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INTERNET TOOL TO HELP UTILITIES DEVELOP DESIRED DRINKING WATER QUALITY

INTERNETOWE NARZĘDZIE WSPOMAGAJĄCE SŁUŻBY KOMUNALNE W OSIĄGANIU POŻĄDANEJ JAKOŚCI WODY PITNEJ

Projekt pt.: "Program Internetowy pomagający stacjom uzdatniania wody osiągnąć wymaganą jakość wody pitnej", sponsorowany I zarządzany przez Water Research Foundation, doprowadził do zaprogramowania narzędzia wspomagającego proces decyzyjny przy uzdatnianiu wody. Ten elektroniczny program, zamieszczony bezpłatnie w Internecie, pomoże przedsiębiorstwom wodnym w podejmowaniu decyzji związanych z wyborem odpowiednich procesów uzdatniania wody służących uzyskaniu zgodności z wieloma, złożonymi regulacjami dotyczącymi czystości wody, włączając w to potencjalnie sprzeczne wymogi i inne niezamierzone konsekwencje. Opracowane zostały dwie wersje tego programu: bardziej techniczny i zaawansowany, program dla dużych przedsiębiorstw uzdatniania wody, a także uproszczona wersja dla małych systemów. Dodatkowo, zaprojektowana została elektroniczna biblioteka zawierająca krótki opis współczesnych technologii uzdatniania wody: ich właściwości, zastosowań i kosztów.

A project titled: "Decision Tool to Help Utilities Develop Simultaneous Compliance Strategies", sponsored and managed by the Water Research Foundation, resulted in development of the decision-making tool for drinking water utilities. This electronic program, posted free of charge on the Internet, will help utilities identify optimal strategies for complying with multiple, complex water quality regulations, including considerations for potentially conflicting regulatory requirements and other unintended consequences. Two versions of the program have been developed: a more technical and sophisticated tool for large utilities, and a simple, self-guiding tool for small systems. In addition, an electronic library has been designed, containing a brief summary of water treatment technologies and their characteristics, applications, and costs.

1. Water Research Foundation's project to develop an web – based tool for water utilities

1.1. Drinking water quality to achieve simultaneous compliance with regulations

Water utilities are facing increasing challenges to achieve compliance with multiple objectives of drinking water regulations and aesthetic quality. In addition to meet all the compliance challenges that are posed to the water utilities by numerous individual drinking water regulations, water systems strive to avoid potential conflicts and negative unintended consequences. For example, due to more stringent disinfection by-products regulations, many water utilities lowered the dose of the primary disinfectant and implemented alternative residual disinfection, soon discovering development of biofilm and corrosion problems in distribution systems, or even the violation of the requirements for inactivation of pathogens. Therefore, it is not practical to focus on a single objective of meeting a particular water quality objective; rather, multiple objectives should be considered ans possible conflicts in meeting these objectives should be analyzed.

1.2. Simultaneous compliance tool on the Internet

A research team, lead by Malcolm Pirnie, Inc., has completed a project sponsored and managed by the Water Research Foundation titled: "Decision Tool to Help Utilities Develop Simultaneous Compliance Strategies". A resulting electronic decision tool, posted free of charge on the Internet, will help utilities identify optimal strategies for complying with multiple, complex water quality regulations, including considerations for potentially conflicting regulatory requirements and other secondary impacts of compliance. Two versions of the tool have been developed: a more technical and sophisticated tool for large utilities, and a simple, self-guiding tool for small systems. In addition, an electronic library has been designed, containing a brief summary of water treatment technologies and their characteristics, applications, and costs.

This Simultaneous Compliance Tool assists in making appropriate choices to comply with various water quality goals emanating from water quality regulations. The tool utilizes a framework of technology-based rules to identify potential unintended consequences based on user defined treatment and source water quality parameters. Users can define anticipated future system conditions to eliminate or minimize potential negative unintended consequences. This exercise will educate the user to make more informed decisions about treatment changes for compliance purposes minimizing negative consequences of their decisions. Additional system-specific testing and demonstration may be needed once a short list of suitable technologies is identified using the tool.

This electronic tool was developed as a result of several workshops, where representatives from drinking water utilities, state regulatory agencies, universities, consulting firms, and manufacturer representatives contributed their expertise and tested the draft product. The US Environmental Protection Agency co-sponsored the project and provided input on the rule compliance issues. The web-based tool is being maintained by the developer, and will be updated periodically. It can be used free of charge. Each session is saved under the user's name and could be accessible several times. The

accompanying electronic library, containing the description of the currently used drinking water treatent technologies could serve an an excellent resource guide.

The presentation includes a demonstration of the use of the web-based decision tool, examples of its use for either treatment optimization, plant expansion, or for training purposes, thus promoting the use of the program by plant operators as well as state regulators, providing training and overseeing rule compliance. The tool is available at the following site:

http://www.simultaneouscompliancetool.org

When the website opens, the user should create a name to log into the program and then has the option to login to the large or small water systems' tool. A typical large system characteristics include: treatment is often more complex than simple disinfection, system employs more than one full time operator, system serves population more than 3,300 people, and a system maintains comprehensive raw water quality record. A typical small system characteristics include: treatment could be as simple as disinfection, system employs a single full-time or part-time operator, system serves 3,300 people or less, and such system usually does not maintain comprehensive raw water quality record.

Fig. 1.   *Starting the Simultaneous Compliance Tool and logging to LARGE or SMALL water system tool*

Rys. 1.   *Rejestrowanie do programu i wybór dużych albo małych systemów wodnych*

If a user does not have a username, he or she can click on the "click here" link near the bottom of the page to create a new username. The screen, presented in Figure 2, should appear. Once a username is created it is applicable to both LARGE and SMALL systems, i.e. the same user name can be used to run both the large and small system tools. If the user already has a Login ID then he or she can enter it and login to the respective tool (large or small). Once a username is entered, the user should click on the button stating "Login" for either the LARGE SYSTEM or the SMALL SYSTEM side.

Fig. 2.   Creating a Username to login to the Tool

Rys. 2.   Rejestrowanie się jako użytkownik programu

The following screen, presented in Figure 3, appears when a user logs into the Simultaneous Compliance Tool.

Fig. 3. Logging to the WATER QUALITY ISSUES or NEW TREATMENT TECHNOLOGY System Tool

Rys. 3. Wybór pomiędzy zagadnieniami jakości wody albo procesami uzdatniania

From the page, pictured in Figure 3, the user can choose either the "Water Quality Issues" or the "New Treatment Technology" button.

After clicking on the WATER QUALITY ISSUES button (one on the left), the screen pictured in Figure 4 should appear - listing the technologies and their intended use for various water quality compliance objectives. Once the user identifies the technology to evaluate based on the issues it can solve for their system, the technology can be selected by either clicking on the technology name, or by highlighting the radio button adjacent to the technology and clicking on the „Submit" button located on the top or bottom of the water quality issues matrix. Clicking the printer icon next to the technology will open a separate window with a PDF file (the user must have PDF reader installed on his or her computer) providing a brief description of the technology. The „Delete" button will delete all the previous values for the selected technology for that user. The „Reset" will reset the values to the default.
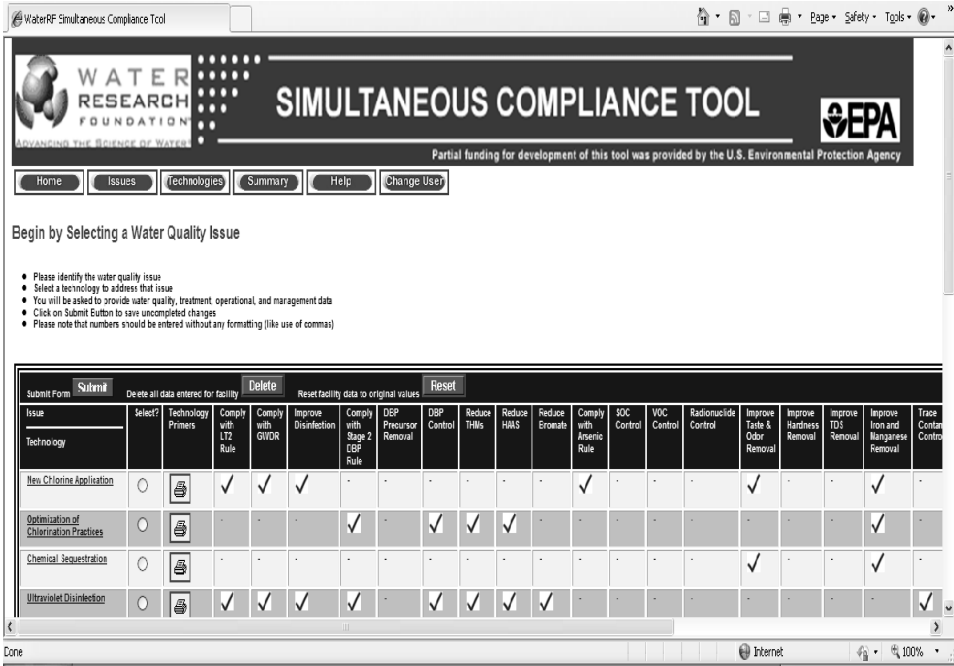
Fig. 4.   Running the Tool via the Water Quality Issues On-Ramp

Rys. 4.   Program skoncentrowany na jakości wody

To run the tool using the New Treatment Technology on-ramp, the user should click on the button (on the right) identified as NEW TREATMENT TECHNOLOGY. After clicking on this button, the screen presented in Figure 5 should appear, listing the technologies and their intended use for various water quality compliance objectives. Once the user identifies the technology to evaluate based on the issues it can solve for their system, the technology can be selected by either clicking on the technology name, or by highlighting the radio button adjacent to the technology and clicking on the „Submit" button located on the top or bottom of the water quality issues matrix. Clicking the printer icon next to the technology will open a separate window with a PDF file providing a brief description of the technology.

Fig. 5.   Running the Tool via the Treatment Technology On-Ramp

Rys. 5.   Program skoncentrowany na procesach uzdatniania wody

For example, the user selected the radio button adjacent to technology New Chlorine Application and clicks on „Submit". Once a technology is selected, the tool functions identically regardless of the on-ramp.

New Chlorine Application-Results of Analysis

IMPORTANT - Please answer all questions with answers that are representative of your system. Default values will be used if answers are not provided for a particular parameter.

Utility Information

Utility Name	ABC
Utility State	AZ
Utility Contact Name	
Water Treatment Plant	ABC
Utility Design Flow (mgd)	5
Utility Average Flow (mg)	3

Water Quality Inputs

Raw water iron in mg/L?	Low(=<0.3)
Raw water manganese in mg/L?	Low(<0.05)
Source Water Type Value?	Surface
Source Water Color Value?	Medium
Source Water Organics Value?	Medium

Water Treatment System Inputs

Chlorination Type Value?	Gas
Chlorination Location Value?	Treatment Plant or Well Head
Filtration After Chlorination?	No

Water Distribution System Inputs

Distribution System Residual Value?	Medium(0.5-1.0)

Submit

Fig. 6.   *Evaluating the technology: New Chlorine Application*

Rys. 6.   *Ewaluawanie technologii: Instalacja chlorowania*

   After clicking on the „Submit" button the user is navigated to Technology Input page for the selected technology selected. For the example of New Chlorine Application technology, the input screen shown in Figure 6 appears. The user is required to go through the various input needed for this technology and select the appropriate parameter values that best describes their water quality and treatment system. After the user is satisfied with the input values, the user then clicks on the „Submit" button to run the analysis. Clicking on the „Submit" button without selecting any input parameters will run the analysis with default values for the input parameters.

After clicking the „Submit" button on the previous step, the program analyzes the technology based on the inputs provided and displays the following screen, presented in Figure 7, with the results of the analysis; summarizing the unintended consequences for implementing the selected technology at the user's treatment system. This page shows the status of the various unintended consequences, provides a reason for any issues of concerns, and provides advisory about the unintended consequences. The status is categorized as either a green flag or a red flag. The red flag indicates that for the given input parameters there could be significant concerns. The Advisory Commentary provides information about how the issue can be mitigated. The input parameters are also listed at the bottom of the page and can be viewed or modified by scrolling down this page. The user can run the tool iteratively by altering the input parameters to achieve a green status for all the unintended consequences.

Compliance Issue or Consequence	Status	Reasons for Red Status (if applicable)	Advisory Commentary
Taste And Odor Complaints	Review	• In surface water systems, moderate chlorine residuals in the distribution system resutls in chlorinous odor.	• Customers who are not exposed to chlorinated water before may detect chlorinous odor of the treated water after the implementation of a new chlorination system. This could be observed even if the treatment system operator maintains a low residual in the distribution system and is more prominent in systems with moderately high chlorine levels. Use of surface water as the source water may also cause additional taste and odor complaints as the chlorine interacts with the algae and other organic matter typically found in surface waters. Steps should be taken to minimize chlorine residual in the distribution system without compromising microbial control. Proper communication with the customers should be undertaken prior to implementation of a new chlorination system. The customers should be advised that the new chnorination system is being implemented to increase the safety of the treated water.
DBP Formation	OK		• Addition of a new chlorination process will result in the formation of disinfection by products some of which (e.g. THMs and HAA5) are regulated. With moderately colored water, the formation may exceed the compliance target of the regulated DBPs. DBPs must be monitored at the treatment plant effluent and agreed upon (with the regulatory authority) locations within the distribution system. If the DBP levels exceed compliance levels, additional treatment process (e.g., coagulation, adsorption, etc.) may need to be implemented at the treatment plant.
Changes to corrosivity of treated water	OK		• Adding a new chlorination step is expected to alter the oxidation state of the treated water which may impact the corrosivity of the treated water. In general, the more oxidized chlorinated water is expected to be more stable, although, in some cases chlorinated water may result in sloughing off of some corrosion products from inside the distribution system pipes. Chlorinated water may also increase corrosion in household plumbing. If corrosion is observed, an evaluation may need to be performed to determine the best way to control corrosion which may need the addition of corrosion inhibitors at the treatment plant.
Iron/Manganese Precipitation leading to color changes	OK		• Adding a new chlorination step is expected to oxidize the dissolved iron and manganese in the source water in to visible precipitates that show up as colored water in customers tap. Due to low levels of iron and manganese in the source water, the colored water complaints are expected to minimum or none; however, there may be colored water in the distribution system due to the implementation of chlorination. To minimize the colored water complaints, a filtration step after chlorination may need to be implemented.
Security/safety issues with new chemical	OK		• The new chlorination system must be properly designed and constructed to ensure safety of chemical handling by the operators. Proper containment and safety procedures need to be implemented to ensure the safety of the surrounding people from accidental release of chlorine gas.
Compatibility with existing technologies	OK		• The new chlorination system must be properly designed and constructed to ensure safety and compatibility with existing technologies at the treatment plant.

Fig. 7. Understanding the output from the New Chlorine Application

Rys. 7. Wyniki analizy decyzji o instalacji chlorowania wody

2. Brief summary of water treatment technologies

2.1. New chlorine application

Chlorine is the most widely used disinfectant in water treatment primarily due to its low costs and relative ease of operation. Chlorine is typically used as a primary disinfectant for the inactivation of microorganisms and as a secondary disinfectant to maintain chlorine residual levels in the distribution system to minimize biological regrowth. For these reasons, chlorine is often used to comply with the requirements of the Surface Water Treatment Rules and Total Coliform Rule. In addition to the disinfecting capabilities, chlorine is a strong oxidizing agent that is used in various water treatment processes such as color removal. Addition of chlorine to water produces hypochlorous acid (HOCl), and various byproducts depending on the type of chlorine used. Chlorine is commercially available in the form of compressed elemental gas (Cl_2), liquid solute ons of sodium hypochlorite (NaOCl), and solid calcium hypochlorite ($Ca(OCl)_2$). NaOCl can also be generated on-site by electrolysis of brine solutions. The brine solution, which is formed by the combination of granulated salt and softened water, is delivered to an electrolytic cell where NaOCl and hydrogen gas are formed. Gaseous chlorine is typically injected into a carrier water stream before injection into the process. The dry forms are typically used to create a saturated hypochlorite solution that is then injected into the process. The liquid forms, whether purchased as a bulk sodium hypochlorite solution are generated on-site, are injected directly into the process. Chlorine reacts with inorganic and organic compounds in the source water. In general, the compounds are oxidized to form other compounds. In the case of microorganisms, chlorine reacts with the critical components of the organism to cause inactivitation. The effectiveness of chlorination is dependent on dose, contact time, pH, and temperature.

2.2. Otimization of chlorination practices

Optimizing chlorination practices can be an effective strategy to reduce disinfection byproducts. It includes several strategies: eliminate pre-chlorination, move the point of chlorine addition, optimize chlorine dose, reduce chlorination pH. Eliminating pre-chlorination can be particularly effective for the control of disinfection byproducts (DBPs). However, failure to replace chlorine with an alternative pre-oxidant, such as potassium permanganate, can result in several process upsets. Algae, taste and odor, iron and manganese, and other contaminants for which pre-chlorination was effective may now pass through the treatment process. Further, failure to maintain oxidizing conditions in the filters can result in desorption of manganese dioxide and cause pink or yellow water problems in the distribution system. Where primary disinfection credit is awarded for prechlorination, alternate disinfection strategies need to be installed prior to elimination of pre-chlorination. Moving the point of chlorination further downstream in the treatment processes, for example, after sedimentation/clarification, can also be an effective strategy for reducing DBPs. Delaying chlorine addition until after coagulated material, including natural organic matter (NOM) is removed from the process, minimizes the concentration of DBP precursors present and reduces DBP formation.

2.3. Chemical sequestration

Chemical sequestration is a method used in water treatment to control metals release and other factors that influence water quality. Chemical sequestering agents do not prevent corrosion so much as they prevent corrosion by-products from precipitating and causing color or other aesthetic issues. Chemicals used for sequestration purpose bind up targeted compounds to prevent reactions that normally that cause corrosion in the piping of the distribution system. Corrosion inhibitors form a protective, relatively insoluble film on the inside surface of the pipe to act as a barrier between the water and the pipe surface and prevent dissolution or release of metals (e.g. lead, copper, or iron) from the pipe wall. Sequestration is generally used for control of red water and other aesthetic problems, whereas corrosion inhibitors are primarily used for compliance with the Lead and Copper Rule. The most common chemical sequestering agents are polyphosphates and include glassy phosphates and hexametaphosphate. Most corrosion inhibitors are also phosphate-based, but are generally of the orthophosphate variety (e.g., phosphoric acid or zinc ortho-phosphate). Orthophosphate/polyphosphate blends are also frequently used to achieve the benefit of both chemical sequestration and corrosion inhibition. To ensure effectiveness of the sequestering/ inhibiting agent, selection of the type of agent is important. For example, polyphosphates can be used as a sequestering agent for iron and control of red water, prevention of calcium carbonate scaling, but should not be used for lead control. On the other hand, orthophosphate can be very effective for the control of lead and copper corrosion, but polyphosphates generally result in increased corrosion of these metals. Selection of an agent is dependent on the water system, operational conditions, water quality of the distribution system, and particular water quality concerns.

2.4. Ultraviolet disinfection

Ultraviolet (UV) light can be used for the inactivation of drinking water pathogens or in combination with hydrogen peroxide as an advanced oxidation process for the oxidation of micropollutants. UV disinfection or oxidation is a physical process that utilizes UV light and does not require addition of any chemicals. This technology is known for its germicidal power in inactivating microorganisms (i.e. bacteria, viruses, algae, etc.) including chlorine- resistant pathogens, such as Cryptosporidium. UV disinfection uses UV light to inactivate pathogens by disrupting their DNA strands making them non-viable and non-infectious. UV light is generated by flowing electrons from an electrical source through ionized mercury vapor. UV lamps commonly used in drinking water treatment are classified as low-pressure (LP) lamps, low-pressure high output (LP-HO) lamps, and mediumpressure (MP) lamps. LP-HO lamps have special design features that allow for higher UV radiation transmittance and are therefore more efficient than MP lamps. MP lamps produce 10 to 20 times higher UV radiation outputs than LP and LP-HO lamps; thereby requiring fewer lamps and decreased maintenance. However, power requirements are significantly higher and higher temperatures generated can cause scaling of sleeves in some waters. LP and LP-HO systems are typically better suited for small and medium sized systems because of their reliability associated with operating with multiple lamps. The UV dosage applied for inactivation is a function of UV irradiance and exposure time (intensity x time, IT) and is analogous to the CT term used in for chemical disinfectants. Compared with conventional chemical disinfection methods, UV disinfection requires a significant amount of electrical power.

2.5. Enhanced coagulation

Enhanced coagulation is now widely practiced for removing DBP precursors, and can also removes inorganic, particulate, and color causing compounds. It includes several optimization strategies: increase coagulant dose, reduce coagulation pH, reduce coagulation pH and increase dose, and change coagulant with/without the above. In coagulation, a positively charged coagulant (usually an alumimum or iron salt) is added to raw water and mixed in the rapid mix chamber. The coagulant alters or destabilizes negatively charged particulate, dissolved, and colloidal contaminants. The optimal pH range for coagulation is 6-7 when using alum and 5.5-6.5 when using iron. For high alkalinity water, excessive amounts of coagulant may be needed to lower the pH to the optimal pH range. In these cases, it may be beneficial to use acid in addition to the coagulant to reduce the amount of coagulant needed and effectively lower chemical costs. Reducing the coagulation pH, increasing the coagulant dose, or changing coagulants can affect finished water stability and corrosion control effectiveness. It is important that any reduction in coagulation pH be adequately re-adjusted prior to distribution to minimize the potential for increased lead, copper, or iron corrosion.

2.6. Microfiltration and ultrafiltration

Microfiltration (MF) and ultrafiltration (UF) are membrane filtration processes commonly used in water treatment. MF and UF are typically applied for the removal of particulate and microbial contaminants, and are frequently used as an alternative to rapid sand filtration in conventional treatment and softening applications. The primary difference between MF and UF is the pore size of the membranes. Both MF and UF membranes are primarily used for particulate and microbiological contaminant removal. Particulates removed include suspended solids, turbidity, some colloids, bacteria, protozoan cysts, and viruses (only UF has been demonstrated to remove viruses to any significant degree). Inorganic chemicals (e.g., phosphorus, hardness and metals) may be removed with suitable pretreatment. Limited dissolved organics removal may also occur by either of these processes. MF and UF membrane systems frequently require some type of source water pretreatment to prevent membrane fouling. The type of pretreatment required depends on the feed water quality and membrane type. Generally, surface water requires more extensive pretreatment than groundwater due to higher suspended solids and biological matter content. Water temperature has a significant impact on water density and viscosity, which impacts MF and UF membrane performance. As the viscosity and density increase, the transmembrane pressure required to pass the water through the membrane also increases. Both MF and UF membrane systems include routine backwashing to remove foulants from the membrane. Backwash frequency and duration depend on the membrane system and specific feed water quality conditions and treatment requirements. Chemical clean-in-place (CIP) is used periodically to control membrane fouling.

2.7. Non-GAC adsorption process

Adsorption is a physical-chemical process in which contaminants accumulate and adsorb onto the adsorbent surface as water passes through the absorbent. Adsorbent materials are subdivided into two major categories: carbon-based (such as granular activated carbon or GAC) and non-carbon based materials. Non-GAC adsorption processes can be used to remove inorganic contaminants, such as arsenic, chromium, and perchlorate, endocrine disrupting chemicals (EDCs), and pharmaceuticals and personal care products (PPCPs). Non-GAC adsorption is most commonly used to comply with the Arsenic and Radionuclides rules. Inorganic contaminants are removed from the water in two ways: electrostatic/physical attraction or chemical attraction. Electrostatic/physical attraction, also known as Van der Waals forces, physically attracts the contaminant ion in the water to the adsorbent surface. Chemical attraction chemically bonds the targeted contaminant ion to the adsorptive media. There are a number of non-carbon adsorbent materials available, such as activated alumina, granular ferric hydroxide, sulfur-modified iron, and other specialty adsorbents. The effectiveness of the adsorptive media depends on the concentration of the target contaminant ion, operating pH, presence of other competing ions, surface-charge of the adsorbents, physical-chemical characteristics of the adsorbent, time and flow characteristics.

2.8. Aeration and air stripping

Aeration and air stripping technologies are used for a variety of water treatment applications including the oxidation and removal of metals, volatile organic compounds (VOCs), volatile disinfection byproducts, and hydrogen sulfide. Air stripping is most commonly used for compliance with VOC regulations; whereas aeration is commonly used as an oxidation technology for iron and manganese removal and taste and odor control (e.g., hydrogen sulfide oxidation). Aeration is a process in which air or oxygen is transferred to water and air stripping is the process in which gas is removed from water. These treatment processes are based on the principle of Henry's Law, which is described as the tendency of a constituent to transfer from the liquid to the gas phase at equilibrium. The Henry's Law constant is the ratio of the equilibrium concentration of a particular contaminant in air to its concentration in water; therefore, the larger the constant the greater the tendency for that contaminant to volatize. There are four general categories of aeration and air stripping methods: waterfall aeration (i.e., spray aeration, cascade aeration, tray aeration, etc.), bubble aeration, mechanical aeration, and pressure aeration. The effectiveness of aeration and air stripping depends on the method selected, the Henry's law constant of the contaminant, design factors such as air-to-water ratio, flow and loading rate, available area of mass transfer, temperature, pH, and algae production/fouling of the aerator.

2.9. Oxidation and pressure filtration

Oxidation and filtration is an effective method in removing both organic and inorganic contaminants from water. Oxidation converts the dissolved inorganic substances to insoluble particulates, which are then removed from the water by filtration. For this

reason, it is most frequently used for iron removal. It can also be used to comply with the turbidity and disinfection requirements of the Long Term 2 Enhanced Surface Water Treatment Rule. Oxidants typically used in water treatment include chlorine, chlorine dioxide, potassium permanganate, and ozone. Oxidation is the chemical process of changing the soluble inorganic species into insoluble precipitates. Effectiveness of the oxidation process depends on water chemistry (e.g. pH, concentration of soluble species) and the chemical dose of the added oxidants. Filtration is a physical process where particulates are removed by mechanical means such as particle interception, sedimentation, diffusion, and attachment. The removal of the particulates is driven by the physical properties of the granular media through which the water passes.

2.10.   Post filtration GAC contactors

Granular activated carbon (GAC) is commonly used in drinking water treatment to adsorb synthetic organic chemicals and natural organic compounds that cause taste and odor, color, and can react with chlorine to form disinfection byproducts (DBPs). Adsorption is both the physical and chemical process of accumulating a substance at the interface between liquid and solids phases. GAC is an effective adsorbent because it is a highly porous material and provides a large surface area to which contaminants may adsorb. The two most common options for locating a GAC treatment unit in water treatment plants are: (1) post-filter adsorption, where the GAC unit is located after the conventional filtration process (as shown above); and (2) filter adsorbers, in which some or all of the filter media in a granular media filter is replaced with GAC. In post-filter applications, the GAC contactor receives the highest quality water and, thus, has as its only objective the removal of dissolved organic compounds. Backwashing of these absorbers is usually unnecessary, unless excessive biological growth occurs. This option provides the most flexibility for handling GAC and for designing specific adsorption conditions. The empty bed contact time (EBCT) and the design flow rate define the size of and amount of carbon in a GAC contactor. The EBCT is a measure of the length of time in which water is in contact with the carbon. As the carbon adsorption sites are consumed, breakthrough occurs and the GAC needs to be regenerated or replaced. A longer EBCT can delay breakthrough and reduce the GAC replacement/regeneration frequency. Typical EBCTs for water treatment applications range between 5 to 20 minutes. Shorter EBCTs are likely to require much more frequent replacement or regeneration of the GAC media and the application is likely to become cost prohibitive. GAC is more effective for the removal of DBP precursors than DBPs themselves. As a result, when used for control of DBPs, facilities that utilize pre-chlorination are likely to discontinue that practice.

2.11.   Ozone and ozone-related advanced oxidation processes

Ozone (O_3) is one of the strongest disinfectants and oxidants available in drinking water treatment. Combinations of ozone and hydrogen peroxide (O_3/H_2O_2) and ultraviolet light and hydrogen peroxide (UV/H_2O_2) are also being used more frequently as advanced oxidation processes (AOPs). The O_3/H_2O_2 and UV/H_2O_2 processes enhance formation of the hydroxyl radical (•OH) which is a more powerful oxidant than molecular ozone and other oxidants and thus has the capability of oxidizing a variety of organic and inorganic contaminants. Ozone is

widely used in drinking water treatment for its oxidation (color, taste and odor, iron and manganese) and disinfection capabilities (Cryptosporidium). AOPs have been demonstrated to be effective for the removal/destruction of compounds not readily oxidized by ozone, or which may require higher than normal ozone doses (e.g., PCE, TCE, atrazine, taste and odor compounds such as MIB and geosmin) and not be cost-effective. AOPs may make oxidation of these contaminants more economical. Ozone can be applied at various points in the treatment train, although it is usually applied prior to coagulation (reduces coagulant demand) or filtration (causes microflocculation which improves filterability). Ozone is typically added to water in a contactor consisting of several enclosed chambers via a diffused bubble system. In the first chamber, water flows downward against rising bubbles while in second chamber, water flows upward. Additional chambers are added to ensure sufficient contact time between ozone and water to achieve the desired treatment objective. The most efficient operational use of O_3/H_2O_2 is to add peroxide into the second chamber of an ozone contactor. This configuration allows the utility to obtain disinfection credits for ozonation while achieving the benefit of AOP for destruction of micropollutants. The most common point of application for an UV/H_2O_2 system is after filtration (lower turbidity, reduced obstruction/shielding of UV light, etc.).

2.12. Chlorine dioxide

Chlorine dioxide is a chlorine compound in the +IV oxidation state and is therefore, a powerful oxidant and disinfectant. It is frequently used to improve the removal of iron and manganese, arsenic, color, taste and odor compounds (phenolic, decaying vegetation and algal-related compounds), and inactivate chlorine-resistant microorganisms such as Cryptosporidium. Chlorine dioxide oxidizes natural organic matter (NOM) reducing disinfection byproduct (DBP) precursor concentrations. Chlorine dioxide can also be used as an alternative primary disinfectant to reduce the total chlorine dose. Both may result in a reduction in the formation of chlorinated DBPs, such as trihalomethanes and haloacetic acids. Chlorine dioxide can be applied at several points during treatment: the raw water as a preoxidant, the sedimentation tank, post-sedimentation or the filtered water as a primary disinfectant. Chloramine or chlorine must be used for secondary disinfection following chlorine dioxide application. Pathogen inactivation with chlorine dioxide is much less affected by pH than chlorine. Consequently, chlorine dioxide is a much more effective disinfectant than chlorine at higher pH levels. Iron concentration, manganese concentration, sunlight exposure, and aeration are among the parameters that exert additional chlorine dioxide demand. Greater dose and contact time, as well as increased temperature correlate with greater oxidation and disinfection with chlorine dioxide application. Chlorine dioxide gas is explosive under pressure and must therefore be generated onsite. The generation process can vary depending on the application. Typically, chlorine dioxide is generated from reaction of sodium chlorite ($NaClO_2$) solution with gaseous chlorine (Cl_2) or hypochlorous acid (HOCl). New generators have been developed that replace the solution sodium chlorite with a solid form for minimized byproduct formation; and electrolysis of sodium chlorite has recently been introduced in the U.S. for low dose applications. Chlorine dioxide yields lower levels of chlorinated byproducts in comparison to free chlorine. However, approximately 70% of the chlorine dioxide applied in water treatment is converted to chlorite (ClO-) – a regulated disinfection byproduct with a maximum contaminant level of 1 mg/L. Chlorate is also a byproduct of chlorine dioxide decay. The maximum recommended sum of chlorine dioxide, chlorite and chlorate in the distribution system should be less than 1.0 mg/L.

2.13.   Lime softening

Lime softening is a process that uses chemical precipitation with lime and other chemicals to reduce hardness and remove disinfection byproduct (DBP) precursors in source waters. It can also be used for the removal of arsenic, radionuclides, dissolved organics, color, and microbial contaminants. For these reasons, lime softening is used to comply with many drinking water regulations, including the Surface Water Treatment Rules, Disinfectants and Disinfection Byproducts Rules, Arsenic Rule, Radionuclides Rule, and others. The three most common types of softening processes are conventional lime-soda ash treatment, excess lime treatment, and split treatment. The type of treatment selected is based on the quality of the source water. In each process, chemicals, typically lime and soda ash, are added to precipitate the targeted ions. The precipitates are then removed by conventional processes such as coagulation-flocculation, sedimentation, and filtration. The effectiveness of the lime softening process is dependent on pH, precipitate properties, oxidation state of the contaminant, and specific ultraviolet absorbance value.

2.14.   Nanofiltration and reverse osmosis

Nanofiltration (NF) and reverse osmosis (RO) are membrane separation technologies that reverse the natural osmotic process by applying a feed pressure which forces water through a membrane against the natural osmotic gradient. This increases the dissolved contaminant concentrations on one side of the membrane. The primary difference between NF and RO is the size of dissolved contaminants that can be removed. NF membranes are typically used for hardness and organics (i.e. DBP precursors) removal. RO membranes are typically used for TDS and monovalent ion removal (e.g., seawater and brackish water desalting, F- and Cl- removal). NF and RO processes include three basic flow streams: the feed, permeate or product, and concentrate or waste streams. A treatment process generally consists of multiple stages, wherein the concentrate from the prior stage becomes the feed for the subsequent stage. The permeate from each stage is blended together for the final product stream. The concentrate from the final stage is usually wasted. NF and RO membrane systems always require some type of pretreatment to prevent membrane fouling. The type of pretreatment required depends on the feed water quality and membrane type. For surface waters, pretreatment may be extensive and include coagulation, sedimentation, pH adjustment, microfiltration, GAC filtration, etc. Residuals generated from NF and RO systems include the concentrate from the membrane processes and the spent cleaning chemicals. Concentrate disposal can be challenging as it is highly regulated by government agencies. Concentrate is typically a relatively high volume, high TDS waste stream and requires a comparatively large body of water for discharge or must be discharged to a wastewater treatment plant or deep well injection. Spent chemical cleaning solutions are generally acidic in nature and require neutralization prior to disposal.

2.15.   Ion exchange ans adsorption

Ion exchange (IX) and adsorption processes are used to remove dissolved ions and other charged species from water. IX processes are reversible chemical reactions that remove dissolved ions from solution and replace them with other similarly charged ions. Adsorption processes rely on surface charges to adsorb charged ionic species. Most IX and adsorption processes in water treatment operate in a continuous mode.

Ion exchange or adsorption occurs as water flow (typically in a down-flow mode) through a packed-bed of IX resin or adsorption media. In water treatment, the most common IX process is cation exchange softening in which calcium and magnesium are removed. Radium can also be removed from drinking water by cation exchange. Anion exchange processes can be used for the removal of contaminants such as nitrate, fluoride, perchlorate, uranium, selenium, arsenic, sulfate, and natural organic matter (NOM), as well as others. Adsorption processes, such as activated alumina and granular ferric hydroxide, are used to remove arsenic and similar species. Competition for ion exchange or adsorption sites can greatly impact a given system's efficiency in removing contaminants. Generally, ions with higher valence, greater atomic weights and smaller radii are preferred by IX resins and adsorption media. Competing ions lead to a reduction in capacity for the target contaminant. When the capacity of the IX resin is exhausted, it is necessary to regenerate the resin using a saturated solution of the exchange ion (e.g., Na^+ or Cl^-).

2.16.   GAC filter adsorbers

Granular activated carbon (GAC) is commonly used in drinking water treatment to adsorb synthetic organic chemicals and natural organic compounds that cause taste and odor, color, and can react with chlorine to form disinfection byproducts (DBPs). Adsorption is both the physical and chemical process of accumulating a substance at the interface between liquid and solids phases. GAC is an effective adsorbent because it is a highly porous material and provides a large surface area to which contaminants may adsorb. The two most common options for locating a GAC treatment unit in water treatment plants are: (1) post-filter adsorption, where the GAC unit is located after the conventional filtration process (as shown above); and (2) filter adsorbers, in which some or all of the filter media in a granular media filter is replaced with GAC. In the filter adsorber configuration GAC is used for the removal of both dissolved organics and turbidity/suspended solids. Filter adsorbers may also be used for achieving biological stabilization of the treated water. Retrofitting existing high rate granular media filters can significantly reduce capital costs, however, filter adsorbers have shorter filter run times and must be backwashed more frequently than post-filter adsorbers. The empty bed contact time (EBCT) and the design flow rate define the size of and amount of carbon in a GAC contactor. The EBCT is a measure of the length of time in which water is in contact with the carbon. As the carbon adsorption sites become used up, breakthrough occurs and the GAC needs to be regenerated or replaced. A longer EBCT can delay breakthrough and reduce the GAC replacement/regeneration frequency. For filter adsorbers to be effective, an EBCT of at least 5 minutes is generally required. Shorter EBCTs are likely to require much more frequent replacement or regeneration of the GAC media and the application is likely to become cost prohibitive. GAC is more effective for the removal of DBP precursors than DBPs themselves. As a result, when used for control of DBPs, facilities that utilize pre-chlorination are likely to discontinue that practice.

2.17. Conversion to chloramines

Chloramines are a family of oxidants formed by the reaction of chlorine and ammonia. In water treatment, chloramines are primarily used as a secondary disinfectant to provide a residual in the distribution system; however, chloramines are occasionally used as a primary disinfectant. Chloramination is often an attractive alternative to chlorine for secondary disinfection because it is more persistent in the distribution system and minimizes the formation of trihalomethanes and haloacetic acids. The ratios at which chlorine and ammonia are fed control the species of chloramines present. Monochloramine (NH_2Cl) is the preferred species, as it is a more powerful oxidant and is less likely to cause taste and odor problems in the distribution system than dichloramine ($NHCl_2$) and trichloramine (NCl_3). Although a weaker oxidant than chlorine, monochloramine oxidizes precursors of disinfection byproducts, inactivates microorganisms, and controls biofilm. Due to its persistence, chloramines are often more effective in controlling biofilms in distribution system. The effectiveness of chloramination is dependent on dose, chlorine to ammonia ratio, contact time, pH, and temperature.

2.18. pH adjustment

Raising the finished water pH is a common method for reducing corrosion of the distribution system piping and the occurrence of colored water. pH determines the solubility of most pipe materials and the films that form in the pipes from the corrosion byproducts. pH adjustment may also be used as a strategy to reduce the concentrations of certain species of disinfection byproducts (DBPs) in the distribution system. For example, a reduction in pH may reduce trihalomethane (THM) concentrations; however, it may also result in a corresponding increase in haloacetic acid (HAA) concentrations. For these reasons, pH adjustment is primarily used as a corrosion control strategy to comply with the Lead and Copper Rule, though it is occasionally used as an optimization strategy to reduce DBPs.

2.19. Permanganate addition

Permanganate is a strong oxidant used to control taste and odors, oxidize dissolved metals, such as iron and manganese, and control biological growth in treatment plants. Though it is a strong oxidant, and can be used as a disinfectant to inactivate microorganisms, the disinfection capabilities of permanganate are limited. Permanganate can also be used to remove color, control zebra mussels in intake structures and pipelines, oxidize disinfection byproduct (DBP) precursors, and reduce the demand for other disinfectants. The most common type of permanganate used in water treatment is potassium permanganate ($KMnO_4$); though sodium permanganate ($NaMnO_4$) is also used. Typically in water treatment permanganate is applied early in the treatment process; for example, in a pre-oxidation basin prior to the primary treatment process or at a raw water intake; however, it can also be applied at the rapid mix tank in conjunction with other coagulants or in the clarification process upstream of filters. Potassium permanganate is available as a dry, crystalline solid. Typical feed systems include a dry chemical feeder, storage hopper, collector, solution dissolver tank with mixers, and metering pumps. Effective-

ness of permanganate addition is dependent on dose, contact time, pH and temperature. Sodium permanganate is available in liquid form, and is highly acidic. Typical feed systems include bulk storage tanks, transfer pumps and day tanks, and chemical metering pumps. Because of its highly acidic nature, material selection is extremely important, not only for the feed system, but also for downstream equipment and processes.

2.20.   Magnetic ion exchange

Magnetic ion exchange (MIEX®) is a proprietary water treatment process used to remove dissolved ions and charged species from the source water that may be associated with disinfection byproduct (DBP) formation. For that reason, MIEX® is most commonly used for compliance with the Disinfectants and Disinfection Byproducts Rules. MIEX® utilizes anion exchange resins to remove the dissolved organic carbon (DOC) from the water by exchanging a chloride ion on the resin surface for the DOC, a significant portion of which is present as complex anions. The resin is located in a fluidized bed ion exchange reactor. The resin is continuously withdrawn from the reactor for regeneration while regenerated resin is placed back into the reactor to provide continuous removal of DOC. Biological growth is minimized in the process by the continual regeneration of the resin with a brine solution.

2.21.   Non-GAC biological filters

Biologically active filters (BAF) remove pollutants by three main mechanisms: biodegradation, adsorption of micropollutants, and filtration of suspended solids. The microbial growth attached to the filter media (biofilm) consumes the organic matter that would otherwise flow through the treatment plant and ultimately into the distribution system. The end products are carbon dioxide, water, biomass, and simpler organic molecules. Particle filtration takes place on the bare filter media as well as the biofilm. BAF is often used by systems that use ozone as adding a strong oxidant converts some of the dissolved organic materials in water into more readily biodegradable compounds. To promote biological activity ozone is added upstream to the filter beds. Key factors in controlling BAF performance include temperature, contact time, backwash operations, and water quality (pH, alkalinity, turbidity, TSS, dissolved oxygen, and biodegradable organic matter measured as BDOC or AOC). In particular, temperature controls biogrowth kinetic. Several studies report that biological activity is high during the summer when temperature is above 20 $^{\circ}$C and decreases during the cooler months with the winter (10 $^{\circ}$C and below). Filter loading rates are similar to those used in rapid sand filtration (2 to 4 gpm/sf). Maintaining biologically active filters will require those facilities that practice prechlorination to discontinue that practice, potentially impacting the removal of dissolved inorganic species, such as iron and manganese. The use of an alternative preoxidant, such as potassium permanganate can help to eliminate this concern. Primary and secondary disinfectant addition locations must be evaluated (to assure that sufficient contact time remains) when considering BAF.

Bibliography

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