Modeling Deterioration And Predicting Service Life Of Concrete Cooling Towers

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ABSTRACT

Hyperbolic natural draft cooling towers and other concrete structures can experience various types and degrees of concrete deterioration caused from years of service in industrial operating environments. Concrete erosion, corrosion of embedded reinforcement, and other deterioration mechanisms can introduce operational risks and significantly reduce the integrity of the structure, ultimately leading to the end of service life. To manage cooling tower assets and plan effective maintenance and repair strategies, the expected condition of the tower over time and its remaining service life must be considered. This paper introduces common deterioration mechanisms that affect concrete cooling towers and provides examples of how such mechanisms can be modeled with calibration specific to the subject asset. A framework is presented describing how deterioration predictions can be used to inform estimates of the remaining service life of the structure.

1. INTRODUCTION

Reinforced concrete cooling towers, including natural draft and mechanical draft towers, are process-critical assets at power generation and industrial facilities around the world due to their large cooling capacity. Many of these cooling towers have been in operation for decades in harsh environments arising from cooling water chemistry and other industrial and environmental exposures. Consequently, these towers can experience various forms of concrete deterioration that increase operational hazards and structural performance risks.

Chapter 13 of CTI's Cooling Technology Manual [1] addresses inspection of cooling towers. Section 6 of this document specifically addresses inspection of reinforced concrete members and provides broad guidance for the structural condition assessment of cooling towers with assessment objectives to (i) identify conditions the represent safety and process concerns, (ii) determine root cause of deterioration and damage, and (iii) develop repair/protection recommendations.

Relating to these objectives, this paper identifies deterioration mechanisms that commonly affect concrete cooling towers and describes how the remaining service life of a cooling tower can be estimated using models calibrated to the mechanisms that are present and the specific conditions at the tower.

2. TYPES OF DETERIORATION

Deterioration of concrete is commonly defined based on physical manifestations of material failure or decomposition caused by environmental influences [2]. As such, deterioration is a function of environmental exposure and is typically time dependent. Concrete damage due to the structural response of a tower (e.g., due to settlement, thermal gradients, out-of-shape construction) is not considered in the present discussion, but may also contribute to deterioration of the tower with time. The range of all possible in-situ conditions for cooling towers is impossible to summarize, but deterioration mechanisms that have been most commonly found to impact reinforced concrete cooling towers are described below.

2.1. Corrosion of Embedded Reinforcement

The corrosion of embedded reinforcement results in strength loss due to cracking, delamination, and spalling of concrete, and reduction in the steel area and bond. Concrete has a naturally high pH (approximately 12 to 14) that protects the reinforcing steel from corrosion by the formation of a thin oxide layer that passivates the steel surface. Corrosion of embedded reinforcement can occur when the protective passive layer is disrupted due to the accumulation of chloride ions or a reduction in the pH of the concrete pore solution in the immediate vicinity of the bar.

2.1.1. Chloride-Induced Corrosion

Chloride ions can penetrate and disrupt the protective passive layer on embedded reinforcing steel. Chloride ions may be introduced into reinforced concrete either during mixing (e.g., by using chloride-based admixtures or salt-contaminated mixing water or aggregates) or by diffusion from the environment (e.g., from the cooling water). When the concentration of chloride ions at the surface of the embedded steel reinforcing reaches a critical "threshold" value, localized corrosion can initiate, typically forming pits on the steel's surface. The critical chloride concentration depends upon a number of factors, including the interfacial properties of the steel and concrete, the pH of the pore solution in the concrete, and the electrochemical potential of the steel [3].

2.1.2. pH-Induced Corrosion

A reduction in pH in the concrete around the embedded reinforcement can break down the passive oxide film; a pH below approximately 11.5 has been demonstrated to depassivate carbon steel [4].

The more common cause of pH reduction in concrete is carbonation - a chemical reaction within concrete between the cement paste and the carbon dioxide (CO_2) in the air that consumes calcium hydroxide and lowers the pH of the pore solution.

A less common cause of pH reduction, but relevant to cooling towers and similar applications where concrete can come into contact with soft water, is calcium leaching (also called decalcification, described further below). Calcium hydroxide provides concrete with its naturally high pH but can leach out of the concrete under certain environments. The dissolution and leaching of the calcium hydroxide phase reduces the pH of the concrete, ultimately destabilizing the passive layer on the surface of the reinforcing steel.

2.2. Chemical Attack of Concrete

Chemical attack is a general term that describes the deterioration of concrete by deleterious reactions between concrete and chemical(s) to which it is exposed. Exposure to aggressive chemicals, including acids, bases, and salts, commonly occurs through water, but can also be sourced from flue gases or other airborne exposures. The consequences of chemical attack are varied and depend on the particular chemical to which the concrete is exposed. As examples, exposure to flue gases containing sulfur oxides can contribute to sulfate attack, while exposure to soft water can dissolve calcium from the concrete, resulting in reduced pH and loss of strength over time. These two mechanisms are described in further detail below.

Other common chemicals that may promote chemical attack of concrete structures in general include hydrochloric acid and ammonium nitrate salt, which can rapidly disintegrate concrete; and sodium sulfate, magnesium sulfate, and calcium sulfate salts, which can form expansive reaction products that cause cracking and spalling of the concrete.

2.2.1. Sulfate Attack

Exposure to elevated concentrations of water-soluble sulfate ions may lead to chemical sulfate attack of the concrete [2]. Sulfate attack occurs when dissolved sulfate ions interact with the cement to form gypsum and ettringite. These phases are larger in volume than the reactants from which they form, and consequently their formation exerts additional tensile stresses on the concrete. The stresses caused by these larger reaction products are known to result in expansion, loss of strength, cracking, and spalling of the concrete. In addition, if the source of some of the sulfate ion in the water is sodium sulfate, this can further result in physical sulfate attack of the concrete due to the cyclic formation of hydrated sodium sulfate salt crystals. If the source of some of the sulfate ion in the water is magnesium sulfate, an ion exchange reaction between the magnesium ion and the calcium within the calcium silicate hydrate gel (C-S-H) can cause softening of the concrete.

2.2.2. Calcium Leaching/Decalcification

Calcium leaching, or decalcification, is a chemical deterioration process in which the calcium-containing phases of hardened concrete dissolve and leach out of the material. It is a specific form of chemical attack caused by exposure to soft water or acidic conditions. Calcium-containing phases of primary interest relative to the service life of the reinforced concrete cooling towers include calcium hydroxide, $Ca(OH)_2$, which gives concrete its high pH and protects the reinforcing steel from corrosion, and calcium silicate hydrate gel (C-S-H), which provides concrete with its strength. Decalcification of concrete can be caused by exposure to acidic water (pH less than 7) or exposure to "soft" water with low concentrations of dissolved calcium, evaluated as lime (CaO) concentration less than 20 mg/L (20 ppm).

Severe decalcification of concrete is a multi-stage process illustrated conceptually in Figure 1, which shows the sequence from unaltered concrete on the interior (Zone 0) to the most severely affected concrete on the exterior surface (Zone 4). Each stage must develop to a certain extent before the subsequent stage can initiate. The stage where decalcification begins, Zone 1, involves the dissolution of the calcium hydroxide phase. During this stage, the pH of the concrete pore solution drops, decreasing from about 12.5 to 10 [5]. As the calcium hydroxide in the concrete is depleted in Zone 2, calcium aluminate phases such as ettringite begin to dissolve, and the pH is further reduced. This dissolution process continues until eventually the water begins to dissolve the C-S-H phase (also in Zone 2), leaving behind only the aggregates loosely bound in a silica gel product in Zone 3 [6]. This weak, friable layer can be easily eroded by air and liquid moving over the surface of the concrete, resulting in Zone 4, where the concrete is no longer present.

Decalcification of concrete results in both loss of concrete strength and stiffness and in corrosion of the embedded reinforcing steel due to pH reduction.

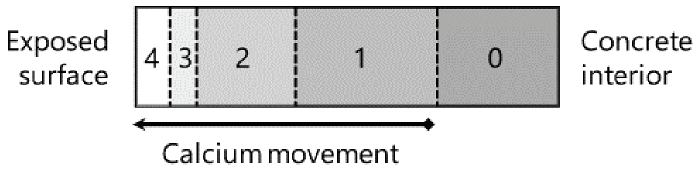

Figure 1. Conceptual illustration of decalcification process. Adapted from [6]. Not to scale.
Zone 0: Unaltered concrete
Zone 1: Calcium hydroxide leaching zone
Zone 2: C-S-H leaching zone (calcium hydroxide depletion)
Zone 3: Fully decalcified zone (C-S-H and calcium hydroxide depletion)
Zone 4: Eroded concrete

2.3. Physical Salt Attack

Physical salt attack is a form of concrete deterioration caused by the crystallization and growth of salts within concrete pores. The most common salts for physical salt attack of concrete include sodium sulfate, sodium carbonate, and sodium chloride. While many of these salts may also participate in other deterioration mechanisms, such as corrosion and chemical attack, physical salt attack represents a distinct deterioration mechanism. No chemical interactions between salts and concrete are required for this mechanism to damage concrete.

The mechanism of physical salt attack involves the precipitation of salts within the concrete. Water containing dissolved salts is first absorbed by the concrete, then evaporation removes the water, leaving the salts behind. As more salty water enters the concrete and then evaporates to the atmosphere, the concentration of salts within the concrete continues to rise. Over time, the concrete becomes supersaturated with these dissolved salts at the evaporation front, until the salts eventually deposit and crystallize within the concrete pores. Tensile stresses generated by the growing crystals can be sufficient to cause surface spalling of concrete, particularly when the concentration of the salts is high, when the pores are small, or when the concrete strength is weak.

2.4. Alkali-Aggregate reactions

The reaction of aggregates with the alkali hydroxides in concrete take the form of either alkali-silica reaction (ASR) or alkali-carbonate reaction (ACR). The more common alkali-silica reaction (ASR) is a chemical reaction between aggregates in the concrete containing reactive silica and alkalis (especially potassium and sodium ions) in the concrete pore solution, in the presence of moisture, to produce an expansive, hygroscopic gel. Expansive pressures are produced when the gel absorbs water and can produce micro-cracking, and eventually macro-cracking, of the concrete. Water can infiltrate into the concrete through these cracks, causing additional gel expansion and possibly accelerating other forms of material deterioration, such as chloride-induced corrosion. Three conditions must be present for deleterious alkali aggregate to occur: (1) a high-alkali pore solution, usually due to the alkali content of portland cement; (2) reactive aggregate; and (3) available moisture.

2.5. Other Mechanisms

2.5.1. Abrasion and Erosion

While many of the mechanisms above result in a loss of concrete section that can be described as erosive in the general sense, abrasion and erosion, by definition, are produced by mechanical contact, exposure to flowing water or particulates, or vapor bubble implosion on exposed surfaces (cavitation) [7]. True mechanical abrasion or erosion of cooling tower shells from drift is unlikely if the surface of the concrete was not first severely weakened through other deterioration mechanisms. However, it is possible for water distribution channels or other supporting elements to experience abrasion and erosion due to bulk water flow.

2.5.2. Freeze-Thaw

Freeze-thaw deterioration occurs due to cyclic volumetric changes of moisture within concrete that occurs as the water freezes and degrades the cement matrix over time. In environments where freeze-thaw risk is anticipated, mitigation is most commonly addressed through the concrete mix design specification; most notably through the addition of air entrainment. In cooling towers, freeze-thaw damage is not expected on tower shells due to operating temperatures and the predominantly vertically oriented surfaces, but such damage is possible, especially on horizontal surfaces in environments of freezing ambient conditions.

3.DETERIORATION MODELING

Understanding the advancement of deterioration mechanisms is crucial for effective cooling tower asset management. Fortunately, rational methods of modeling deterioration can be developed for many of the above-identified mechanisms and provide a quantitative basis for projecting conditions and damage. Two examples are discussed below.

3.1.Corrosion

Assuming environmental exposure that can result in corrosion of the reinforcing steel, due to either chloride exposure or a pH-reducing reaction, corrosion-related damage of concrete at a given location can be conceptualized in two stages: (1) ingress of chlorides or advancement of the pH-change front and subsequent initiation of corrosion at the bar, followed by (2) corrosion propagation, which causes an internal build-up of corrosion product and culminates in the development of delaminations, cracking, and spalling at the concrete surface. This is illustrated conceptually in Figure 2.

In the specific case of chloride-induced corrosion, the corrosion and the subsequent deterioration of the concrete can be modeled based on (1) the transport of chloride ions through the concrete and (2) the corrosion reaction that generates corrosion product on the surface of the reinforcing bar leading to concrete damage.

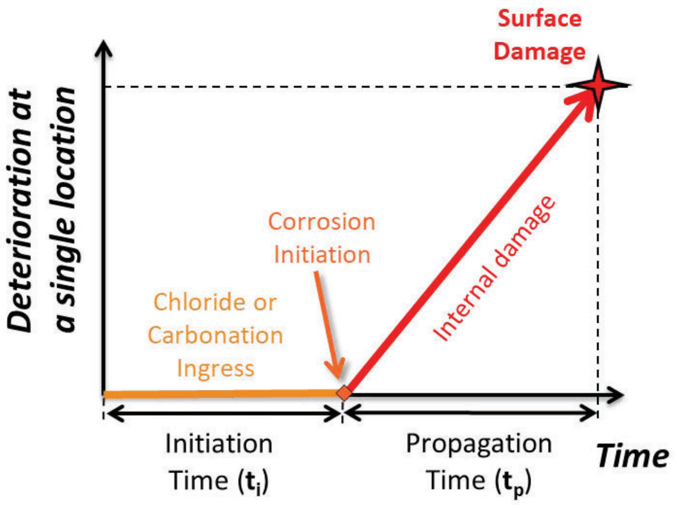

Figure 2. Corrosion sequence (adapted from Tutti, 1982 [8])

3.3.1. Chloride Transport

Chloride-related corrosion initiation is governed by the rate at which chloride ions move through concrete and accumulate at the bar surface. This is determined by the chloride exposure, the resistance of the concrete to chloride ingress, and the concrete cover over the bars. Chloride ion transport in concrete is complex and in cooling tower applications, may occur through a combination of diffusion (caused by chloride ion concentration gradient), capillary absorption (wetting and drying), and permeation (driven by pressure gradients) [9]. Chloride transport may also be slowed by chemical binding of chlorides with aluminate phases in the cement, or by physical absorption or trapping of chloride ions in the cement paste microstructure. Despite the potential complexity of the chloride penetration process in concrete, diffusion typically plays the largest role.

Diffusion of chlorides over time due to a concentration gradient can be described as a function of exposure (surface chloride concentration) and concrete chloride penetration resistance (diffusion coefficient). To develop inputs for a model of chloride diffusion on an existing tower, it is common to measure the concentration of chloride ions versus depth at multiple coring locations to generate chloride profiles like those shown in Figure 3a. In this example, the illustrated profiles were obtained from full-thickness cores sampled on a cooling tower shell, where chloride exposure was present on both shell faces. The two profiles represent data collected from a core sampled in

2006 and a second core sampled in 2013 immediately adjacent to the 2006 location. The progression of measured chlorides over the 7-year timeframe can be seen in the curves fit to the data.

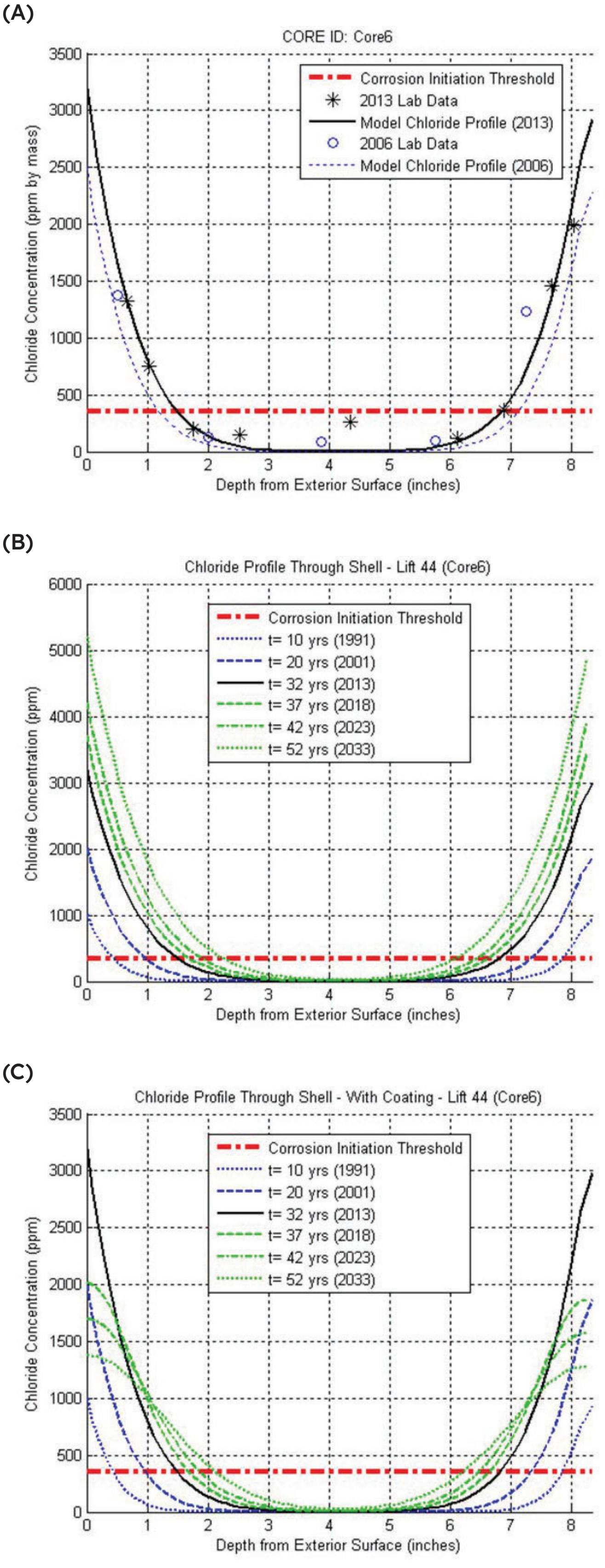

Figure 3. Chloride diffusion modeling from single location of a cooling tower shell. (a) as-measured chloride profiles (b) model-projected chloride profiles (c) model-projected chloride profiles with barrier coating installed in 2013.

Based on the known age of the structure at the time of core sampling and the history of chloride exposures at the site, a chloride diffusion model can be developed that can then be used to project the chloride profiles at this location at other times (Figure 3b). The chloride transport models can also be modified to account for various repair or maintenance interventions, which may alter future chloride exposures and/or the rate at which chlorides advance through the concrete. Figure 3c shows the projected chloride profiles at the same location assuming a barrier coating was installed at both faces in 2013, effectively eliminating additional buildup and ingress of surface chlorides. This case illustrates that despite the barrier coating, chloride concentrations will continue to increase at depths beyond approximately 1 inch from each surface due to diffusion of the chlorides already present in the shell. Given infinite time and idealized effectiveness of the barrier coating, the chloride profile would equilibrate to a uniform value over the thickness of the shell.

3.1.2. Corrosion Initiation

Note that in the above example, a single corrosion initiation threshold value of 350 parts per million by mass of concrete (0.035 percent) is shown. This value is converted from 0.2 percent weight of cement, which can be considered a lower bound of the threshold for corrosion initiation for uncoated, mild carbon reinforcing steel. However, a statistical distribution of corrosion initiation risk is a more comprehensive representation of corrosion initiation probability, shown in Table 1 and Figure 4.

Table 1. Chloride Concentrations for Assumed Risk Categories: Corrosion Initiation of Uncoated Reinforcing Steel[1]

		Chloride Content	
Risk Category [2]	**Probability of Corrosion**	**% by Weight Cement**	**% by Weight Concrete[3]**
Negligible	< 1%	< 0.2	< 0.03
Low	1-10%	0.2 to 0.3	0.03 to 0.04
Moderate	10-50%	0.3 to 0.5	0.04 to 0.07
High	50-90%	0.5 to 0.7	0.07 to 0.10
Very High	>90%	> 0.7	> 0.10

[1] Adapted from (Broomfield 2007 [4]), based on data from (Breit 1997 [10])

[2] Corrosion "Risk" expressed here is based on assumed percentile values in a cumulative probability distribution of critical chloride threshold.

[3] Conversion assumes normal weight concrete with 335 kg cement

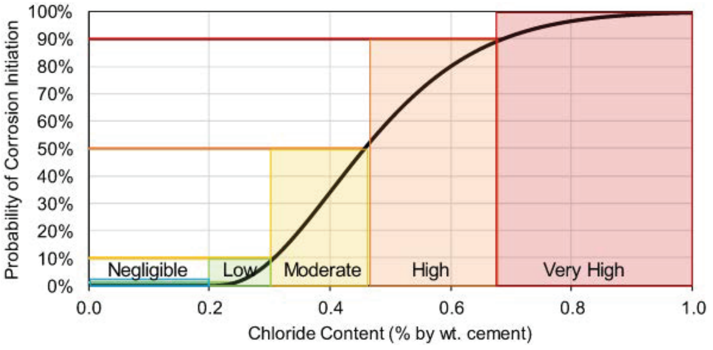

Figure 4. Cumulative probability density of chloride threshold with corrosion risk for the cases illustrated in Table 1.

Directly interpreting measured and projected chloride concentrations at various locations around the cooling tower structure is a valuable end in itself and informs an understanding of the risk of corrosion initiation in the structure. However, estimates of damage over the structure can also be explicitly modeled and projected forward with time through probabilistic modeling of the full corrosion sequence.

3.1.3. Probabilistic Approach to Deterioration Modeling

While the prior two sections discuss the corrosion process as it occurs at a single location, in damage models developed and employed by the authors, a probabilistic approach is based on statistical distributions of key parameters (Figure 5). The model recognizes the fact that corrosion is a local process that progresses simultaneously at multiple locations over time depending on the local propensity for corrosion. For example, corrosion can be expected to initiate more readily at locations where cover is low, where the ability of the concrete to resist chloride ingress or carbonation is low, and where the chloride exposure is high. Corrosion will then advance over time to areas where the concrete element is progressively less susceptible to corrosion.

Statistical distributions are used to describe the spatial variation of the corrosion-controlling parameters over an element's surface. Because of the complexity of the probabilistic analysis and because it is well suited to the consideration of distributions based on empirical field data, a Monte Carlo simulation is used to consider the interaction between the considered variables. Based on this interaction, the probabilistic model evaluates the progression in initiation and subsequent damage at individual locations and reports an estimate of surface area damaged over time (Figure 5).

While the above discussion has focused on chloride-driven corrosion modeling, the probabilistic approach is applicable to and has been used to model deterioration associated with other mechanisms.

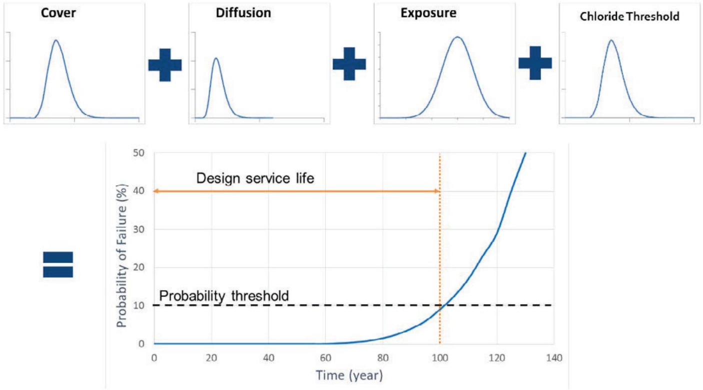

Figure 5 . Conceptual representation of probabilistic modeling approach.

3.2. Decalcification/Leaching

In addition to chloride diffusion and damage, rational models can also be developed for predicting the advancement of other deterioration mechanisms for cooling tower projects. One such example is a model for the decalcification mechanism described in Section 2.3. Modeling of this phenomenon was developed by the authors for a particular cooling tower asset based on the observed condition of the structure, specifically the depths of the various deterioration zones illustrated in Figure 1 identified by laboratory petrographic studies performed on cores. These observations formed the basis of what the authors describe as a "scientist" model – that is, a scientific description of the extent of the deterioration occurring within the cooling tower shell. Like the ingress of chloride ions to initiate corrosion and subsequent corrosion-related damage to concrete, the decalcification-associated deterioration phenomena identified by the "scientist" model needed to be translated into an "engineer" model that relates the deterioration to its impact on the strength or durability of the structure. This translation from the "scientist" model to the "engineer" model (Figure 6) facilitates projecting advancing deterioration in terms that support formulation of remaining life estimates (discussed in Section 4, below). The "scientific" zones of paste erosion and C-S-H depletion are translated to a single "loss front" over which the concrete is considered to have no strength or stiffness; the two "scientific" zones identified petrographically as secondary calcite deposition are modeled as a single zone of reduced pH and increasing strength and stiffness marked by an advancing "pH-change front"; and the zone of unaltered paste remained as an unaltered region of concrete that maintained its original strength and stiffness. Thus, the model is reduced to considering two advancing fronts: the loss front and the pH-change front.

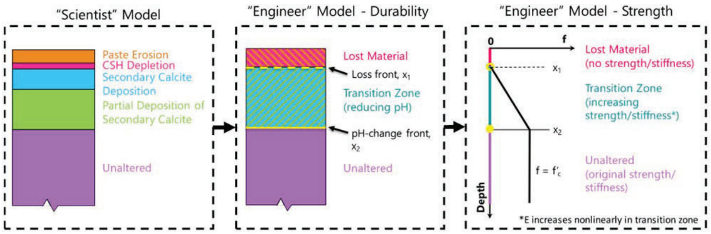

Figure 6. Conceptual illustrations of decalcification mechanisms as measured from the surface of the tower shell.: "Scientist Model" based on laboratory findings and associated "Engineer Model" based on interpretation of the laboratory findings

In modeling the advancement of deterioration, the "loss front" was considered to initiate after the concrete has leached sufficient calcium to deplete the concrete of C-S-H and was modeled as advancing at a constant rate with time. Advancement of the "pH-change front" was considered to be governed by diffusion though the transition zone concrete and was therefore modeled as a function of the square-root of time, which is a common function to assume for the movement of a boundary of a diffusion-driven process (a similar approach is often taken for modeling of carbonation depth with time, for example [11]). The advancement of the pH-change front was coupled with the advancement of the loss front so that as the surface eroded, the rate of further advancement of the pH-change front was increased based on the reduction of material remaining within the transition zone. Figure 7 illustrates an example of projecting these fronts with time for a single location on the cooling tower asset; in this figure, the shapes of the curves are calibrated to the measured depths taken 41 years after the cooling tower was constructed and placed into service and the current condition is indicated as the circular data point on each curve. Like chloride diffusion, the projection of the pH-change front serves as an input into probabilistic modeling that can predict corrosion damage. The projections of section loss characterize conditions that directly influence the tower's structural performance and can be used as inputs into associated structural analyses (described below).

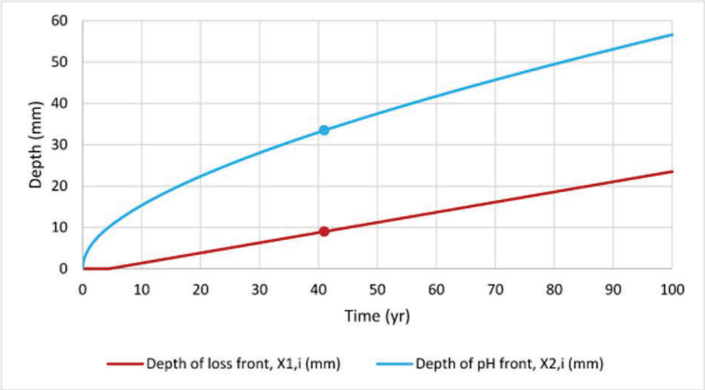

Figure 7. Progression of loss and pH-change fronts for interior face of example location of a 41-year-old structure with a measured loss front depth (circular point) of 9 mm and a pH-change front depth of 33.5 mm.

3.3.General Considerations

To accurately and meaningfully model projections of tower conditions, it is essential that the data that forms the basis for the models be relevant and representative of the subject asset. Models are calibrated to the conditions of the structure, and account for both "deterioration-driving" (e.g., environmental exposure) and "deterioration-resisting" (e.g., cover, concrete diffusion) factors. As such, effective field assessments and laboratory studies that comprehensively characterize these factors specific to the structure are essential.

4.SERVICE LIFE ESTIMATES

4.1.Overall Approach

Modeling techniques, like those described above, can serve to inform the remaining service life of in-service cooling tower assets and provide a rational basis for asset management decision making. Over the tower's life, deterioration causes it to deviate from its original condition, reducing reliability (i.e., an increase in risk) relative to original construction. Assessing when such deviations represent intolerable risk requires establishing limit states that define the end of the service life of the tower. The definition of intolerable risk generally must consider multiple types of risk and varies depending on owner risk tolerance and asset-specific objectives. Applicable limit states may consider structural reliability (e.g., strength and stability), operational hazards (e.g., risk of falling objects), and other owner priorities. Accurately modeling deterioration conditions over time provides a basis for evaluating the timing of when such end-of-life limit states are violated.

Figure 8 conceptualizes how the various contributions of assessment and analysis interrelate. Central to the approach is engineering interpretation, which relies on expertise and experience. This presented framework is consistent with that described by Section 13.6 of CTI's Cooling Technology Manual [1], which recognizes the need for the condition assessment to be conducted by a forensic structural engineer familiar with cooling tower operations.

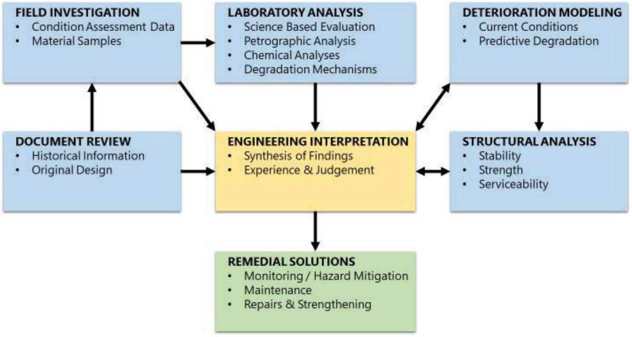

Figure 8. Interrelation of a comprehensive cooling tower assessment.

4.2. Application to Remediation Strategies

Selection of remedial actions to target a desired service life of the tower can utilize quantitative service life assessments through the following rational approach:

1. Identify when end-of-life limit states are violated.
2. Select an intervention action to address the earliest occurring limit state violation.
3. Reevaluate the next occurring limit state violation.
    a. This can be either a different limit state not addressed by the previously selected intervention action or can be a recurrence of a previously violated limit state based on the effectiveness or maintenance interval of a previously selected intervention action.
4. Select the next intervention action. This may be a repetition of the prior action if the durability of the action is less than the desired service life.
5. Repeat steps 3 and 4 until the next occurring limit state violation occurs after the target end of service life.

The combination of the selected intervention actions forms the overall remediation strategy. Note that the same target service life can be achieved through different remediation strategies.

4.3.Limitations

Due to the massive size and continual operation of most reinforced concrete cooling towers, the data solicited through field assessment and laboratory testing are frequently limited by access and typically represent only a small percentage of the total structure. Further, the data tend to have appreciable variability that reflects both the variable conditions of in-situ reinforced concrete as well as the error inherent to the available methods of measurement. In light of unavoidable sources of error, well-judged assumptions are necessary to quantitatively assess the remaining life of a structure, and such estimates require appropriate judgement in their application to decision making.

5. CLOSING

Reinforced concrete cooling towers are process-critical assets at power generation and industrial facilities around the world due to their large cooling capacity. While many of these assets are aging and in various stages of deterioration, assessment methods are available to identify, characterize, and predict the advancement of deterioration mechanisms that degrade towers over time. The accuracy of such predictions is dependent on how representative the available field and laboratory data is of the true tower conditions. However, if supported by the experience of forensic structural and materials engineers, these methods can provide rational, quantitative information to facilitate effective cooling tower asset management.

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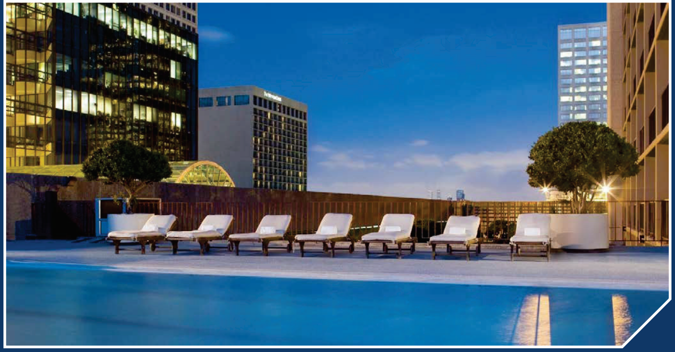

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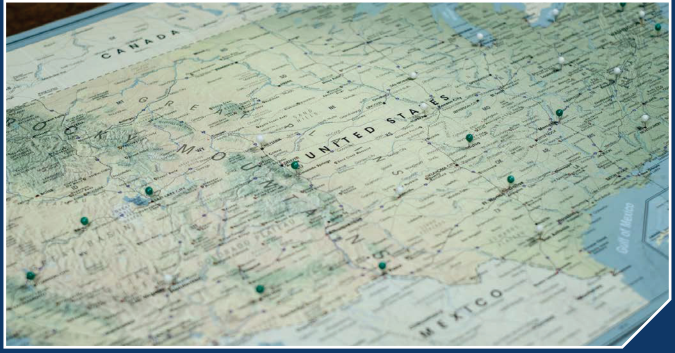

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