

From Red Water to Pump Failures— Corrosion Control Activities & Related Studies

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The Tampa Water Department operates a surface water treatment system that utilizes standard and Actiflo coagulation/sedimentation processes to reduce color and total organic carbon (TOC), ozonation for oxidation and primary disinfection, biological enhanced filtration, followed by chlorine/chloramine for secondary disinfection. The raw-water source is a reservoir on the Hillsborough River adjacent to the plant.

The water department experienced a high “red water” complaint episode during the drought conditions leading up to 2000. The lack of rainfall in the Hillsborough River watershed required the supplementation of the source of raw water. Sulphur Springs, a groundwater source, was used to maintain a minimum river flow volume. The groundwater source, however, contained high total dissolved solids (TDS) in the form of calcium hardness and chlorides, and it raised the TDS concentrations of the reservoir source (see Figure 1)

The higher calcium hardness in the blended raw water required operations to adjust the plant’s process chemistry to prevent precipitation of calcium on the equipment. These changes were reflected in the finished water chemistry altering the tuberculation/corrosion layer in the matrix of distribution system piping. Staff believed that this change caused a release of iron and turbidity in the distribution system creating over 10-fold jump in “red water” complaints by customers from 60 per month to over 800 per month (note rise in Figure 2 below).

As a result of that episode, the water department undertook a series of studies to eliminate the problem of “red water” generated within the distribution system that could result during changes in the raw-water supply. The first study¹ was conducted to identify the source and fix the “red water” problem prior to the city of Tampa hosting the NFL Super Bowl in January 2001.

Because of the need to resolve the problem in a short period of time, the city’s con-

Continued on next page

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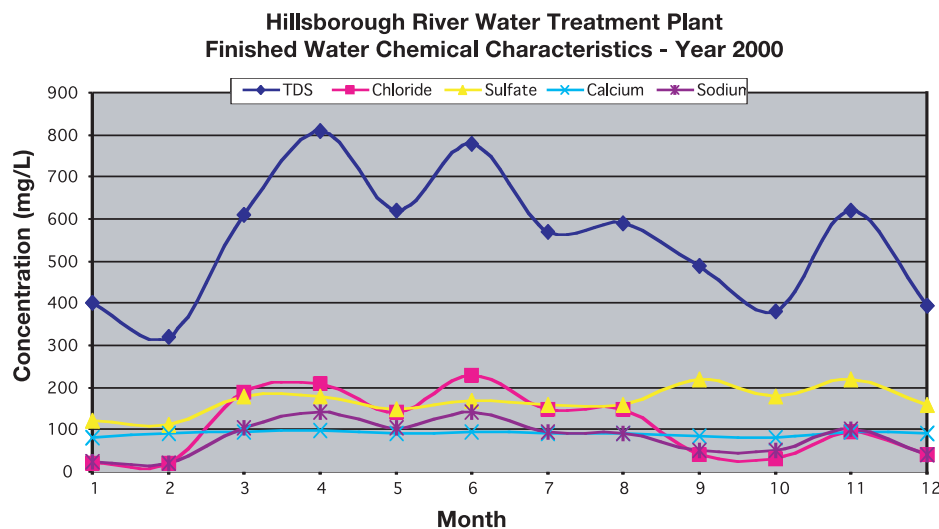


Figure 1: TWD Finished Water – 2000

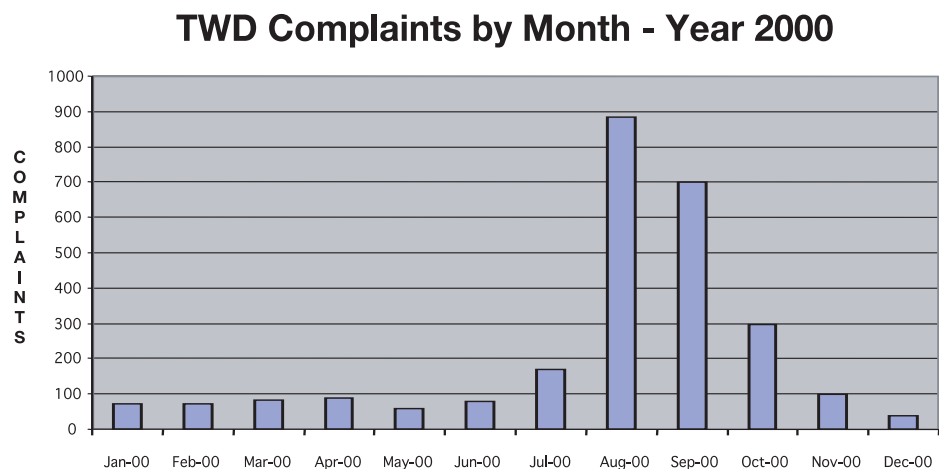


Figure 2: Combined Complaints to Tampa Water Department

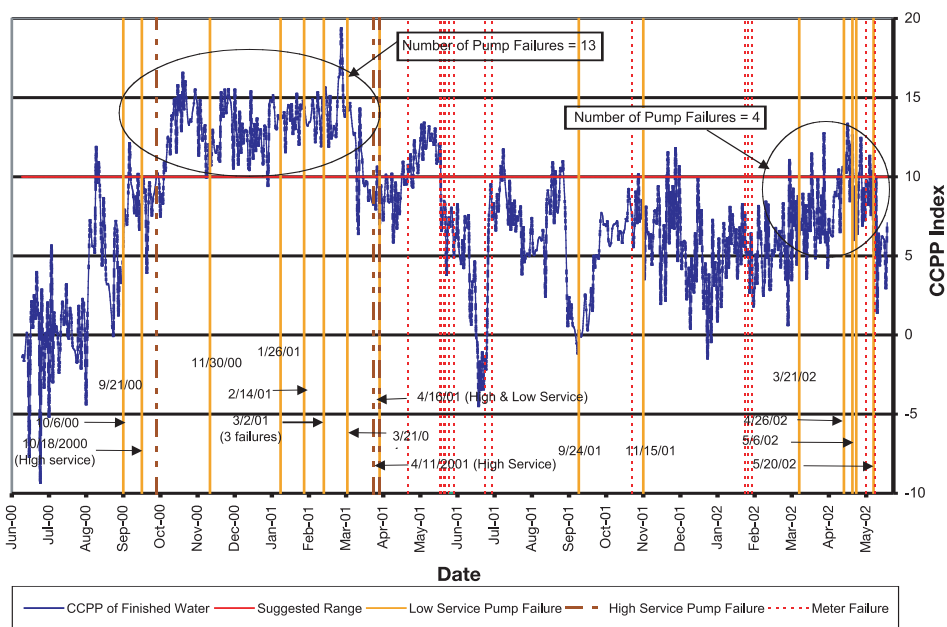


FIGURE 3: CCPP Versus Time

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sultant utilized test equipment and the approach from a successful Tucson, Arizona, project with similar issues to expedite the study. The study was aimed at what change was responsible for the stability of the protective layer in the distribution system, and how to provide protection from corrosion byproducts when these changes in conditions occur.

A panel of experts evaluated the study data and determined that the river's wide variation in TDS had caused the release of iron and turbidity from the water distribution system pipes. The panel recommended that the pH be raised in a step-wise manner to 8.0 in the finished water. Using that approach created a monthly reduction back to the normal levels of "red water" complaints.

Adjusting the pH upward potentially creates the opportunity for calcium carbonate to precipitate on the pipe and the equipment which the water contacts. Langelier Saturation Index (LSI) has been the long-standing index for scale formation. More recently the Calcium Carbonate Precipitation Potential (CCPP) has been used to monitor the precipitated coating in a number of water distribution systems.

The Rothberg, Tamburini & Winsor (RTW) "Model for Corrosion Control and Process Chemistry" allowed the staff to perform a simple CCPP calculation and adjust the pH based on the predicted potential impact TDS and pH changes have on the potential for calcium carbonate precipitation. The first study's panel recommended that the facility's finished water be kept between the normal CCPP range of 4 and 10 mg/L, wherein a mild deposit of calcium carbonate will form on the surface of the pipes.

The Tampa Water Department utilized a process of coagulation/sedimentation for color/TOC reduction and filtration as the primary treatment process during the first study. To maintain the CCPP in the finished water, the department successfully adjusted the pH after the sedimentation process by chemical addition (mainly lime and sodium hydroxide), based on a daily calculation performed with the RTW model. Process pH conditions were modified to target the end CCPP of 4 to 10 mg/L.

While using this range of CCPP to reduce iron and turbidity release in the sys-

tem, the staff observed a number of episodes in which the CCPP moved above 10 mg/L to as high as 15 mg/L, (shown in Figure 3). The "red water" problems, however, were resolved by the pH correction and the cessation of use of the Sulphur Springs water source.

Nevertheless, the staff observed pump problems with the pH correction program. During this period, a number of pump failures, including high-service pump and service meter failures occurred due to the rapid precipitation of calcium carbonate in the pump bowls.

In response to the failures, a third study² resulted in lowering the recommended level of CCPP for operational control to a range of 3 to 7 mg/L. To accomplish that goal, it was recommended that the finished-water pH be maintained between 7.5 and 8.5 with the use of lime and caustic soda.

A rather elaborate control scheme was devised in table format to give the operators a guide for which chemicals to dose, based on desired CCPP and water quality conditions. It was also recommended that distribution system CCPP be monitored (see Figure 4) and that a program of coupon monitoring be started.

During the course of the problem definition and solution of the first study, the staff determined that a planned-approach second study³ be conducted to evaluate corrosion inhibitors such as blended orthophosphate/polyphosphate and stannous chloride. The water department was constructing an ozone treatment unit for water disinfection after the coagulation/sedimentation units; therefore,

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Calcium Carbonate Precipitation Potential

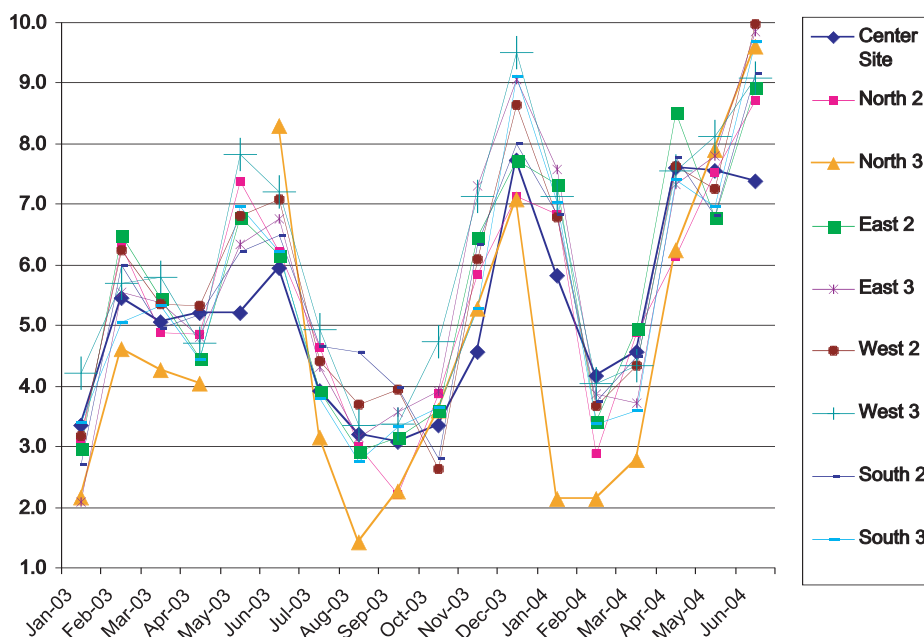


FIGURE 4: System-wide CCPP Monitoring Performed by TWD's Lab

Continued from page 43

the second study would also evaluate the impact that high dissolved-oxygen levels produced by the ozonation process had on corrosion control and iron/turbidity release in the distribution system.

A pipe-loop bench test system was established using sampled sections of the city's water distribution piping. A total of 14 pipe loops were tested in the second study. The test results of this study indicated that higher levels of dissolved oxygen had a minor impact on the level of soluble iron and turbidity found in the pipe loops. It was concluded that the new ozonation process, therefore, should not contribute to any new "red water" complaints by customers.

A second part of the study investigated the use of blended orthophosphate/polyphosphate and stannous chloride as corrosion inhibitors. The compounds tested showed no substantial impact on soluble iron and turbidity. It was found that color was reduced by a slight amount in the pipe loop test conditions.

A continued rise in water losses has led the water department to enter into a fourth study⁴. Venturi meters located inside the plant boundary and service meters outside the plant boundary have been found to contain coatings, indicative of calcium carbonate precipitation. The service meters have been replaced several times in some instances during routine meter testing. A water-loss evaluation for leakage also has been conducted.

For the water-loss evaluation, Boyle and the water department determined that there is probable cause with scale coatings on the meters to account for the type of water-loss trends the department was observing, namely up to 15 percent and increasing; consequently, better ways to control scale, yet provide the positive benefits of controlling the pH to get a protective scale coating, were sought. Another study objective was to determine the more sensitive control parameter, if possible, for the pH correction program.

The continuing deposition of scale in an area surrounding the plant has raised the question of lowering the CCPP again to eliminate this scale formation. Also, an enhanced approach to the complex CCPP control table was desired; therefore, the latest study examined the facility operating data and the department's flow meter studies and developed computerized modeling/planning tools.

The computerized tools utilize Visual Basic for Applications (VBA) within an MS Access database to automate the determination of CCPP on a large set of data and to tie the calculations to the facility's Supervisory Control and Data Acquisition (SCADA) data tables for input to the tools.

The current approach through modeling and continuing operational data collection is to reduce the CCPP to a range of 2-5 mg/L, maintain a tighter deadband on either side of the range, and optimize chemical costs. The refinement of the CCPP control and facility monitoring of operational and corrosion conditions will provide the water department with the tools needed to reduce customer complaints and increase longevity of the distribution system and service metering components from both corrosion and excessive scale formation.

The water department has requested as part of the fourth study that a review of monitoring parameters and hardness loading be evaluated to determine if CCPP is the appropriate tool in process control of corrosion for the facility. To that end, the following portion of this paper looks at CCPP to determine what it is, how it is used at the Tampa Water Department, and what limitations it presents in providing corrosion control.

History of Development of Calcium Carbonate Precipitation Potential (CCPP)

Calcium Carbonate Precipitation Potential is an indication of the potential quantity of calcium carbonate (CaCO_3) to precipitate from oversaturated waters or dissolve in undersaturated waters. The concept for CCPP is borne from the work of W.F. Langelier in 1936 in what is modernly referred to as the Saturation Index (S.I.), or Langelier Saturation Index (LSI), originally devised as an indication of the driving force behind CaCO_3 precipitation or dissolution.⁵

Due to interest in the use of the Saturation Index, Langelier sought to standardize the S.I. by his introduction of stability diagrams.⁶ Langelier's stability diagrams provided a graphical way to assess equilibrium conditions, namely, to determine the S.I.; however, for determination of the quantity of chemical to use in water treatment, the stability diagrams proved time-consuming to use.

In the 1950s D.H. Caldwell and W.B. Lawrence, using Langelier's stability diagrams as a basis, developed the Water Conditioning Diagram, now known as Caldwell-Lawrence diagrams (C-L diagrams).⁷ C-L diagrams provided equilibrium concentrations of calcium, magnesium, total alkalinity, and pH as related to the dosage of common treatment chemicals.

In 1976, D.T. Merrill first described oversaturation of CaCO_3 as the CaCO_3 precipitation potential.⁸ In 1977 and 1978, in a three-part series, D.T. Merrill and R.L. Sanks proposed methods for solving water-conditioning problems and graphically determining CaCO_3 precipitation potential through use

of C-L diagrams.⁹⁻¹¹

In 1983 J.R. Rossum and D.T. Merrill published an analytical procedure to generate CCPP, thus providing a straightforward basis to derive CCPP through computer analysis.¹² Presently there are several mentions of computer programs that evaluate CCPP in literature on the subject.¹²⁻¹⁵

Determination of Calcium Carbonate Precipitation Potential

As outlined by the historical development, CCPP was not derived in one landmark article; rather, it evolved from several different sources over a period of 40 years. Similarly, the computation of CCPP is not provided by one equation or set of equations; rather, calculating CCPP depends upon establishing chemical equilibrium for a particular water, which is an iterative process.

Analytically, there are several methods available to converge to chemical equilibrium conditions, and the simplicity or complexity of the method depends upon the underlying assumptions about the water subject to analysis. For treatment waters sent to the distribution system, some typical assumptions include:

- ◆ There are not significant amounts of ions such as Mg and SO_4 present.
- ◆ Calcium is inorganic.
- ◆ Complex ion formation such as $(\text{CaOH})^+$, $(\text{MgHCO}_3)^+$ and $(\text{CaHCO}_3)^+$ is limited.
- ◆ Temperature remains relatively constant.
- ◆ The water's exposure to the atmosphere does not occur.

These reasonable assumptions allow for chemical equilibrium calculation without significant error and, therefore, reliable CCPP calculation. One method for calculating the CCPP value is given by J.R. Rossum and D.T. Merrill:¹²

$$\text{CCPP} = 50000(\text{Alk}_i - \text{Alk}_{\text{eq}}) \quad (1)$$

where:

Alk_i = initial, or pre-equilibrium alkalinity
 Alk_{eq} = equilibrium alkalinity

The Rossum and Merrill derivation of CCPP is based upon the correlation that equivalents of calcium precipitated equal to the equivalents of alkalinity precipitated.^{12,16} Alk_i is usually determined by measurement and may correspond to a condition of over- or undersaturation of CaCO_3 . Alk_{eq} is provided by the chemical equilibrium calculation for the analyzed water. The multiplier of 50,000 is particular to the Rossum and Merrill method of solving for chemical equilibrium.

Regardless of the method employed to resolve chemical equilibrium, correct CCPP

determination results in a quantitative measure of the potential for a water to precipitate or dissolve CaCO₃.

CCPP Compared to Langelier Saturation Index

Due to the still-popular use of the Langelier Saturation Index (LSI) as a corrosion-control index, a brief comparison between LSI and CCPP seems appropriate. The primary difference between LSI and CCPP is that LSI indicates a tendency to either precipitate or dissolve CaCO₃, whereas CCPP indicates the tendency and quantity of CaCO₃ dissolution or precipitation.

Although LSI has undergone several corrections over the years to improve accuracy, CCPP, which better incorporates chemical equilibrium, provides a more accurate picture of CaCO₃ over- or undersaturation. Also, it has been noted that CCPP has more of a direct relation to the reaction kinetics involved in CaCO₃ crystal growth than does LSI or other CaCO₃ saturation indexes.¹²

While LSI has the advantage of being more computationally direct than CCPP, computer techniques have allowed for CCPP calculation to be performed with the same ease as calculating LSI; therefore, when considering the CaCO₃ saturation state or the capacity to dissolve or precipitate, it no

longer seems necessary to refer to LSI where CCPP is available. Although CCPP is preferable to LSI, it does have some limitations that need to be clearly understood.

Limitations in the Use of CCPP in Corrosion Control

CCPP is an accurate, versatile measure of the potential for a water to deposit or dissolve CaCO₃; however, it was never intended to serve directly as a corrosion index.¹⁷ Although deposition of a protective film of CaCO₃ has been thought to provide a sound method of corrosion control since the early 1900s, research shows that CaCO₃ saturation indexes may fail to indicate ability to control corrosion.¹⁷⁻¹⁸

The effectiveness of CCPP as a control parameter must be considered within the context of other water-quality parameters, as well as the overall distribution system. For example, it has been suggested that alkalinity and buffering capacity may be useful additional water-quality control parameters in corrosion control.

It is important to consider that the CCPP value indicates the *potential* for CaCO₃ to precipitate or dissolve; however, the CCPP value alone does not provide an indication *when* or *where* precipitation or dissolution occurs. The historical analysis of the Tampa

Water Department facility operation shows that as the CCPP control parameter was adjusted, areas where excessive scaling occurred also changed.

Although analytical techniques exist to evaluate the CaCO₃ precipitation and dissolution reaction kinetics, such analytical techniques presently fail to accurately predict CaCO₃ deposition and dissolution within an entire distribution system. Since accurate location of CaCO₃ precipitation formation is not clearly understood, it must be noted that the distribution system water characteristics may fall within the interim (pre-equilibrium) and final (at equilibrium) water characteristics predicted by modeling tools.

Also, CCPP may indicate the *quantity* of CaCO₃ deposited, but it does not indicate the *quality* of the CaCO₃ film deposited on the pipe and therefore the ability for the CaCO₃ film to provide protection against corrosion. The CaCO₃ film may not achieve the required density, uniformity, or adherence to the pipe. Several factors may influence the quality of the CaCO₃ coating on a pipe wall: pH¹⁹, biological activity, pipe material, dissolved oxygen, water velocity, and others.

J.E. Singley summarizes a reasonable approach to corrosion control through CaCO₃ precipitation protection:

Continued on page 46

Temp. °C	Raw Water pH	TDS	Alkalinity	Calcium	Chemical / Dosage (mg/L)	Final pH	CCPP
27	6.67	410	53	59	Quicklime / 18.00	8.10	24.25
27	6.67	410	53	59	Caustic Soda / 17.00	8.10	2.40
27	6.67	410	53	59	Soda Ash / 59.00	8.10	15.55

TABLE 1: Constant pH Versus CCPP

Continued from page 45

“The method of controlling the type and effectiveness of the coating is quite site-specific and must be correlated with and supplemented by continuous surveillance of the system.”¹⁶

From the consideration of the limitations of the CCPP index for corrosion control, CCPP alone is not the only solution to proper protection of the distribution system against corrosion.

Utilization of CCPP as Corrosion Control Index

Although CCPP should not be the sole corrosion-control criteria, CCPP, when used in conjunction with other control parameters, is a valuable control index. Furthermore, in the case of the Tampa Water Department, the value of CCPP for maintenance of the protective CaCO₃ coating is underscored through correlation with historical distribution system performance.

The historical record demonstrates that effective utilization of CaCO₃ protection for corrosion control depends on: 1) establishing the proper treatment plant finished water CCPP ranges, and 2) implementing an effective CCPP control mechanism. These points will be discussed in further detail in the following sections.

Establishing the Operational Finished-Water CCPP Ranges

Naturally, as part of establishing a corrosion-control strategy through using CaCO₃ passivation, it is first necessary to answer the question of how much CaCO₃ precipitation is appropriate for a given distribution system. Since the inception of the Langelier Index, the conventional wisdom has been to maintain CaCO₃ in a slightly oversaturated state. With the introduction of CCPP, the range of 4-10 mg/L has been considered desirable;

however, when the operating range for finished water CCPP was established at the 4-10 mg/L range, failures of the high-service pumps were experienced due to excessive CaCO₃ scaling.²

Subsequently, the operating CCPP range was adjusted to 3-7 mg/L, with an ideal target set at 5 mg/L.² With the CCPP range of 3-7 mg/L, the excessive scaling seemed to “move away” from the plant and increase in the distribution system, i.e. in residential meter inaccuracies.²

As discussed previously, the “right” CCPP range will not be the same for all systems. Arriving upon the optimal CCPP range, therefore, is best decided through correlation with distribution system performance; hence, the adjusted CCPP range of 2-5 mg/L is believed to offer the necessary balance between pipe corrosion and excessive CaCO₃ deposit.

Although the CCPP range adjustment recommendation clearly benefits from the historical data, additional considerations also suggest the new CCPP range. First, the lower operational boundary of 2 mg/L is considered reasonable because it maintains the desired oversaturation of CaCO₃. Theoretically, a CCPP value that is slightly greater than zero would be close to the CaCO₃ saturation at equilibrium and therefore desirable.^{11,20}

An operational lower limit less than 2 mg/L, however, could lead to occasions on which the water leaves the plant dissolving CaCO₃ scale, disrupting the protective CaCO₃ coating, which could lead to another red-water episode; therefore, 2 mg/L provides a reasonable factor of safety against weakening the CaCO₃ protective coating, yet remains close to the CaCO₃ equilibrium saturation.

Second, the 2-5 mg/L range was established by answering the question, “How tight a CCPP control range can reasonably be required and maintained?” Fortunately, the David Tippin Water Treatment Plant treatment processes favor control over the fin-

ished-water CCPP.

The treated water pH is typically between a range of 6.5-7 SU following ozonation and prior to filtration. As a result, it is always necessary to raise the pH (and hence, CCPP) post-ozonation and prior to discharge into the distribution system.

The increase to pH is usually accomplished by treatment with Ca(OH)₂ (slaked lime) or NaOH (caustic soda); therefore, to achieve the desirable CCPP, the appropriate amounts of lime and/or caustic must be added. With proper plant monitoring mechanisms in place and rapid water-quality analysis, it may be possible to maintain a smaller spread in CCPP operating parameters; however, a CCPP range spread or “window” less than 3 mg/L can not be justified at this point. From a safe lower limit of 2 mg/L and a control range spread of 3 mg/L, the suggested CCPP operating range is arrived at: 2-5 mg/L.

Implementing an Effective CCPP Control Mechanism

With the operational CCPP range established, it is critical that the appropriate control mechanism is in place at the plant to achieve the desired finished-water condition; therefore, as discussed previously, a computer program was developed in this phase as a tool to aid in finished-water CCPP control and scenario planning.

A brief description of the control mechanism in place during the past three studies the water department conducted is appropriate. CCPP was calculated with the RTW Model utilizing the average calcium hardness, average alkalinity, and average pH from the previous day’s finished-water data. The total dissolved solids (TDS) values were obtained from the laboratory analysis of the current day’s raw water, usually sampled from 8 a.m.-10 a.m. Temperature used in the CCPP calculation was from the previous day’s raw-water data. Based on the resultant CCPP value, a pH window was then established for post-ozonation pH control.

Part of the accuracy of the previous control method is based on water quality essentially remaining the same from day to day. Examination of the David Tippin Water Treatment Plant monthly operation reports (MORs) support the assumption that the finished-water characteristics do not vary greatly from day to day; however, CCPP control would be improved if analysis were based on data collected from the most current water to receive treatment.

Also, using a pH range or window to control CCPP also poses some difficulties in CCPP control. Generally, as pH is decreased, the precipitation potential of

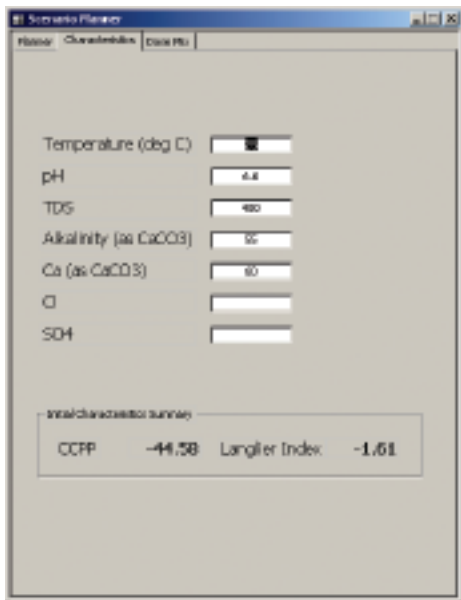


Figure 5: Water Characteristics Input Window for CCPP Scenario Planner Tool



Figure 6: CCPP and pH Input Parameter Window with Two Dose Recommendations

CaCO₃ decreases; inversely, the CCPP is increased as pH is increased. Depending on the treatment chemical selected, however, change in pH does not equally affect change in CCPP. To illustrate, consider Table 1 above using actual David Tippin Water Treatment Plant raw water (TDS assigned) for initial water data:

As shown above, achieving a pH goal may produce a variety of different outcomes for CCPP, depending on the treatment chemicals selected; therefore, CCPP control is best achieved by considering treatment alternatives against outcome on CCPP while satisfying pH criteria. With SCADA-based input data, the scenario planning tool developed in this study is aimed at generating viable treatment alternatives that meet CCPP finished-water goals while economically utilizing treatment chemicals.

The method to converge to chemical equilibrium was developed for use within VBA-based algorithms. The tool developed this phase also has additional features useful for the Tampa Water Department's purposes, but they are not outlined here.

The scenario/planning tool developed in this study is generally based on the method established by Rossum and Merrill¹² described earlier, and the results have verified against the RTW Model. The tool allows the operator to input water characteristics (either manually or from the SCADA data tables) (see Figure 5), input CCPP and pH parameters, and quickly evaluate treatment alternatives (see Figure 6).

The tool also allows the operator to consider chemical mixture alternatives with the

"Dose Mix" feature of the tool (see Figure 7).

Although the tool discussed here provides a direct and simple way for an operator to evaluate treatment alternatives, limitations in maintaining the suggested CCPP range due to raw-water conditions will still present challenges in corrosion control. The primary aim of the tool, however, is to provide a means of better controlling CCPP to reduce the large variations in CCPP evident historically (see Figure 3) and to aid in maintaining an effective CaCO₃ coating on pipe walls.



Figure 7: Example of Dose Mix Feature of CCPP Scenario/Planner Tool

Conclusions

The Tampa Water Department has gone from suffering an episode of "red water" and turbidity generated by an unusual event in raw-water quality that caused scale dissolution to a period of time in which there is too much scale being formed, resulting in inaccurate meter readings at the plant and in the distribution system. Along the way, success and failure has helped in developing an ongoing process of process chemistry.

Through refinement in corrosion-control techniques, the department is evaluating the effectiveness of using CCPP (and LSI) as the primary control parameter(s) of corrosion control. The tools and understanding developed during these series of studies will take some time to evaluate the direct impact that they can make on the cost savings and improved stability of the distribution system.

The first study brought about the implantation of CCPP as a calculated parameter in monitoring daily operations and the impact upon corrosion control in the distribution system. The second study evaluated and found limited benefit in applying corrosion inhibitors to the current system.

The third study corrected oversaturation in the plant and established complex scheme for operations to apply a range of CCPP to various water conditions. The fourth and current study is refining the CCPP parameter and automating the complex scheme to allow better interactive control of corrosion and more precise operational control with real-time information, in order to better dose pH adjustment to effect a tighter margin with CCPP.

Continued on page 48

Recommendation 1	
FSRWMS Corrosion Control Presentation	
Initial Water	
Measured Temperature	25 (deg C)
Measured pH	8.6
Measured Total Dissolved Solids	400 (mg/L)
Measured Alkalinity, as CaCO ₃	55 (mg/L)
Measured Ca, as CaCO ₃	60 (mg/L)
Measured Chlorides	0 (mg/L)
Measured Sulfates	0 (mg/L)
Treatment Chemicals (mg/L)	
Lime (siked)	18.88
Treated Water	
Pre-CaCO₃ Precipitation	
Interim pH	8.15
CCPP	248 (mg/L)
Langlier Index	0.31
Post-CaCO₃ Precipitation	
Final Alkalinity	78 (mg/L)
Final Ca	83 (mg/L)
Final Acidity	90 (mg/L)
Final pH	7.92
Final DIC	158 (mg/L)

Figure 8: Sample Output from CCPP Scenario/Planner Tool

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