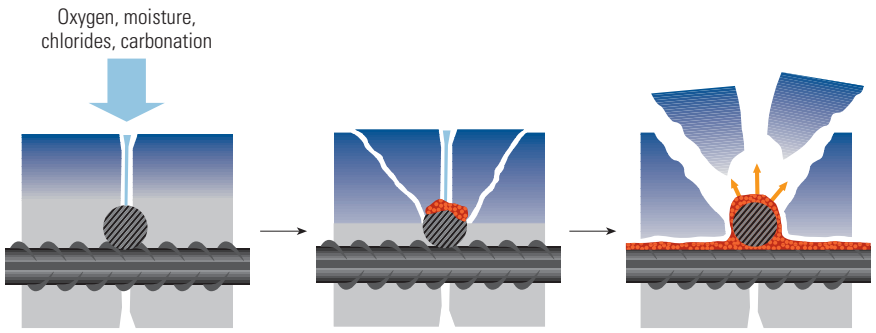
Deterioration of natural-draft hyperbolic shells—in the form of cracking, delamination, and/or spalling—is typically most pronounced at the throat of the shell, where its radius is smallest. The damage mechanism is well known and begins with the corrosion of steel embedded in the concrete shell. The shell's structural integrity is reduced when corrosion products—which occupy more space than the parent material—increase tensile stresses on the concrete in the immediate proximity of the corroding steel. Although inherently strong in compression, concrete is relatively weak in tension. As a result, the concrete cracks at the corroding bar interface.

Once cracking exposes the steel, delamination—a separation within the concrete that usually originates at the level of the reinforcement—follows. Further, along the deterioration curve, spalling—detachment or dislodging of areas in the cross section of the concrete—can occur. Finally, if the water the tower cools has a chloride content of as little as 0.15%, that can be sufficient to initiate corrosion of embedded steel in concrete in the presence of oxygen and moisture. The different stages of corrosion-induced concrete deterioration are depicted in Figure 2.

Another mechanism of corrosion-induced deterioration is carbonation. Carbonation results when carbon dioxide from the surrounding air reacts with the calcium hydroxide molecules of concrete to produce calcium carbonate. Because calcium carbonate is more acidic than the parent material, it effectively "depassifies" the alkaline environment of concrete. An alkaline environment is necessary for a passive film to form on the steel reinforcement and inhibit the electrochemical process of corrosion. It has been determined that at pH levels lower than 9.8, the concrete mass can be assumed to be an "active participant" in the corrosion process. Cooling tower environments characterized by high temperatures and humidity promote the progression of the carbonation front.

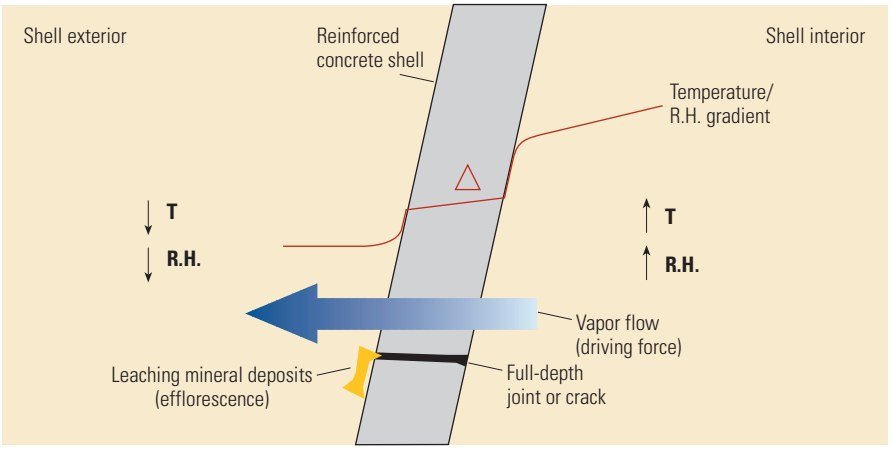
The same conditions inside a hyperbolic tower cause water vapor to diffuse through the concrete shell, carrying with it mineral products that deposit on the exterior of the shell in the form of leachates and efflorescence. Faults in the concrete, such as cracks or construction joints in jump-form construction, facilitate the penetration of water. The penetration is greatest at the shell throat because the velocity and density of water vapors are highest there. Once

2. Drivers of damage. Stages of corrosion-induced concrete deterioration. *Source: Structural Preservation Systems Inc.*



1. Elegant but exposed. The concrete and steel in counterflow (left) and crossflow (right) natural-draft hyperbolic cooling towers are vulnerable to corrosion-induced deterioration. *Source: Structural Preservation Systems Inc.*

3. Catalysts of corrosion. The damage caused by the flow of water vapor driven through joints and cracks in the shell wall is a function of the temperature and humidity gradients. *Source: Structural Preservation Systems Inc.*



Notes: T = temperature, R.H. = relative humidity

moisture penetrates the cross section, corrosion of the embedded reinforcing steel can begin (Figure 3).

All of the moisture available to attack a cooling tower may not come from ambient air. Other possible sources are the flue vapors exiting that tower or neighboring towers. These vapors, driven by the wind, cascade onto the higher elevations of the shell and promote corrosion there.

Fixing and delaying damage

Surface repairs of corrosion-induced damage entail removing the deteriorated concrete, undercutting around the reinforcing steel, cleaning and protecting the reinforcing steel, and reestablishing the original concrete section. The repairs themselves involve forming and pouring or pneumatically applying rapid-setting, pre-bagged cementitious materials with consistent characteristics and properties.

Surface repairs can be done online or offline, depending on the location and extent of the deterioration. However, because removing extensive amounts of a concrete shell might compromise its structural integrity, any repair program should take the area and depth of concrete removed into account. That said, some shells—for example, those with slender walls manifesting overlapping interior and exterior deterioration—may not require full-depth removal and repair. Indeed, full-depth repairs are not always beneficial, because they introduce full-depth joints through which flue gas can pass and promote corrosion around the perimeter of the repair areas. Accordingly, any repair program should attend to the sealing of partial or full-depth repair joints.

As for forestalling damage, coatings and membranes added to the interior and/or exterior of a shell can minimize the penetration of corrosive agents to the level of the reinforcing steel. If both interior and exterior coatings are applied to the shell, the vapor permeability of the exterior coating should be considerably less than that of the interior coating, to minimize debonding of the exterior coating. Bear in mind that vapors from neighboring hyperbolic cooling towers may prevent effective application of coatings.

Shell game

A hyperbolic shell's circumferential supporting elements typically comprise cast-in-place pedestals on the cooling tower basin that support cast-in-place or precast diagonal columns. Many cooling tower designs also incorporate a circumferential beam at the bottom of the shell that transfers loads to the diagonal columns. Deterioration of circumferential supporting elements often occurs at their corners.

Circumferential supporting elements can be classified according to their environmental exposure. For example, because they are typically permanently submerged, pedestals within the cooling tower basin are prone to corrosion-induced damage. However, any such damage is typically minor, because steel corrodes very slowly under water. By contrast, columns and circumferential beams corrode more quickly, because they are splashed by high concentrations of chlorides, moisture, and oxygen. Further, significant deterioration is often found toward the top of the shell (at the circumferential beam and the top of the columns) as a result of high-velocity drafts.

Unfortunately, too many repair programs address the effect but not the cause of shell corrosion. When deteriorated concrete is removed, high chloride concentrations may remain in native concrete areas. A standard repair may actually exacerbate the problem by introducing corrosion cells between steel embedded in chloride-free patch material and steel embedded in chloride-contaminated native concrete. This phenomenon is referred to as the "halo" or "anode ring effect."

As for other remedies, cathodic protection has proven effective at preventing corrosion of certain circumferential supporting elements. The technique works by supplying a source of current to counteract the internal corrosion existing in the corrosion cell. Specifically, galvanic zinc-based thermally applied metallic coatings provide an effective long-term rehabilitation strategy. It should be noted that understanding the electrical continuity of the reinforcing steel is a prerequisite for designing an effective cathodic protection system for a hyperbolic cooling tower.

The final discussion of remedies here addresses the water distribution structures that provide support to the cooling tower's fill and the water distribution piping. In crossflow (wet-ring) designs, they typically consist of precast radial and circumferential elements stacked in several levels. In counterflow designs, they take the form of precast structural frames within the footprint of the shell.

Under similar exposure conditions, the level of corrosion-induced deterioration of precast concrete elements has been found to be higher in crossflow than in counterflow designs. That's because the circumferential supporting elements in a counterflow design are exposed to a constant moist and high-humidity environment. In contrast, water distribution elements in a counterflow design are subjected to splashing and intermittent wetting and drying—conditions that are ideal for the initiation of embedded metal corrosion.

—Contributed by Leandro Etcheverry, PhD, *manager of engineering services for Structural Preservation Systems Inc. (Houston, Texas).*

COOLING WATER TREATMENT

Scale formation and removal

Over the past decade, concerns for water conservation and the environment have caused a wholesale shift from once-through cooling to evaporative cooling of power plants. When a power plant rejects condenser heat to an evaporative cooling tower, the dissolved and suspended matter in the makeup water must be removed from the system. An uncontrolled cooling water system encourages the formation of sparingly soluble electrolytes. Open recirculating cooling water systems are especially prone to scale and deposit-related problems. Species commonly associated with these deposits (depending on water chemistry) are calcium carbonate, calcium phosphate(s), and silica/metal silicates.

Undesirable releases of depositions and scale can be avoided by careful application of three chemical water treatment techniques that are often symbolized by a triangle (Figure 4) whose sides represent inhibition of scale deposits, inhibition of corrosion, and prevention of microbiological fouling.

Understandably, most industrial water users would rather prevent scale from forming in the first place than have to take the more costly (and potentially dangerous) step of chemically removing it. Examples of scales that require laborious mechanical cleaning are silica and silicate salts. Phosphorus-containing compounds (usually referred to as organic phosphates or phosphonates) and dispersant polymers are the targets of many cooling water treatment programs.

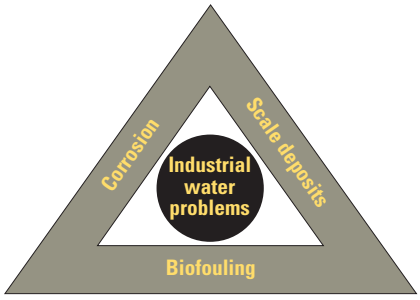
The underlying complex chemistry of scale formation and control is often neglected or ignored, leaving plant operators struggling to combat an unknown enemy. Understanding how silica scale forms is the necessary first step of any strategic and cost-effective plan to control it. Let's take a look at several of the important issues related to silica/silicates scale formation and deposition by examining the physicochemical processes that create scale.

No deposit, no return

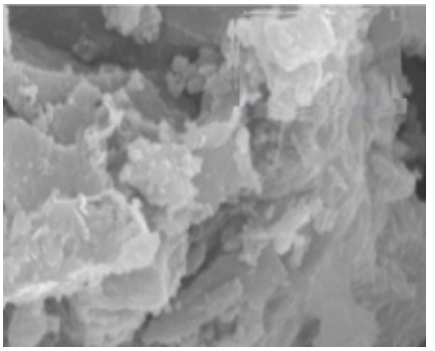
The term "scale" usually refers to an intimate mixture of sparingly soluble mineral salts. The formation of calcium carbonate, calcium phosphate, silica, silicate salts, calcium sulfate, and corrosion products depends on the pH and the temperature of water and the concentrations of impurities in it.

The main driver of scale formation is the concentration of dissolved solids by repeated partial evaporation of the water. Therefore, even those cooling waters that have little inherent tendency to scale will eventually become

4. Virtuous triangle. Industrial water users seek to control these three scaling problems by chemically treating their cooling water. *Source: Kostas Demadis*



5. Complex and amorphous. Morphology of a silica deposit. *Source: Kostas Demadis*



scale-forming, given today's practice of reusing water repeatedly to minimize its consumption.

Silica scale formation is a serious problem with cooling water that has high dissolved silica content, such as sea water. Silica and/or magnesium silicate deposition limits industrial water users to low cycles of operation. In certain regions (such as the Pacific Rim, Latin America, Texas, New Mexico, and southern Europe), water used for industrial cooling contains "high" concentrations of silica (defined as 50 to 100 ppm, as SiO_2). Silica's solubility has been measured at 150 to 180 ppm, depending on the dissolved species and temperature. This difference imposes severe limits on water users and forces them to take either of two approaches: Operate at very low cycles of concentration (thus consuming enormous amounts of water) or chemically treat the cooling water to prevent silica scale formation and deposition.

Silica scale formation usually takes place at pH levels below 8.5, whereas magnesium silicate scale forms at a pH above 8.5 (in waters with high Mg_2+ levels). These pH regions are dependent on the "intricacies" of the individual cooling system. Silica has "normal" solubility, in contrast to the "inverse" solubility of magnesium silicate. The formation of the latter is favored as temperature increases, whereas solubility of the former is higher at elevated temperatures. When a silicate ion polymerizes, it forms a number of structural motifs: rings of various sizes, cross-linked polymeric chains of different molecular weights, and structures of "oligomeric" polymers (polymers consisting of two, three, or four monomers). The resulting silica scale is a complex and amorphous product (colloidal silica) and a complicated mixture of numerous components, often including metal ions (Figure 5).

In practice, the formation of silica scale can be prevented in any of three ways:

- By removing silica from the makeup water through "hot-lime softening" (precipitation with $Mg(OH)_2$ or $MgCl_2$, followed by filtration).
- By inhibition (retardation or elimination of colloidal silica formation).
- By dispersion (elimination of surface attachment of "larger" silica colloids). Inhibition stops silica polymerization at early stages, whereas dispersion prevents growth of larger particles and their attachment to surfaces (Figure 6).

Chemical dependency

In water treatment programs, other components are often formulated with scale inhibitors. For example, "yellow metal" (copper, admiralty brass) corrosion inhibitors, dispersant polymers, and tracers can be components of the same treatment, whereas biocides for microbial control (such as chlorine or bromine) are usually fed separately.

Many factors have to be taken into account during the choice of a chemical treatment program process. Among the most critical are the following.

Water chemistry. Before selecting a program, one needs to know the species present in the makeup and process (recirculating) water. Increasing economic pressures dictate the use of low-quality water for cooling purposes. This poses severe limitations on achieving high cycles of concentration because fouling becomes a serious concern. The presence of other species in water will dictate the treatment approach. For example, because high chloride and sulfate content increase the risk of localized corrosion, measures must be taken to protect the system from it. As another example, although silica may be present in the makeup water at low levels, the chemical treatment program must include projections of potential silica scaling in the water after its cycles of concentration are increased.

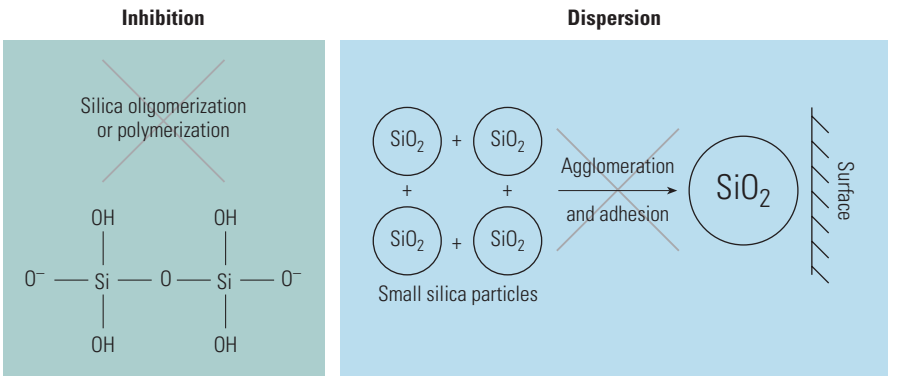
Water tendency. In general, water can be either corrosive or scaling. Although "soft" makeup water has virtually no scaling potential (due to its low concentrations of scaling ions), it can nonetheless be extremely corrosive. "Hard" waters, on the other hand, are more prone to scaling/fouling and therefore require treatment.

Cost. Chemicals used in multi-component treatment programs are not free. Furthermore, there are cost-effective programs and more costly ones. Budgetary concerns rather than technological considerations often are responsible for program selection. Either way, one should consider the capabilities and limitations, as well as the costs, of a variety of chemical treatment programs when selecting the one most appropriate for the characteristics and needs of the facility.

Implementation. The success of a chemical treatment program depends in large part on whether it is properly implemented. To ensure its satisfactory performance, operators must perform several physicochemical measurements either in the field or in the laboratory. These indicate whether a certain component of the program is failing and whether the overall program is achieving its goals.

Corrosion monitoring can be done online with commercially available corrosion monitors. It should go without saying that the instruments must be maintained prop-

6. Nipping silica in the bud, and later. This drawing shows mechanisms for silica inhibition and dispersion. Inhibition maintains silica solubility; dispersion prevents silica particles from forming larger agglomerates and depositing them onto critical surfaces. *Source: Kostas Demadis*



erly and calibrated frequently, and ideally their measurements should by complemented by observations based on corrosion coupons. Monitoring of underdeposit corrosion is vital in systems with a history of severe deposition problems.

Scale monitoring likewise requires the use of properly calibrated and functioning on-line instruments. Water chemistry tests performed on-site also offer great benefits. By monitoring D Cycles (the number of cycles based on a nonscaling ion minus the number of cycles based on a scaling ion, for example, calcium), the loss of soluble species can be determined. Theoretically, D Cycles should be zero. A small increase is a warning sign, whereas a "split" of 1 or higher indicates active precipitation and deposition. In the case of silica scale, monitoring needs to be careful and reliable. Silica scale cannot be eliminated by simple pH adjustments or routine cleanings. Warning signs such as a drop in predicted soluble silica should be taken seriously.

Microbiological growth monitoring in bulk water may be useful. But it also can be deceiving because it fails to take into account biofilm growth, a phenomenon that can have a big negative impact on heat transfer. Usually, maintaining a low biocide residual and monitoring it carefully will ensure that the process water is free of major problems.

"Actives" monitoring also is required because water treatment chemicals can degrade over time or be depleted due to precipitation. Occasionally, scale inhibitors precipitate as calcium salts because of overfeeding or very high calcium levels. Dispersant polymers can be consumed due to adsorption onto surfaces. Oxidizing biocides can be consumed not in the control of biological growth, but rather in the oxidization of treatment chemicals. Therefore, monitoring of critical treatment actives becomes very significant, ensures performance, and can indicate a problem in its genesis.

pH control of a large portion of open recirculating water systems is typically by acid injection. Failure to control pH can result in pH upsets that can cause corrosion rates to dramatically increase, threatening the integrity of the entire system. If high levels of silica and magnesium are both present in the recirculating water, a pH upset in higher regions may cause magnesium silicate fouling.

Heat exchanger efficiency should be monitored to ensure proper system performance. If the efficiency is lower than specified, chemical or mechanical cleaning may be needed to restore system performance.

Final perspective

Cooling is the purpose of most of the water consumed by industrial users. Many cooling systems conserve water by operating under conditions of high supersaturation of dissolved species. Here, the use of inhibitors and dispersant polymer is required to prevent the formation of scale.

A thoughtful selection of the combination of inhibitors and dispersants allows the water chemist/system operator to develop high-performing, cost-effective formulations to minimize both scale and corrosion at high cycles and with any biocide program. Although antiscalant additives are abundant for the more "traditional" scales—calcium carbonate(s), calcium phosphate(s), and calcium sulfate(s)—inhibitors for silica or magnesium silicate are less common. However, more choices now are available to cooling water system operators who opt to use chemicals, including removing silica

before it enters the cooling tower. A well-conceived and carefully implemented mitigation approach will minimize the system's downtime and maximize its effectiveness.

—Contributed by Kostas Demadis, *assistant professor of chemistry at the University of Crete. He can be reached at demadis@chemistry.uoc.gr.*

INFORMATION TECHNOLOGY

Digital controls = lower costs

JDI Contracts Inc. (Cohasset, Minn.) recently released a study that quantifies the potential cost savings that would result from outfitting a typical, $840 million, 600-MW, greenfield, pulverized coal-fired supercritical power plant with digital controls during its construction.

The report, titled "The Economic Impact of Digital Bus Technology on New Plant Construction," compares the traditional approach of using a traditional engineer-procure-construct (EPC) model for an instrumentation and control (I&C) system (in which field signals are hardwired to I/O cards using dedicated cables) to an almost all-digital approach. The latter uses an alternative selection process—PepC (procure strategic suppliers, engineer, procure balance of plant, construct)—to build an integrated system of high-speed field communications networks, intelligent field devices, and bus I/O technologies. However, it also uses the traditional I/O connection scheme for certain high-speed and safety-related loops.

The study found that the digital bus approach to new plant construction provides opportunities for reduced costs in the areas of system selection, engineering, construction, start-up, and overheads. The total costs associated with new plant construction for a traditional I&C system were pegged at approximately $50.1 million, compared with $30.4 million for the digital I/O bus approach (see table). That represents a savings of more than $19 million (39.4%), or a substantial $2,000 per I/O point.

"This study details a methodology that would give stakeholders in the utility industry the ability to save millions of dollars in costs during the construction of a highly automated plant with state-of-the-art I&C systems," said Roger L. Hoyum, owner of JDI Contracts and author of the study.

The analysis used a set of existing plans and specifications with roughly 5,200 hard and 4,250 soft I/O points whose locations were defined by general arrangement drawings. The location of motor control centers also was defined. Costs for the traditional tray and conduit approach, including materials and labor, were then developed based on the layout plan (Figure 7). The analysis then was repeated for the total digital approach, with smart transmitters, digital I/O, and intelligent motor interfaces. Estimates for plant checkout and start-up were subsequently developed that included overhead, interest during construction (IDC), and other plant indirect costs. IDC savings result from the reduction of checkout and firing time. According to the study, the use of digital I/O bus technology could cut two months or more from a six-month checkout and up to one month from a three-month start-up period.

Summary cost rollup: savings from using all-digital controls

	Cost		
Item	**Traditional approach**	**Digital approach**	**Savings**
System selection	$459,000 (EPC)	$157,600 (PepC)	$301,400
Engineering	$5,353,538	$1,851,683	$3,501,854
Construction	$10,402,980	$6,775,638	$3,627,341
Startup	$834,424	$408,533	$425,891
Overheads	$33,068,487	$21,184,242	$11,834,245
Totals	**$50,118,428**	**$30,377,697**	**$19,740,732**
Percentage of total plant cost	**5.97%**	**3.62%**	**2.35%**
Cost per I/O point	**$5,301**	**$3,213**	**$2,088**

Notes: EPC = engineering, procure, construct; PepC = procure strategic suppliers, engineer, procure balance of plant, construct

Source: JDI Contracts Inc.

7. Due digital. A recent study concluded that outfitting a new power plant with all-digital controls would reduce instrumentation and control construction costs, by slashing outlays for installation labor and materials. Included in the study was a comparison of a typical cable and tray installation (left) with a digital network cable installation (right). *Courtesy: Emerson Process Solutions*

Driving to digital

For customers of St. Louis–based Emerson Process Management, PlantWeb is the blueprint for implementing a comprehensive, digital solution that delivers installed cost and operations savings. A key deliverable of PlantWeb is predictive intelligence—the ability to constantly monitor actual equipment condition and use the information to predict when a problem is likely to occur. This is made possible by the integration of intelligent HART and Foundation Fieldbus instruments—including transmitters, analyzers, and digital valve controllers—equipped with on-board microprocessors.

As an example, significant savings in commissioning costs are possible from going all-digital, according to Al Novak, business development manager for Emerson Process Management's Power & Water Solutions industry center. He explained that an all-digital architecture makes device installation, communications verification, and troubleshooting less labor- and time-intensive. "Technicians don't need to go into the field to manually verify the identity and communication links of every device because the control system automatically senses and addresses the devices as they are connected," he said.

Sustainable results

In addition to reducing engineering, construction, and start-up costs, the digital architecture approach also translates into long-term O&M cost savings due to the efficiencies possible in a highly automated, intelligent plant. For example, the JDI Contracts study indicated that an advanced asset management system can prevent forced outages by detecting and diagnosing potential equipment problems before they occur. The implications of this are significant, because the ability to preclude two forced outages per year would translate into savings of more than $8 million over a 30-year period, according to the study.

Based on the experience of other industries, Novak expects that the electric power industry will realize operational savings resulting from increased plant availability, heat rate improvement, reduced maintenance costs, and other operational efficiencies not included in the study.

According to Novak, the biggest hurdle to early adoption of a multifaceted digital architecture is convincing utility stakeholders that this approach translates into meaningful, measurable results.

"Emerson understands that this is a new concept for the power industry, but the bottom line is that the savings are real and the technology is proven," he said. "Emerson looks forward to helping the developers, architect engineers, owners, and operators who are the stakeholders in new power generation facilities realize the tangible benefits possible from building and operating highly automated, state-of-the-art plants." ■