ON LINE CONTROL STRATEGIES FOR DISINFECTION SYSTEMS: SUCCESS AND FAILURE

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ABSTRACT

There are many levels of automation for control of chlorination systems. To select the best control approach for a facility, both control strategies and chlorination chemistry must be understood. Permit conditions including organism concentrations and operating data must also be fully identified. Many States require compliance with organism concentrations, as well as residual chlorine and disinfection byproduct concentrations.

Breakpoint chlorination chemistry will play a role in most disinfection systems. This paper discusses combining on-line monitoring and automated control with chlorine chemistry to develop several levels of process control that will result in effective disinfection. Another factor must be considered while developing a process control strategy is disinfection byproduct formation. Disinfection byproducts (DBPs) in wastewater effluent are being regulated and the limits being imposed are much stricter than SDWA standards. Data from a recent disinfection study is presented to examine DBP formation and other selected chemical properties.

KEYWORDS

Breakpoint Chlorination, On-line Analyzers, Flow-paced Control

INTRODUCTION

Many attempts have been made to automate chlorine-based disinfection systems. Two basic problems are always encountered when controlling chlorination systems: the lag time inherent in the feedback control of plug flow systems and interpreting the impacts of chlorine chemistry on process control. Until these two issues are properly addressed in the control system logic, the control system will have serious limitations and may be more trouble to operate than the money spent to install the equipment.

Strict nutrient limits are forcing many chlorine disinfection systems to vacillate between monochloramines and free chlorine. Both will effectively disinfect a wastewater, but each has its

own characteristics. Along with strict nitrogen limits, some geographical regions in the United States are implementing end-of-pipe limits for trihalomethane (THM) compounds for control of DBPs. Drinking water standards regulate THMs as an aggregate parameter; however, the standards that govern water quality standards specify individual limits for each THM compound.

Many States are setting low organism limits for reuse applications and for effluent receiving streams that are used for recreation. Some States are going so far as to set non-detect limits. To meet these stringent limits, chlorine addition must be carefully controlled. Overdosing is no longer a viable alternative because it would lead to THM formation and because of the increasing costs of chlorination and dechlorination.

Effective control of the chlorination process will achieve the following results:

- Meet either permit limits or target levels for organisms.
- Minimize chlorine use.
- Lower the chemical costs.
- Reduce the use of dechlorination chemicals.
- Minimize THM formation.

This paper will describe various levels of chlorination system control, from manual control through complete automation, and will discuss the benefits and limitations of each approach.

CHLORINATION CHEMISTRY

In order to develop an effective control strategy, the chemistry of chlorination must be thoroughly understood. Wastewater treatment plants use chlorination to kill pathogenic micro-organisms and viruses. The NPDES permits issued to utilities throughout the U.S. define many different water quality goals. Disinfection limits are usually expressed as concentrations of groups of organisms or specific types of organisms. "Total coliforms" is a generic term for a large group of organisms, whereas "fecal coliforms" are still a group of organisms but a more specific group of organisms known to be present in wastes from warm-blooded organisms. E. coli and enterococci are examples of specific organisms found in wastewater that are being regulated in some parts of the U.S.

Chlorine is a strong oxidant that will react with a wide range of organic materials. As chlorine oxidizes the organic material in cell walls or in other cell components, it kills the target organism. The effectiveness of chlorine as a disinfectant depends on its concentration and on contact time. Increasing the chlorine dose or the contact time will result in killing more organisms. A common NPDES permit limit for discharge to many watersheds is a 30-day geometric mean of 200 CFU/100 mL (CFU = Colony Forming Unit). NPDES permits for environmentally sensitive areas such as watersheds used for water supplies and reuse systems will have lower limits that can range from a 30-day geometric mean of 22 Total Coliforms/100 mL, to nondetect for fecal coliforms. In order to design a successful disinfection system, the designer must clearly understand chlorine chemistry to ensure that the system dispenses enough disinfectant to produce an effluent that meets the NPDES permit limits.

Chlorine is an indiscriminate oxidant. This means that chlorine will react with a wide range of materials and that it will react with the first material it comes into contact with that will act as a reducing agent. In every reaction involving chlorine, the chlorine is reduced to a lower oxidation state (hypochlorite OCl⁻ is converted to chloride, Cl⁻) and the target material or the reducing agent is oxidized. This oxidation reaction may change the target material into a new compound, because some oxygen has been inserted into its chemical structure. Some such reactions are beneficial in that they result in unwanted organisms being killed; others merely consume chlorine and remove it from solution without killing any unwanted organisms. As organic compounds react with chlorine, they may be completely oxidized to carbon dioxide and water, but the chlorine dose is usually low enough to only partially oxidize the parent compound. In such cases, the chlorine reacts with the organic material to form different compounds, such as disinfection byproducts (DBP).

The formation of disinfection byproducts is becoming a nationwide issue. As the States evaluate each POTW's discharge for compliance with water quality standards, the four primary DBPs have very restrictive water quality standard-based limits. This is where the dilemma begins. The POTW must add enough chlorine to comply with both the disinfection limits and minimize the formation of DBPs to meet the water quality-based permit limits. Therefore, it becomes even more important that treatment plan personnel understand disinfection as well as chlorine chemistry.

To understand the chemistry of breakpoint chlorination, three forms of chlorine must be defined: Free Chlorine, Combined Chlorine and Total Chlorine.

- Free chlorine is the amount of hypochlorite (OCl⁻) in solution.
- Combined chlorine is the measure of monochloramine (NH_4Cl) in solution.
- Total chlorine is the sum of free chlorine plus combined chlorine.

Breakpoint chlorination is a stepwise reaction that begins with the formation of monochloramine. As more chlorine is added to a solution, all of the ammonia is converted to monochloramine and the reaction is almost instantaneous. As still more chlorine is added to the solution, dichloramine will begin to form. Dichloramine formation is slow, requiring about 20 minutes of time to proceed to completion. However, as a higher free chlorine residual is present (and all ammonia is converted to monochloramine), dichloramine will be formed more rapidly because the rate of dichloramine formation is a function of the free chlorine residual concentration. If enough chlorine is added, dichloramine will react with free chlorine to form trichloramine. Trichloramine formation is also a rapid reaction. As trichloramine is formed, it can be easily vented out of solution at any point of turbulence.

Figure 1 is a graphical representation of breakpoint chlorination. In Zone 2, monochloramine is formed and, when analyzed, is defined as combined chlorine. As more chlorine is added, the system transitions into Zone 3 as shown on Figure 1. The effective chlorine residual actually declines as dichloramine and trichloramine are formed. In Zone 3, the transition zone, most of the chlorine residual measured would be combined chlorine. Some free chlorine can exist for short periods, but for the most part only combined chlorine will be measured. Once all of the

dichloramine is converted to trichloramine, free chlorine can exist (Zone 4). This relationship is very important in the selection of on-line chlorine residual analyzers for control of the disinfection process. The chlorine chemistry must be clearly understood in order to specify the correct chlorine analyzer and to devise the correct control strategy.

Figure 1: Breakpoint Chlorination Curve
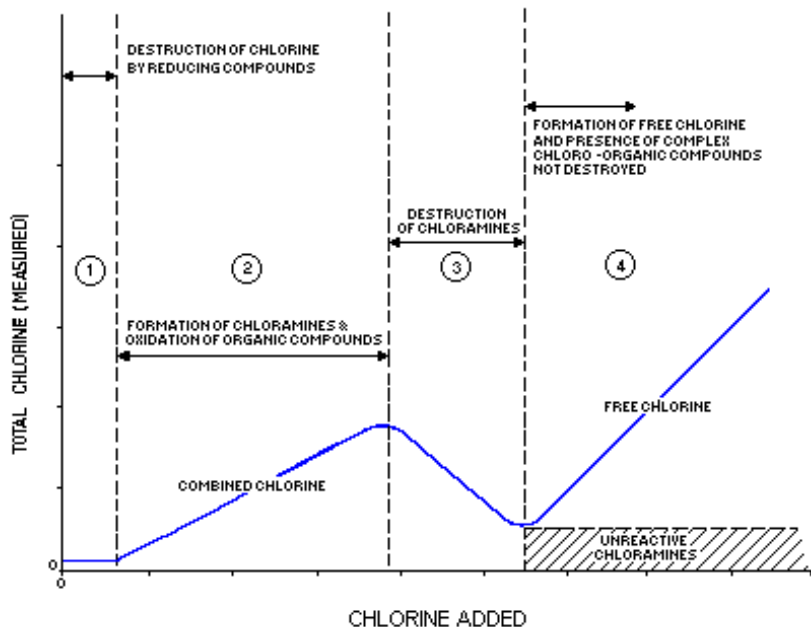
While breakpoint chlorination is not the intended goal of disinfection, it is one of those unwanted side reactions that happen. Breakpoint chlorination cannot be stopped, but it can be understood and it can be taken into account in developing the control scheme.

In general, one of three conditions involving breakpoint chlorination will occur in disinfection. The easiest reactions to understand and the condition that usually predominates are a high ammonia concentration in the wastewater treatment plant effluent. The reaction results in the formation of monochloramine.

The second condition is very low ammonia concentrations (less than 1 mg/L as N) in the treated effluent. In this condition breakpoint chlorination will probably be complete. With this condition, it may be difficult to maintain a free chlorine residual, because of the potential for side reactions that consume free chlorine.

The third condition is most troublesome from a process control perspective. What happens when the effluent ammonia concentration varies? If the effluent ammonia concentration varies, either seasonally or diurnally, from 1 mg/L to 5 mg/L as NH_3-N, the disinfection mechanism will vary between monochloramine and free chlorine. The control system must be able to cope with both chemistries and detect when the transition from one to the other occurs. For example, during breakpoint chlorination, there are conditions when adding more chlorine would be the wrong

control response, because it would produce more dichloramine and reduce disinfection effectiveness. By adding more chlorine and progressing through Zone 3 and into Zone 4 (Figure 1), more chlorine would be used for disinfection, whereas the correct response might have been to reduce the chlorine dose and to increase the monochloramine concentration by forming less dichloramine.

Many other reactions can occur with chlorine in the treated effluent. Biological treatment systems effectively remove almost all of the soluble BOD (biochemical oxygen demand) and most of the soluble COD (chemical oxygen demand). All treated POTW effluent contains some non-biodegradable soluble COD, typically from 10 to 50 mg/L. Reactions of chlorine with the non-biodegradable soluble COD can result in the formation of DBPs. Some of the non-biodegradable organic compounds, if partially oxidized, are converted back into BOD.

Soluble COD can be divided into two fractions: biodegradable and non-biodegradable. Biodegradable COD is BOD. The microbes in the POTW use oxygen to oxidize COD. It is a weak yet effective oxidation process. The biodegradable COD is oxidized and the non-biodegradable COD is left behind. Chlorine is a more powerful oxidant and can react with the non-biodegradable COD. As the non-biodegradable COD is partially oxidized, some of it can be converted into a biodegradable material. For POTWs that have permits with a 30 mg/L BOD limit, conversion of non-biodegradable COD into biodegradable COD or BOD is of no consequence. However, for POTWs that have permits with effluent BOD limits (less than 10 mg/L), formation of BOD through oxidation of COD by chlorine may become an important compliance issue.

Retention time also affects disinfection effectiveness. It is known that extended exposure to chlorine will kill more organisms. Up to two hours of contact time may be needed to sufficiently reduce the coliform concentration for the POTW effluent to meet strict reuse limits. In addition to meeting the strict discharge limits, State standards may require that the POTW that uses chlorine for disinfection maintain and record a measurable chlorine residual in the chlorine contact basin effluent. POTWs using free chlorine for disinfection may find it nearly impossible to maintain a residual chlorine concentration without having several chlorine injection points in the chlorine contact basin. Simply increasing the influent chlorine dose may only produce more DBPs without an increase in the effluent chlorine residual. Covering the chlorine contact basin may reduce dissipation of chlorine through exposure to sunlight as well as by discouraging the growth of algae that may consume chlorine.

Residual chlorine in the POTW effluent is known to be highly toxic to aquatic life, and the NPDES permits of many POTWs include dechlorination requirements. What happens during dechlorination? Free chlorine reacts with the dechlorinating chemical (a reducing agent) and degrades the chlorine to chloride ion.

Combined chlorine is monochloramine which is converted to chloride ion when a dechlorinating agent is added. The unique aspect of monochloramine dechlorination is that as monochloramine is converted, ammonia is formed as a reaction product. Equation 1 (which appears in many textbooks) gives the appearance that the ammonium compound is a solid, however, in water the ammonia compound dissociates into sulfate and ammonium ion.

NH$_2$Cl + H$_2$SO$_3$ ⇔ NH$_4$HSO$_4$ + H$^+$ + Cl$^-$ ……………………………Equation 1
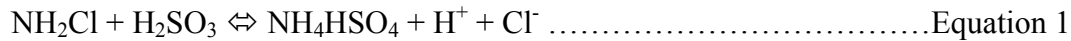
So, the ammonia that was removed when chlorine was added is re-formed when the residual combined chlorine is dechlorinated. If part of a facility's ammonia control strategy involves breakpoint chlorination, enough chlorine must be added to complete the breakpoint reactions, or the ammonia will be re-formed during dechlorination or during the natural degradation of the monochloramine.

CONTROL STRATEGIES: THEORY

What is really controlled in a disinfection system? The addition of chlorine to wastewater flowing through a contact chamber is controlled and it is hoped that the correct environmental conditions are created to kill enough of the regulated organisms to comply with permit limits. In all cases it is important to remember that the control system is indirectly controlling the final concentration of organisms. The control system is controlling the environment in which the target organisms are killed. It is a subtle but important distinction.

Nearly all disinfection control systems use plug flow feedback control. Feedback control means that the chlorine is added and the chlorine residual is measured at some point downstream. The measured chlorine residual is then compared with the setpoint concentration, and based upon this comparison, the control system will either increase or decrease the chemical dose in an attempt to match the measured concentration to the setpoint value.

One important fact to remember is that the concentration of the target organism is not being measured continuously. Chlorine is added at a dose designed to kill enough organisms to meet the permit limits, and it is assumed that sufficient chlorine is added to maintain an effluent chlorine residual to comply with the NPDES permit limits. In all cases, feedback control is used in a plug flow treatment system.

Chlorine contact chambers are designed as plug flow systems. The serpentine configuration of the channels prevents or minimizes short-circuiting of liquid through the system. As a result of this design, it will not be known whether the residual chlorine goal or setpoint is met until the water has passed through the chamber and past the sampling location. If the retention time is 30 minutes, it will be 30 minutes before the control system can detect the effects of changing the chlorine dose on the residual chlorine concentration in the chlorine contact chamber effluent.

Assuming that a chlorine residual analyzer is located at the effluent end of the chlorine contact chamber, unless the proper dose has been determined by jar tests, it is not known how much chlorine dose should be added to maintain a chlorine residual of 1 mg/L in the contact chamber effluent. The chlorine demand of the water cannot be known without jar test results or plant operating data. So an initial chlorine dose is selected. Also assuming that the retention time in the chlorine contact chamber is 30 minutes, that the residual analyzer takes 5 minutes to process a sample for analysis, it will be at least 35 minutes before effluent chlorine residual data is available.

Feedback control often uses a PID controller. The PID controller uses three modes of operation to develop an output signal in an attempt to control the measured constituent to a given setpoint. The three models of developing a control signal are proportional, integral, and derivatives.

Turning a PID controlled to make use of the three control functions is a separate topic for another paper. The key issue to remember when using a PID controller is that it is a feedback control system designed to control rapidly-changing process conditions. Disinfection is a plug flow process. The retention time needed for disinfection is a lag time that makes feedback control difficult.

When the chlorine feed system is started, it will take 30 minutes for the treated water to reach the chlorine analyzer sampling point. It will take another 5 minutes for the analyzer to produce a residual chlorine reading. If the feedback control system responds, it will have started feeding more chlorine before the first slug of chlorinated water has reached the sampling location. Because of the long lag time, the response of any feedback control system must be dampened to prevent serious overdosing or underdosing of chlorine. The long lag time inherent in the disinfection system, which makes automated control difficult, is the single factor that is often overlooked when automating chlorine feed systems.

Feedforward control approaches can work for chlorination systems. Flowpacing is a form of feedforward control that can be used alone or in conjunction with a feedback control system. Flowpacing merely increases the total control signal (metering pump or feed system output) in response to changes in flow. If the flow increases by 20 percent, flow pacing immediately increases the output signal by 20 percent in an attempt to keep the chlorine dose constant.

DEVELOPMENT OF CONTROL STRATEGY

Several methods of automated process control are possible, each of which has its advantages and disadvantages.

Manual Control. The first level of automation is manual control, which will serve as the baseline for comparison (Figure 2). In this control mode, the operator will set the feed rate on the chlorine feed system. This feed rate will remain constant until the operator decides to change it. With this method, the operator must sample the chlorine contact chamber effluent for both residual chlorine and the target organism concentration to determine compliance.

Since the diurnal flow variations are well known, the only drawback associated with the manual control method is its operating cost. As the WWTP influent flow varies throughout the day, the operator is faced with two basic choices: (1) leave the chlorine feed rate unchanged and use too much or too little chlorine, or (2) change the feed rate to match the flow (or at least reduce the high afternoon feed rate for late-night operation) and increase his workload. These two choices lead to a number of other factors to be considered. For example, if the operator elects to leave the chlorine feed rate constant through the day he is not only adding more chlorine than absolutely necessary, he is also requiring the dechlorination system to use more chemical, so there is a

Figure 2. Manual Process Control

Distance Downstream of Chlorine Addition in Contact Basin
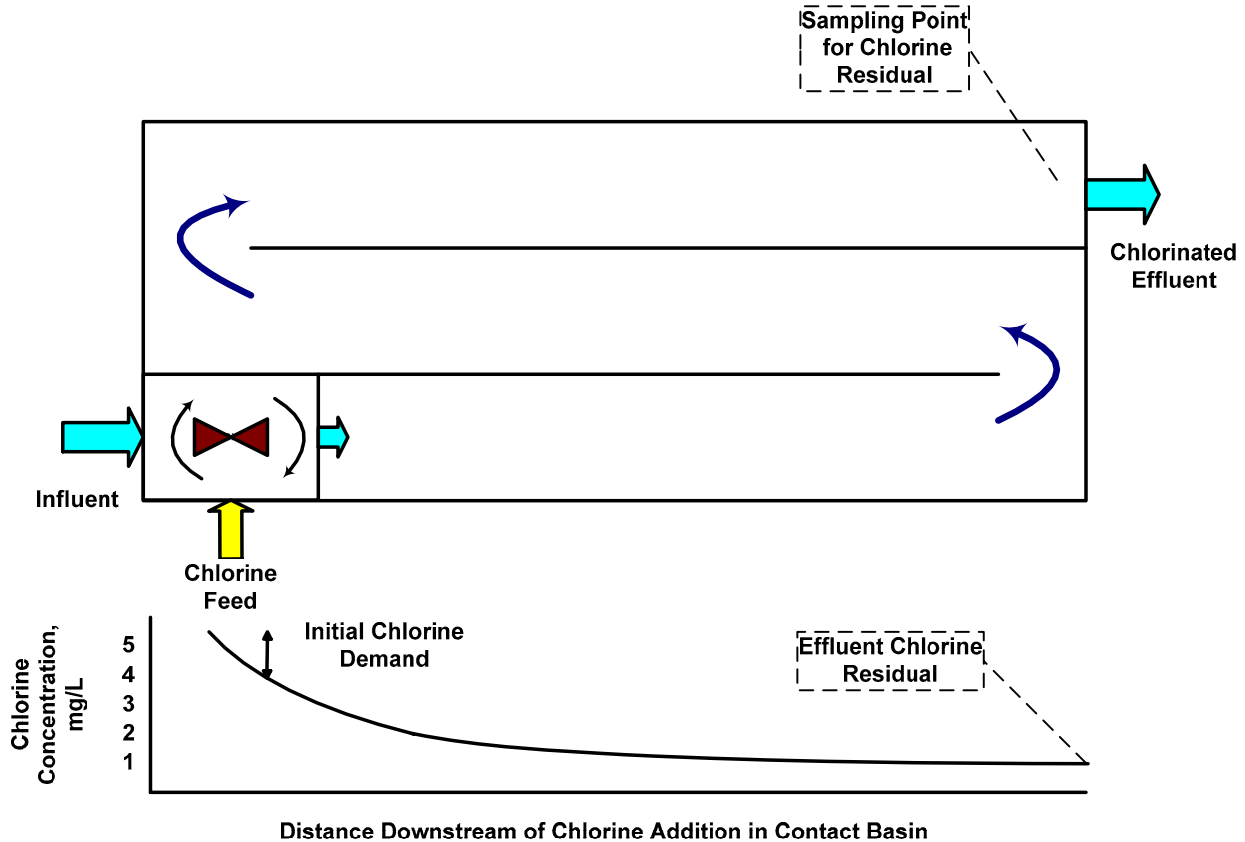
double impact on the operating cost. There is one other dilemma: the operator must also ensure that the effluent remains in compliance at all times. At a minimum he is gambling with saving a few hundred dollars a day in chemical costs versus a fine of $20,000 to $25,000 per day for permit violations. So the default approach is to always ensure that sufficient chlorine has been added to avoid noncompliance.

The only way to satisfy management through lowering operating costs is either to add less chemical and hope that the POTW stays in compliance, or to pay very close attention to the operation and to adjust the chlorine feed rate periodically throughout the day. Once the correct chlorine dose has been determined, it is a simple matter to develop a delivery chart of chlorine feed rate versus plant flow to enable operators to quickly determine how to manually set the chlorine feed system to dispense the correct dose of chlorine for the wastewater being treated. The only question is how many times a day does the operator need to adjust the chlorine delivery rate. While the operator is checking and adjusting the chlorine feed rate, he cannot be performing other tasks in the plant, and it does take time to walk from one end of the plant site to another.

To make the manual control approach work, the operator must collect and analyze samples of chlorine contact chamber effluent to determine whether the proper chlorine residual is being

maintained for adequate disinfection. Additional analyses for the effluent microbial concentrations are usually conducted in the laboratory and take 24 hours or longer for results.

This method of control sounds cumbersome, but it has been the standard approach for chlorination systems since EPA established permit limits for bacteria. And it works, even though it is not the most chemical-efficient or labor-efficient approach, but it has minimal maintenance needs. It merely takes human effort, concentration, and dedication. However, it has the potential to waste chemicals in both chlorination and dechlorination. Manual chlorination control usually uses more chemical, and operating staff can reduce the chemical costs by frequently changing the chlorine feed rate to keep pace with the influent flow rate. The system fails most often during periods when the influent flow changes rapidly. The operations staff must remember to change the chlorine feed rate as the influent flow rate changes.

Manual Control with On-Line Instrumentation. Using an on-line chlorine residual analyzer to monitor the chlorine contact chamber effluent simplifies the operator's job in controlling the chlorine feed rate setting (Figure 3). If the chlorine feed valve or pump can be operated remotely, the operator can monitor and control the feed rate from the plant control room. The operator would adjust it based on readings of the plant flow rate, and the chlorine residual concentrations on the local display. This approach takes only a couple of minutes and can be done hourly. It has the potential to closely control chemical use and to keep a close watch on the chlorine residual to achieve good disinfection.

**Figure 3. Operator Control with On-Line Monitoring**
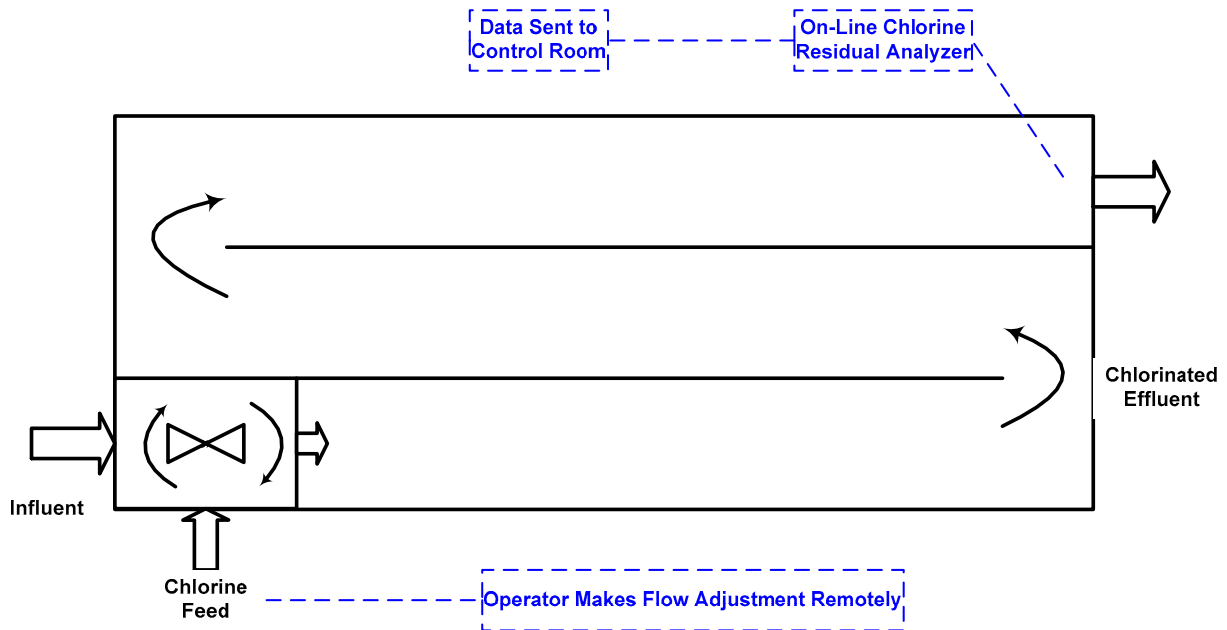
While the control of the disinfection process has been significantly improved, a new variable has been added to the maintenance equation: the on-line chlorine residual analyzer will require routine maintenance and frequent calibration, which will entail additional training for selected

staff to ensure that the analyzer is maintained properly to produce accurate, reliable readings. Analyzer performance is a whole separate issue that will be discussed later in this paper.

The chief advantage of this control approach is that, without leaving the control room, the operator can closely monitor the effluent chlorine residual and adjust the chlorine feed rate, effectively minimizing chemical costs. The disadvantage is the cost of the on-line chlorine residual analyzer and its maintenance. Letting the analyzer get out of calibration is a common cause of failure in this system. Again, rapidly changing influent flow rate is the most common cause of failure for this system (permit violations).

Flow Pacing. Flow pacing is a commonly used approach to controlling chemical feed when it is advantageous to maintain a constant dose into the wastewater (Figure 4). Flow pacing involves the use of a flow rate monitoring device just ahead of, at the effluent, or just after the chlorine contact chamber and remote control of the chemical feed system using a flow control valve or a variable delivery metering pump. With flow paced feed control the operator will input the desired chlorine dose to be maintained under all flow conditions and as the flow rate changes, the control system will adjust the rate of chlorine addition to maintain this dose. This approach assumes that the dose remains unchanged under all plant operating conditions, and does not require the use of an on-line continuous analyzer.

Figure 4. Flow Pacing Process Control
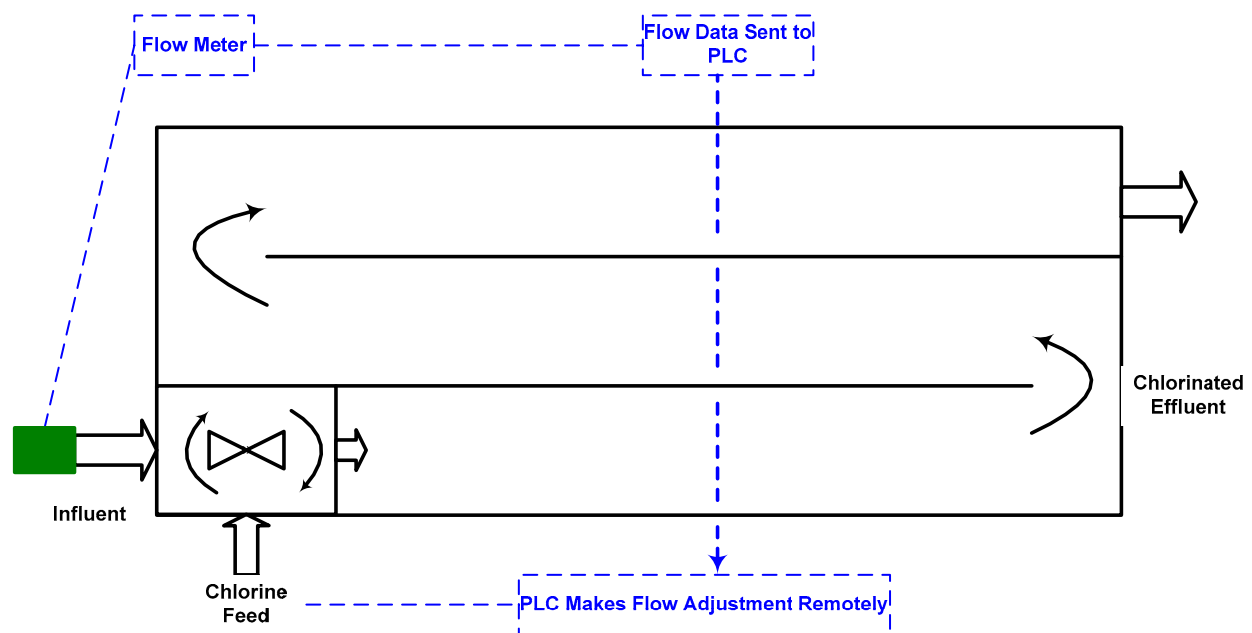
Flow pacing is essentially a feedforward control system even if the effluent flow is measured. It assumes that the input dose is always correct and adjusts the chemical delivery rate to keep a constant concentration in the wastewater. Flow pacing assumes the chlorine demand never changes. The operator's primary involvement with a flow paced control system is checking the chlorine residual in the chlorine contact chamber effluent to determine if the input dose needs to be adjusted.

The advantage of the flow paced control system is that the operator does not need to continually adjust the chemical delivery rate, since it is automatically adjusted by the control system; however, the operator must check the chlorine contact chamber effluent for the chlorine residual to determine whether changing the dose is warranted. The disadvantage of this approach is that the operator still has to manually monitor the effluent chlorine residual and effluent bacterial count. This system requires that the operator periodically check the chlorine decay curve to make sure that the proper chlorine dose is selected for use. The chlorine dose may not change often, but sudden increases in chlorine demand can cause the system to fail (exceed permit for fecal coliforms).

Flow Pacing with On-Line Effluent Monitoring. Adding an on-line monitor to the system simplifies the operator's job (Figure 5). If the chlorine concentration in the chlorine contact chamber effluent is monitored and transmitted to the control room, the operator can determine whether the current dose setpoint is correct. This approach reduces the operator's labor by adjusting the chemical feed rate in response to flow changes and by eliminating the need for collecting samples and analyzing them in the field. The residual chlorine concentration can be trended over time and if needed, a control algorithm can be developed to change the selected dose. Most of the process control adjustments can be made from the control room.

Figure 5. Flow Pacing with On-Line Chlorine Residual Analyzer
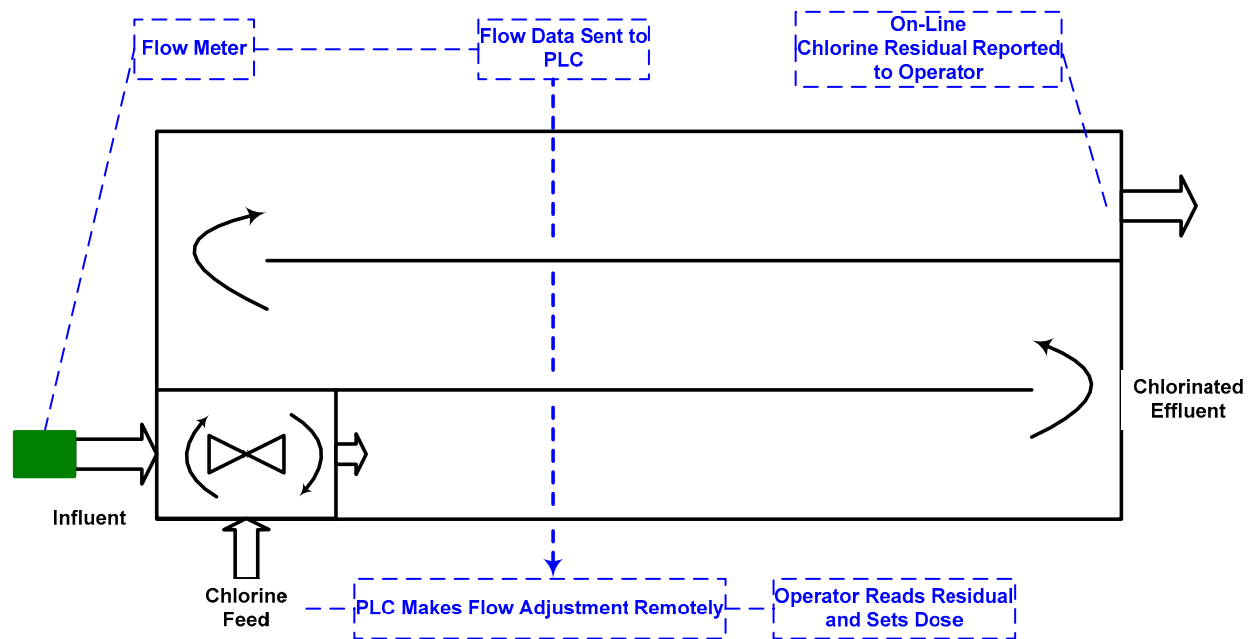
The on-line analyzer requires maintenance. It must be serviced to keep it in calibration, and a program must be devised for collecting grab samples to check for drift in the instrument readings. Units with auto-calibrating features would reduce the quality control aspects of the maintenance program. This is true for any on-line analyzer. This system requires that the operator periodically check the chlorine decay curve to make sure that the proper chlorine dose is selected for use. The chlorine dose may not change often, but sudden increases in chlorine demand can cause the system to fail.

Flow Pacing with On-Line Effluent Monitoring and Automatic Control. In this application the on-line analyzer will determine the residual chlorine concentration at the effluent end of the chlorine contact basin (Figure 6). Its setpoint will be the residual chlorine value that is known to achieve the microbial kill needed to comply with the facility's NPDES permit.

Figure 6. Flow pacing with Effluent On-Line Residual Measurement and Automatic Control
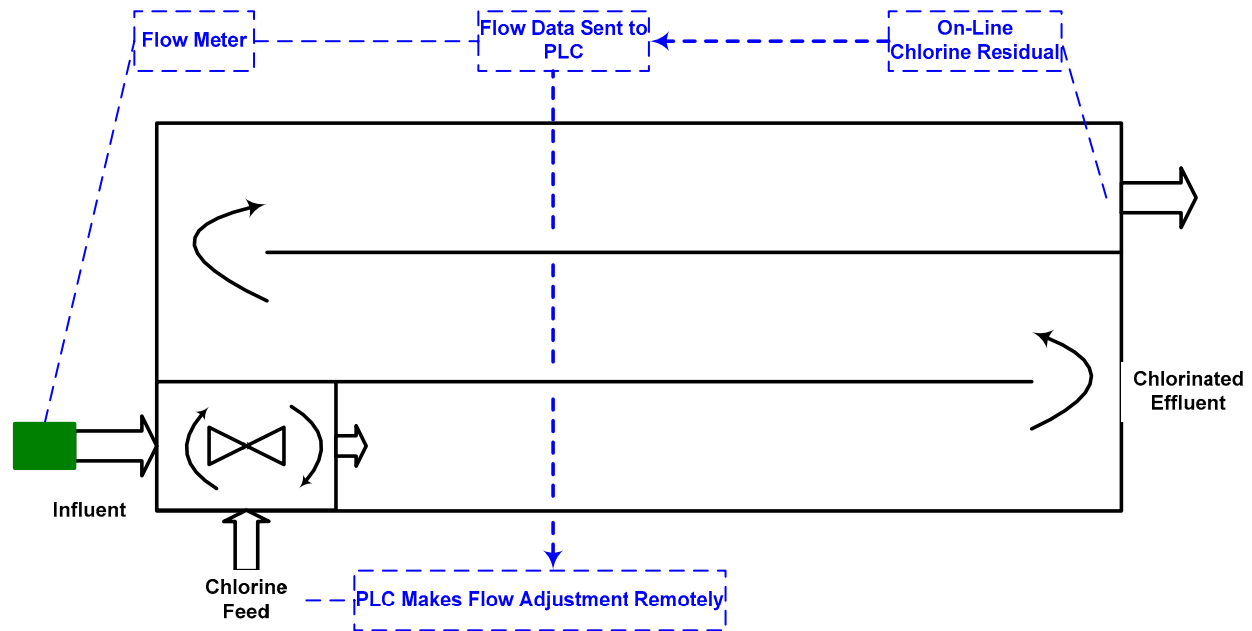
Many on-line instruments collect a batch of wastewater and analyze it for chlorine residual. There is a lag time during the analysis before the concentration is determined. The reading from a given batch is displayed until the next batch of wastewater is analyzed.

If the analyzer is placed at the basin effluent, there will be a lag time between the chlorine addition and the chlorinated wastewater reading the effluent end of the basin. The control loop must wait until the wastewater has passed through the system and the residual chlorine concentration has been measured by the on-line instrument. If the flow rate changes, the flow pacing function will still adjust the chlorine feed rate independently of the feedback control, to change the chlorine dose, so the concentration of chlorine added to the wastewater remains constant. The control system must be able to compare the residual chlorine concentration with the setpoint value and then decide how much to change the target chlorine dose. It must then wait until the wastewater that received the changed dose has had time to flow through the chlorine contact basin, so that the analyzer will measure its chlorine residual. Then the PLC can determine whether the chlorine dose should be increased or decreased to meet the desired chlorine residual setpoint.

This is a feedback control loop but the traditional PID control features cannot be used. Control logic must be developed to cause the PLC to generate a signal that will adjust the chlorine feed rate and maintain the proper residual. In flow-paced chlorine feed systems, the PLC actually

changes the dose and the flow paced control loop uses the dose set by the PLC to actually calculate the feed rate to be used. Since the flow time through the chlorine contact basin will vary with the actual wastewater flow rate, the PLC must be able to calculate a retention time through the chlorine contact basin in order to determine when to read the residual chlorine concentration and compare it with the setpoint.

This control approach is cumbersome and slow to respond to rapid changes in wastewater chlorine demand. To compensate for the slow response time, the change made in the target dose when the PLC calls for an increase in the chlorine dose must be large. Making large changes to increase the chlorine dose will shorten the time the effluent chlorine residual concentration is too low. A special increase in chlorine dose can be programmed into the system to make a large step change in the chlorine feed rate in the event the chlorine residual concentration drops close to zero. These correction factors can be made to be operator adjustable, which will enable the operator to change the response time of the control system without reprogramming by adjusting only the magnitude of the chlorine feed correction factor.

For example, under normal conditions the system is set to increase the chlorine feed rate by 10 percent, if needed. Assuming that the current chlorine dose is 5 mg/L and the setpoint chlorine residual is 1.0 mg/L, the measured chlorine residual is less than 1 mg/L the chlorine dose would be increased to 5.5 mg/L.

If the residual chlorine concentration ever drops to near zero, the PLC can make an emergency correction to the chlorine dose by increasing the chlorine dose by 2 mg/L, so the chlorine dose for flow-paced feeding would increase from 5 mg/L to 7 mg/L, which should be adequate to restore effluent residual chlorine concentration to the desired level.

The 10 percent increase in the chlorine feed concentration and the 2 mg/L increase in the chlorine dose would be operator adjustable based on system performance as a form of system tuning. If the dose corrections are too large, they can be reduced or adjusted to fit current conditions.

Conversely, if the chlorine dose needs to be reduced, a similar approach would be used. To keep the system from an oscillating sequence, the correction factors to decrease the dose should be different from the correction factors to increase the dose. For example, if the correct factor to increase the dose is 10 percent, the factor to decrease the dose should not be 10 percent. If a signal is received indicating that too much chlorine was added and the dose is reduced by the same factor, the dose would return to the condition that triggered the sequence. If the PLC reduces the dose by 3 percent, the control system will slowly reduce the chlorine dose to the setpoint value or until it is reduced too much. Overdosing is acceptable because the permit limit is met, but it will waste chlorine. Therefore, it is better to overdose the chlorine to ensure compliance and then to slowly reduce the dose until the desired residual is obtained.

Another approach is to use an acceptable range of values rather than a specific setpoint. For example, a range between 1.0 and 1.2 mg/L can be used instead of attempting to maintain a chlorine residual of 1 mg/L. If the chlorine residual is below 1 mg/L , the dose should be

increased. If the chlorine residual is between 1 and 1.2 mg/L, the chlorine dose need not be changed. If the chlorine residual is above 1.2 mg/L, the dose should be decreased.

When programming the PLC, it must be remembered that the lag time in the chlorine contact basin is a physical reality that must be considered in the control logic. If the lag time is not considered, the chlorine will be either overdosed or underdosed and in the latter case, the effluent will fail to meet permit limits. A "sample-and-hold" type lag control function should be programmed to take into account the lag time versus the flow rate. The sample-and-hold function provides a method for freezing the dosage in the PID controller until the next treated batch of flow reaches the effluent chlorine analyzer. The flow is divided by the fixed basin volume to yield the desired lag time. When the calculated lag time has expired, the PID control function will calculate the readjusted dose for a fixed period, and the PID control function will return to the frozen state until the next lag time has expired.
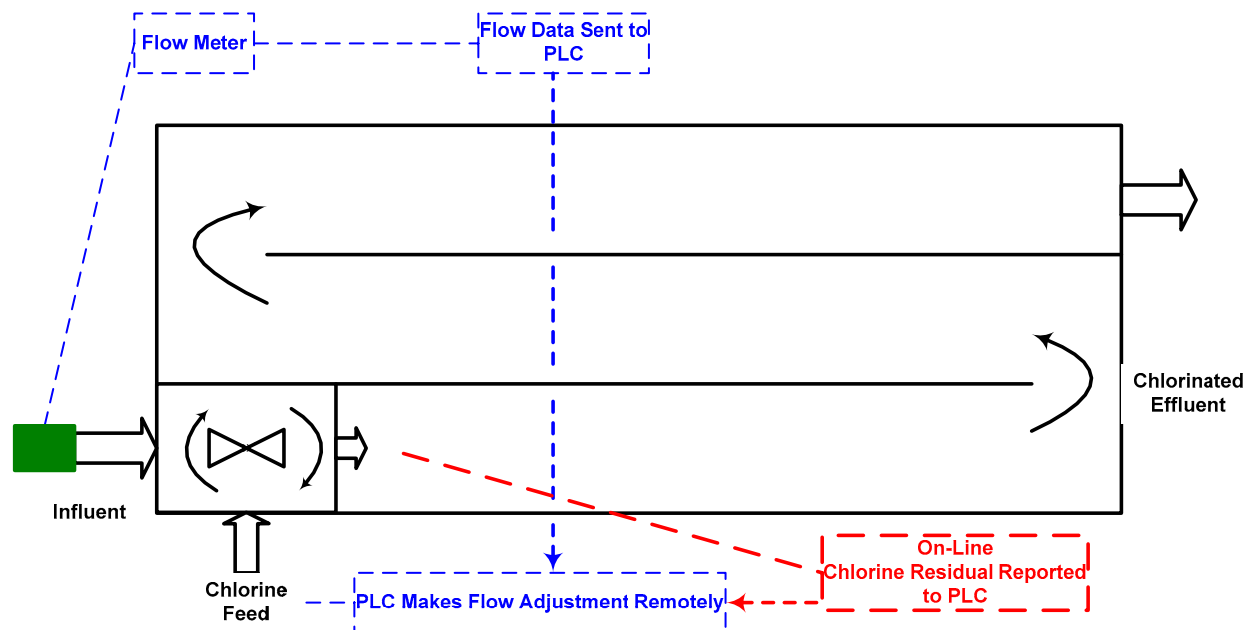
This control approach includes built-in process control redundancy. If the chlorine residual analyzer fails, the control system can revert to flow pacing only, thus there is no need for a back-up chlorine analyzer. The usual cause of process failure in this system is control loop tuning and analyzer maintenance/ calibration. This system is only as reliable as the reported chlorine residual data. Forgetting about the inherent lag time in the control loop will also result in frequent process upsets.

Flow Pacing with On-Line Monitoring and Automatic Control. In this application the on-line analyzer will determine the residual chlorine concentration immediately after chlorine addition (Figure 7). It will collect a wastewater sample 5-10 feet downstream from the chlorine injection point or the rapid mix chamber, at a point where the immediate chlorine demand will have been satisfied. Chlorine is an indiscriminate oxidant: it will almost instantly react with the first easily oxidized material that it comes into contact with. Oxidizing the more difficult to oxidize materials may take 20 minutes or longer. This is why the chlorine decay curve shows an initial rapid drop in chlorine residual followed by a much slower rate of decay.

This process control approach assumes that a sufficient chlorine residual concentration can be set to maintain the desired chlorine residual in the contact chamber effluent. The readily oxidized material will be oxidized before the chlorine residual is measured, and it is assumed that the rate of chlorine decay with the remaining materials will be more constant or predictable. This control approach is comparable to assuming a chlorine dose and waiting 30 minutes to check the effluent residual chlorine. The big advantage is that with the proximity of the sampling point to the chemical addition point, there is a small but manageable lag time which makes it possible to use standard feedback PID control to control the chlorine feed rate.

A second analyzer could be installed to monitor the chlorine concentration in the contact basin effluent to provide trend information, or it could be added to the "sample-and-hold" control function. If used for automatic control, the second analyzer would change the setpoint used by the upstream chlorine feed control system. However, this approach too is subject to the long lag time issues.

Figure 7. Flow pacing with On-Line Residual Measurement and Automatic Control

This approach has built in process control redundancy. If the chlorine residual analyzer fails, the control system can revert to flow pacing only, and a back-up chlorine analyzer is not required unless desired. The usual cause of process failure in this system is control loop tuning and analyzer maintenance/ calibration. This system is only as reliable as the reported chlorine residual data. Forgetting about the inherent lag time in the control loop will also result in frequent process upsets. The operator must also track the chlorine demand of the system to properly set the residual setpoint for the control system. Changes in demand will result in either under or over addition of chlorine.

Summary. Any of the process control approaches described above will work. Some approaches are better than others in terms of maintaining permit compliance while minimizing overdosing of chlorine. POTW management will be focused on permit compliance and reducing annual chemical costs. Proper automation will work as long as the on-line analyzer produces reliable, accurate, and representative data.

The key to successful automated system is maintenance of the on-line chlorine analyzer. Operating staff must be committed to keeping the analyzers in operation. In all cases, if the analyzers fail, the default control mode becomes either flow-paced control or manual control. Automation will reduce the operator's workload and will improve process control.

BLENDING CHEMISTRY WITH CONTROL

The process control procedures do not control the chemistry of chlorination. They merely control the dose and the effluent chlorine residual concentration. The system operator or system designer

must consider the chlorine chemistry when designing the control logic in the PLC. For example, in specifying a chlorine residual analyzer, is free, total or combined chlorine being measured? If a free chlorine analyzer is being specified and the water chemistry results in monochloramine formation and disinfection, then the analyzer will never encounter free chlorine until the breakpoint chlorine demand has been met.

As stated previously, it is easy to blend process control with chemistry when the facility's effluent ammonia concentration is less than 1 mg/L as N. Such facilities will always use free chlorine for disinfection. Any facility that discharges ammonia at concentrations in the 1-5 mg/L range will be faced with operating in either Zone 2, 3, or 4 on the breakpoint chlorination curve. See Figure 1.

Breakpoint Chemistry Process Control. So how does a control system cope with the two chlorine chemistries? The designer or the operator must make the PLC smart enough to distinguish between free and combined chlorine and to choose between free and combined chlorine control responses. Both free and total chlorine analyzers must be added to the control system so that the PLC can interpret the data and determine which chemistry is in use and which control response should be used.

The success of the control system begins with selection of the chlorine analyzer. The capabilities of chlorine analyzers are continually being improved, so recommendations made in this paper could be outdated within a year. Therefore, capabilities and considerations will be discussed only in general terms, and it will be up to the readers to find the specific analyzer best suited for their application.

If a single chlorine analyzer can distinguish between free and combined chlorine, it may be the best choice. Otherwise it may be necessary to specify two analyzers; one to measure total chlorine and the other free chlorine concentration. Combined chlorine would then be calculated as total chlorine minus free chlorine. Or, if total chlorine equals free chlorine, the system is using free chlorine for disinfection. If the free chlorine concentration is zero, only combined chlorine is present. The PLC must be able to interpret this data to determine the appropriate dose response.

Control systems often get confused during breakpoint chlorination. As shown on Figure 1, the chlorine residual increases as chlorine is added (Zone 2) until all ammonia is converted into monochloramine. The response that confuses control systems is Zone 3 on Figure 1, where monochloramine is converted to dichloramine. Since the combined chlorine is monochloramine, conversion of monochloramine to dichloramine results in a decrease in the chlorine residual. Unless the PLC is programmed to recognize this, the control system response will respond by adding more chlorine and force the system through breakpoint chemistry to the formation of free chlorine. It is important to remember that either free chlorine or monochloramine will kill enough pathogens to maintain compliance with the NPDES permit; however, this is accomplished at significantly different chlorine doses. Operating costs will be higher if the disinfection process proceeds through breakpoint chlorination.

The PLC must be programmed to recognize the Zone 3 response. The proper response should be to first reduce chlorine dose to move back into Zone 2 to maximize the monochloramine

concentration. The control system can be programmed to respond automatically or to sound an alarm to alert the operator.

When dealing with variable effluent ammonia concentrations it may be wise to routinely monitor the ammonia concentration data ahead of chlorination by periodic grab sampling or through continuous on-line monitoring. Using the chlorine contact chambers influent ammonia concentration, the PLC can calculate the chlorine dose that will convert all the ammonia to chloramines and use this value as an alarm point or as part of the PLC control logic to determine when the chemistry is transitioning into Zone 3.

All of these considerations address only effluent residual chlorine concentrations. The control system cannot monitor the effluent organism concentrations. This must be done by the operator who then must determine the proper chlorine dose and decide whether to leave the control system in automatic mode or to return it to flow-paced control. Occasionally during process upsets or peak loads on the upstream biological process, the ammonia concentration may fluctuate. Under these conditions it may be preferable to operate the system in flow-paced mode and to concentrate on correcting the biological system upset.

Meeting Strict Disinfection Limits. Some States have placed a 4 of 7 day median limit of 2.2 CFU/100 mL on total coliforms or non-detect on fecal coliforms. In such cases, the chlorine contact chamber will be designed to provide a contact time of 30-120 minutes, which poses a greater challenge for disinfection process control. Another approach, if allowed, is to operate at a higher chlorine dose.

Prolonged exposure to direct sunlight will cause chlorine to degrade. For systems that use free chlorine for disinfection, the challenge is to maintain a chlorine residual through the contact chamber. If the permit allows some ammonia in the effluent, one solution is to add ammonia to convert the disinfection process from free chlorine to combined chlorine. When monochloramine is dechlorinated or fully reacted, it degrades into ammonia, so ammonia addition may be limited based on the allowable effluent ammonia concentration. In fact, both monochloramine and dichloramine revert to ammonia when dechlorinated, so be sure to understand chlorine chemistry and the NPDES permit limits.

If ammonia addition is not the solution, multiple chlorine addition points should be provided. Simply adding more chlorine at the beginning of the chlorine contact chamber does not ensure that an effluent residual will be maintained in systems with a long retention time: as the chlorine concentration increases, chlorine can participate in more chemical reactions, thus adding a higher chlorine dose may increase the chlorine demand without producing a net increase in the effluent residual. Instead, it may result in the formation of more DBPs.

DBP Control. Trihalomethanes (THMs) are a group of compounds composed of a halogen-substituted single carbon compound that is named as a derivative of methane. Each THM is formed by the reaction of free chlorine with a precursor material. Humic and fulvic acids resulting from the breakdown of organic matter have been identified as the primary THM precursors. Humic and fulvic acids are generic names for a wide range of compounds of various

molecular weights. Since THMs are known to be carcinogenic to humans: these compounds need to be identified and regulated.

The Safe Drinking Water Act (SDWA) requires potable water treatment facilities to remove THMs to an aggregate concentration of not more than 80 ppb. Water plants typically adjust their processes and operating conditions to avoid or minimize the formation of THMs, but may not concentrate on the removal of the THM precursors. Therefore, any THM precursors present in the finished public water supply will eventually appear in the domestic wastewater as well as any additional humic and fulvic acids discharged into the wastewater collection system. Treated wastewater effluent may contain higher concentrations of THM precursors than were initially present in the domestic water supply. This becomes extremely important when chlorine compounds are used for disinfection because THMs are also being regulated in wastewater effluent.

The reactions that form THMs are not instantaneous and are complicated by the many factors that affect both the rate of THM formation and total yield of THMs. The primary variables are the concentration of THM precursors; the concentration of free chlorine; the contact time; temperature, and pH of the water and the concentrations of bromide and iodide ions in the water being chlorinated. Bromide and iodide ions are oxidized by free chlorine to species capable of participating in organic substitution reactions resulting in the formation of pure- and mixed-halogen THMs. It appears that bromine substitution is favored over chlorine, even though chlorine is present in large excess compared to the initial bromide concentration.

There are ten typical THM compounds; however, only four of them are regulated. The four THM compounds regulated by SDWA and the six non-regulated THMs are listed in Table 1

Table 1. Trihalomethane Compounds

Compound	Formula	Compound	Formula
1. Chloroform[1]	$CHCl_3$	6. Bromochloroiodomethane	$CHClBrI$
2. Bromodichloromethane[1]	$CHBrCl_2$	7. Chlorodiiodomethane	$CHClI_2$
3. Dibromochloromethane[1]	$CHBr_2Cl$	8. Dibromoiodomethane	$CHBr_2I$
4. Bromoform[1]	CBr_3	9. Bromodiiodomethane	$CHBrI_2$
5. Dichloroiodomethane	$CHCl_2I$	10. Iodoform	CHI_3

[1] Regulated Under SDWA

Table 2 presents a comparison of SDWA standards with Federal and state water quality standards.

EPA developed water quality standards in PL 92-500 in 1972. The water quality program has evolved over time to refine the numerical in-stream standards. EPA requires that the delegated. states either adopt the EPA program or develop their own water quality program and review its applicability every three years. It has taken time but the States are beginning to implement all phases of water quality-based permitting. As NPDES permits are renewed, there is often a requirement to provide monitoring data for a long list of compounds, often referred to as the priority pollutant scan. The four THMs listed in Table 2 usually are included in the EPA priority pollutant scan. The data from the scan will become the information that the State will use to determine whether a facility has a "reasonable potential

Table 2. Comparison of THM Standards

Compound	Federal Water Quality Standard (WQS), ug/L			State 1 WQS, ug/L	State 2 WQS, ug/L	
	Fresh Water	Human Health		Fresh Water	Human Health	
	Acute	Water and Organisms	Organisms only		Water and Organisms	Organisms only
$CHCl_3$ [2]	28.9	5.7	470	470.8	5.7	470
$CHBr_2Cl$ [2]	NR[1]	0.41	34	34	0.41	34
CH_3Cl [3]	NR	NR	NR	470.8	NR	NR
CHBrCl2 [2]	NR	0.27	22	22	0.56	46
CHBr3 [2]	NR	4.3	360	360	4.3	360

[1] NR = Not regulated

[2] Safe Drinking Water Act Limits the sum of these four compounds to less than 80 ppb rather than separate limits for each individual compound.

[3] Chloromethane is not a THM but falls under the more general heading of a halogenated organic chemical under the water quality program.

to exceed water quality standards." If the data shows that the facility does have a "reasonable potential to exceed water quality standards," numerical limits will be developed for the applicable pollutants.

Since water quality standards apply at the edge of the mixing zone, if one has been granted by the regulatory authority, not all wastewater treatment plants discharging these pollutants at the same concentration will receive numerical limits in their NPDES permit. The size of the mixing zone and the background concentration of those pollutants in the receiving stream strongly affect the "reasonable potential to exceed" analysis. However, facilities located on effluent-dominated streams may find that the State will require them to meet water quality standards at end-of-pipe, which may prove to be a difficult or impossible task.

For wastewater treatment plants that either do not nitrify or whose discharge permit for NH_3-N is higher than 5 mg/L, it has been assumed that DBP formation would be minimal. When chlorine is added, monochloramine is formed rapidly so the exposure time of free chlorine to the THM precursors will be limited. However, recent bench-scale tests have shown that DBP formation can occur even when the ammonia concentration is high.

Both primary clarifier and secondary effluent where chlorinated and the samples were analyzed for the formation THMs and haloacetic acids (HAA) for three treatment facilities. One plant was a trickling filter facility and the other two were activated sludge plants. Target doses were 7.5 mg/L as sodium hypochlorite in secondary effluent and 15 mg/L in primary effluent. Samples were withdrawn over a thirty-minute contact time. The THM and HAA profiles are shown on Figures 8, 9, and 10 for the Kansas City, Missouri Blue River, Birmingham, and Westside WWTPs.

Figure 8. THM and HAA Profile in the Blue River (Trickling Filter) WWTP Primary and Secondary Effluent
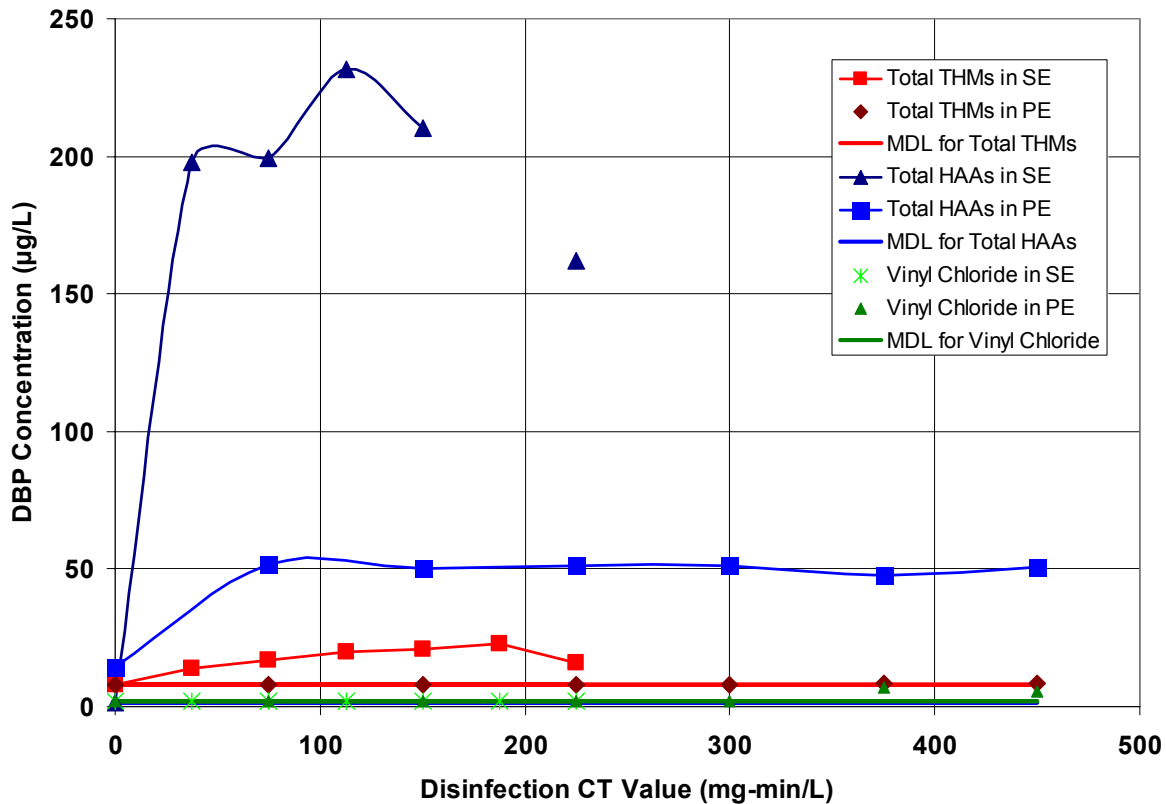

There is a fundamental difference between the effluent from the trickling filter plant and the activated sludge plants. Trickling filter effluent is composed of a significant concentration of soluble BOD, while the activated sludge plant effluent has very little soluble BOD. Soluble BOD is significant because it is easily oxidized so it will be readily reactive with chlorine. Some of the soluble BOD may be THM precursors. In general, the BOD in a trickling filter effluent will be higher than the effluent TSS concentration because of the soluble BOD concentration. However, in an activated sludge plant, the effluent TSS concentration should always be higher than the effluent BOD concentration because activated sludge removes nearly all of the soluble BOD.

In Figure 8, more THMs are formed in the secondary effluent from the trickling filter than in the primary effluent. There is little difference in the ammonia concentration in the two samples but the soluble BOD concentration in the primary effluent is much higher than the secondary effluent. On Figures 9 and 10, more THMs were formed in the primary effluent than in the secondary effluent. Neither activated sludge plant nitrifies. The activated sludge process appears to remove more of the THM precursors, which minimizes formation of THMs in the secondary effluent.

Ultraviolet light transmittance (UVT) was measured to develop a data base (Figure 11) for

Figure 9. THM and HAA Profile in the Birmingham (Activated Sludge) WWTP Primary and Secondary Effluent
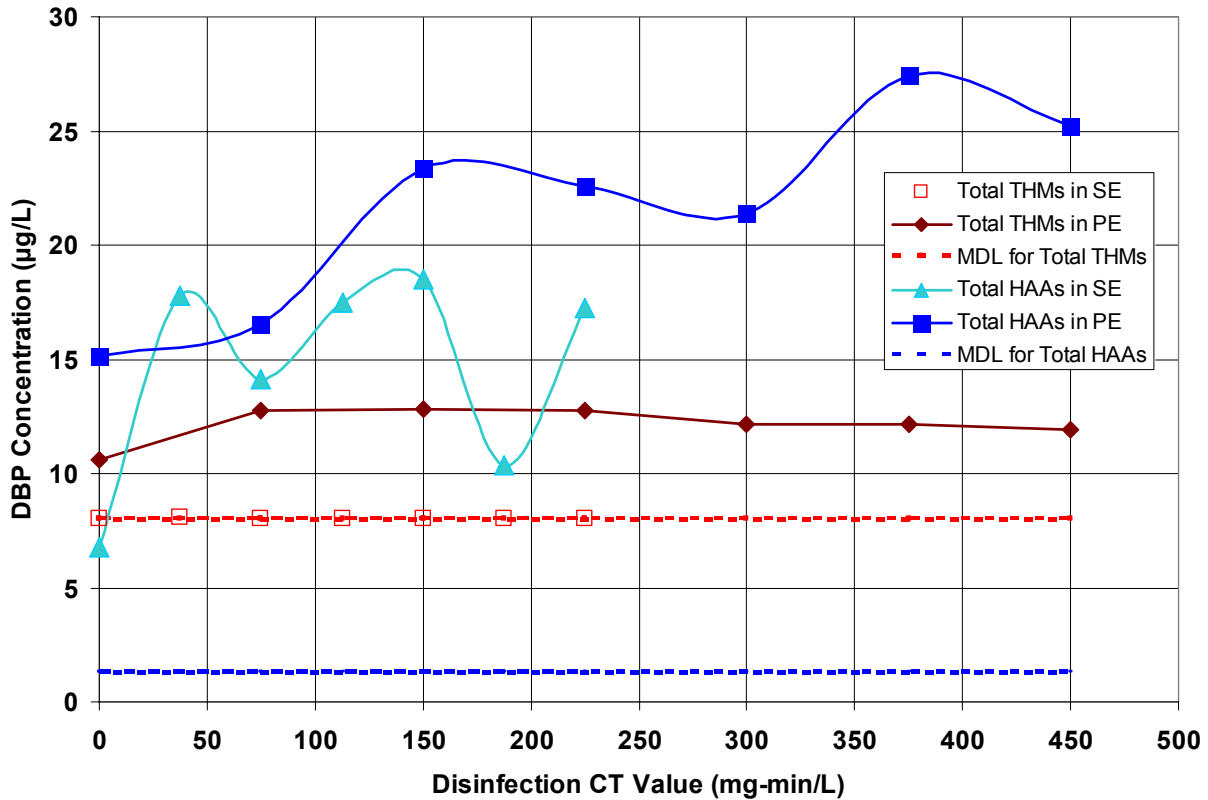
design of an ultraviolet light (UV) disinfection system for St Joseph, MO. While this paper does not address UV disinfection, the UVT data is still applicable to chlorine systems. The UVT reflects the soluble material that has UV absorbing properties. In simple terms, the UVT measures the concentration of non-biodegradable COD in a plant effluent. For an activated sludge system, there will be very little soluble BOD in the effluent but every activated sludge plant has some non-biodegradable COD in the effluent. A lower UVT value means a higher soluble non-biodegradable COD concentration. The non-biodegradable COD can react with chlorine as part of the system chlorine demand and may even be THM precursors.

The data on Figure 11 shows a steady decrease in the UVT over the first three months of 2006. A new industry was starting production in St Joseph during this same time. Several industries were sampled for UVT, and three industries had low UVT values in their discharge to the sewer. A fourth industry showed a steady decrease in its effluent UVT that mirrored the same decrease in UVT in the WWTP effluent as shown on Figure 11. The moral of this story is that industrial discharges can affect effluent quality even though the WWTP effluent BOD concentration has stayed constant. Adverse impacts to WWTP effluent quality do not have to be visible.

The increased UVT is an indicator for the presence of more non-biodegradable COD in the WWTP effluent. These soluble materials can affect chlorine demand. Therefore it is

Figure 10. THM and HAA Profile in the Westside (Activated Sludge) WWTP Primary and Secondary Effluent
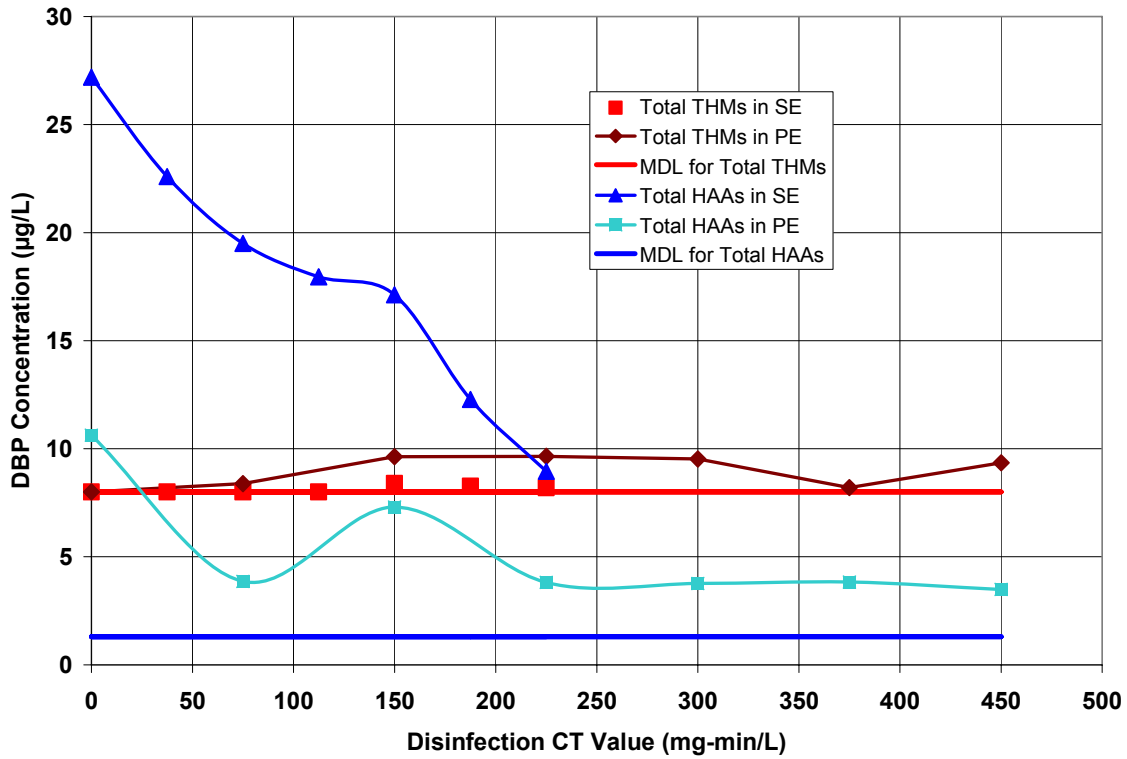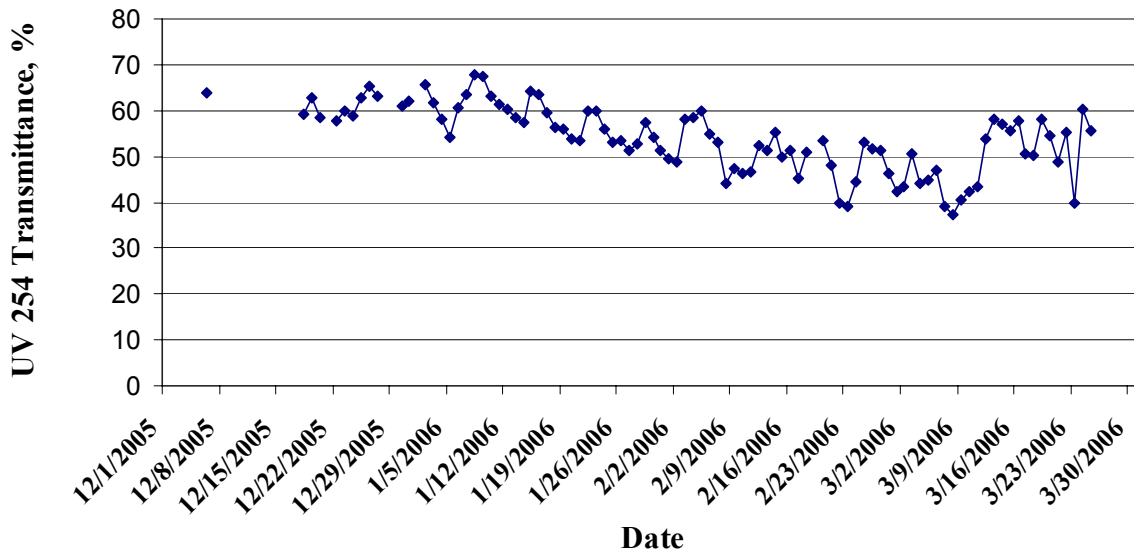

Figure 11. UV Transmittance Data from St Joseph WWTP Effluent

recommended to periodically test any WWTP effluent for chlorine demand even though effluent quality does not appear to change when conventional pollutants like BOD are examined.

Other methods of THM formation control involve other areas of the WWTP. Coagulants can be added to improve THM precursor removal in primary clarification. Filtration ahead of disinfection will remove solids that contain THM precursors. Removal of bromide or iodide from the system will also reduce the formation potential of THMs. Increasing the sludge age can also result in lower THM formation potential. Of course, reducing chlorine contact time is a possible approach, but one that may not be practical because of regulatory or code limit.

SUMMARY

Disinfection using chlorine is not as simple as it used to be. When designing or updating a chlorination control system, the following basic information is needed:

- Know the permit limits including both the organism numerical limit, the residual chlorine numerical limit and reporting requirements.
- Identify the chemistry to be used which also means reviewing the permit and process design to determine the probable variations in the effluent ammonia concentration.
- Determine if there are limits or concerns about THM formation.
- Set the basin retention time and channel configuration.
- Define the level of automation desired.
- Select the sampling locations and on-line instruments to be used (if needed) in your control approach.
- Whenever possible perform jar tests to determine chlorine demand. Pay special attention to changes in chlorine demand when a new industry moves to town.
- Develop the control strategy and write a verbal description of the control logic, including the "what to do when this fails" logic.
- Develop a list of alarms and their level of importance.

From the preceding discussions, it is evident that chemistry does affect how the plant chlorination system must be operated and the information needed to make timely process control decisions. One constant in the whole process is the chlorine chemistry. In the past, understanding the chemistry was not so important; however, as the permit limits get progressively stricter and the cost of chemicals keeps rising, process control to meet permit without wasting money becomes more of a challenge.

Process automation reduces the immediate demand on the operator's time because it takes care of the minute-to-minute decisions. The control system will not check the effluent organism concentration data; this is a task that the operator must perform. Finally, the automation only works if it is maintained. Analyzer maintenance must be added to the workload and someone must be identified to be the instrumentation expert to troubleshoot problems. When automating chlorination, it is highly probable that other areas of the plant are also being automated; thus, the instrument technician position will become a key staff position.

Always keep up on training. Automation makes people forget the basics of plant operation. It may be a good idea to test your staff occasionally by requiring staff to run the plant with no automation to ensure that everyone remembers how to control the plant manually. After all, who knows when the next PLC failure or software crash will occur?

REFERENCES

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