

Finished Water Storage Facilities

1.0 Introduction

The goal of this document is to review existing literature, research and information on the potential public health implications associated with covered storage reservoirs.

Finished water storage facilities are an important component of the protective distribution system “barrier” that prevents contamination of water as it travels to the customer. Historically, finished water storage facilities have been designed to equalize water demands, reduce pressure fluctuations in the distribution system; and provide reserves for fire fighting, power outages and other emergencies. Many storage facilities have been operated to provide adequate pressure and have been kept full to be better prepared for emergency conditions. This emphasis on hydraulic considerations in past designs has resulted in many storage facilities operating today with larger water storage capacity than is needed for non-emergency usage. Additionally, some storage facilities have been designed such that the high water level is below the hydraulic grade line of the system, making it very difficult to turnover the tank. If the hydraulic grade line of the system drops significantly, very old water may enter the system. If tanks are kept full yet are underutilized, the stored water ages and water quality is affected.

The main categories of finished water storage facilities include ground storage and elevated storage. Finished water storage does not include facilities such as clearwells that are part of treatment or contact time requirements per the Surface Water Treatment Rules. Ground storage tanks or reservoirs can be below ground, partially below ground, or constructed above ground level in the distribution system and may be accompanied by pump stations if not built at elevations providing the required system pressure by gravity. Ground storage reservoirs can be either covered or uncovered. Covered reservoirs may have concrete, structural metal, or flexible covers. The most common types of elevated storage are elevated steel tanks and standpipes. In recent years, elevated tanks supported by a single pedestal have been constructed where aesthetic considerations are an important part of the design process. A standpipe is a tall cylindrical tank normally constructed of steel, although concrete may be used as well. The standpipe functions somewhat as a combination of ground and elevated storage. Only the portion of the storage volume of a standpipe that provides water at or above the required system pressure is considered useful storage for pressure equalization purposes. The lower portion of the storage acts to support the useful storage and to provide a source of emergency water supply. Many standpipes were built with a common inlet and outlet.

2.0 Description of Potential Water Quality Problems

Water quality problems in storage facilities can be classified as microbiological, chemical or physical. Excessive water age in many storage facilities is probably the most important factor related to water quality deterioration. Long detention times, resulting in excessive water age, can be conducive to microbial growth and chemical changes. The excess water age is caused by 1) under utilization (i.e., water is not cycled through the facility), and 2) short circuiting within the reservoir. Poor mixing (including stratification) can exacerbate the water quality problems by

creating zones within the storage facility where water age significantly exceeds the average water age throughout the facility. Distribution systems that contain storage facilities where water cascades from one facility to another (such as pumping up through a series of pressure zones) can result in exceedingly long water age in the most distant tanks and reservoirs. Although the storage facility is normally an enclosed structure, numerous access points can become entry points for debris and contaminants. These pathways may include roof top access hatches and appurtenances, sidewall joints, vent and overflow piping.

Table 1 provides a summary of water quality problems associated with finished water storage facilities.

Chemical Issues	Biological Issues	Physical Issues
Disinfectant Decay	Microbial Regrowth*	Corrosion
Chemical Contaminants*	Nitrification*	Temperature/Stratification
DBP Formation*	Pathogen Contamination*	Sediment*
Taste and Odors	Tastes and Odors	

*Water quality problem with direct potential health impact.

All issues listed in Table 1 can deteriorate water quality, but only those with direct potential health impacts (identified by an asterisk) are discussed in the following sections or in other White Papers.

2.1 Potential Health Impacts

Various potential health impacts have been associated with the chemical and biological issues identified in Table 1. The Chemical Health Effects Tables (U.S. Environmental Protection Agency, 2002a) provides a summary of potential adverse health effects from high/long-term exposure to hazardous chemicals in drinking water. The Microbial Health Effects Tables (U.S. Environmental Protection Agency, 2002b) provides a summary of potential health effects from exposure to waterborne pathogens.

2.1.1 Sediment

Sediment accumulation occurs within storage facilities due to quiescent conditions which promote particle settling. Potential water quality problems associated with sediment accumulation include increased disinfectant demand, microbial growth, disinfection by-product formation, and increased turbidity within the bulk water. Instances of microbial contamination and disinfection by-product formation due to storage facility sediments are described in the Pathogen Contamination and Microbial Growth section and the Disinfection By-Product formation section, respectively.

2.1.2 Pathogen Contamination and Microbial Growth

Microbial contamination from birds or insects is a major water quality problem in storage tanks. One tank inspection firm that inspects 60 to 75 tanks each year in Missouri and southern Illinois reports that 20 to 25 percent of tanks inspected have serious sanitary defects, and eighty to ninety percent of these tanks have various minor flaws that could lead to sanitary problems (Zelch 2002). Most of these sanitary defects stem from design problems with roof hatch systems and vents that do not provide a watertight seal. Older cathodic protection systems of the hanging type also did not provide a tight seal. When standing inside the tank, daylight can be seen around these fixtures. The gaps allow spiders, bird droppings and other contaminants to enter the tank. Zelch (2002) reports a trend of positive total coliform bacteria occurrences in the fall due to water turnover in tanks. Colder water enters a tank containing warm water, causing the water in the tank to turn over. The warm water that has aged in the tank all summer is discharged to the system and is often suspected as the cause of total coliform occurrences.

Storage facilities have been implicated in several waterborne disease outbreaks in the United States and Europe. In December 1993, a *Salmonella typhimurium* outbreak in Gideon, Missouri resulted from bird contamination in a covered municipal water storage tank (Clark et al. 1996). Pigeon dropping on the tank roof were carried into the tank by wind and rain through a gap in the roof hatch frame (Zelch 2002). Poor distribution system flushing practices led to the complete draining of the tank's contaminated water into the distribution system. As of January 8, 1994, 31 cases of laboratory confirmed salmonellosis had been identified. Seven nursing home residents exhibiting diarrheal illness died, four of whom were confirmed by culture. It was estimated that almost 600 people or 44% of the city's residents were affected by diarrhea in this time period.

A 1993 outbreak of *Campylobacter jejuni* was traced to untreated well water that was likely contaminated in a storage facility that had been cleaned the previous month (Kramer et al. 1996). Fecal coliform bacteria were also detected in the stored water.

In 2000, a City in Massachusetts detected total coliform bacteria in several samples at one of their six finished water storage facilities (Correia, 2002). The tank inspector discovered an open access hatch and other signs of vandalism. This tank was drained and cleaned to remove several inches of accumulated sediment. Three other finished water storage facilities were cleaned in 2001 without being drained and removed from service. The tank closest to the filtration plant was found to contain two to three inches of accumulated sediment and the tanks in outlying areas contained four to six inches of sediment. Shortly after the tanks were returned to service, the City experienced widespread total coliform occurrences in the distribution system (Correia, 2002). The City's immediate response was to boost the free chlorine residual in the distribution system to 4.0 mg/L (including at tank outlets). Also, the distribution system was flushed continuously for two days to remove the contaminated water. These measures resolved the coliform bacteria problem. A boil water order was not required. To prevent the problem from recurring, the City has instituted a tank cleaning program in which all tanks are cleaned on a three year cycle. City engineers are planning to improve water turnover rates by separating the tank inlet and outlet piping.

In 1995, a water district in Maine traced a total coliform bacteria occurrence in the distribution system to two old steel tanks with wooden roofs (Hunt 2002). Upon inspection, many roof shingles were missing and large gaps were present in the tank roofs. After the tanks were

drained, an interior inspection found two feet of accumulated sediment, widespread coating failure on the tank sidewalls, and evidence of human entry. The tanks were cleaned and the distribution system was flushed and disinfected. A boil water order was in place until system water quality was restored. The tanks have since been replaced with a modern preload concrete tank.

Uncovered storage reservoirs provide the greatest opportunity for contaminant entry into the distribution system. These reservoirs are potentially subject to contamination from bird and other animal excrement that can potentially transmit disease-causing organisms to the finished water. Microorganisms can also be introduced into open reservoirs from windblown dust, debris and algae. Algae proliferate in open reservoirs with adequate sunlight and nutrients and impart color, taste and odor to the water on a seasonal basis. Organic matter such as leaves and pollen are also a concern in open reservoirs. Waterfowl are known carriers of many different waterborne pathogens and have the ability to disseminate these pathogens over a wide area. For example, *Vibrio cholerae* has been isolated from feces of 20 species of aquatic birds in Colorado and Utah (Ogg, Ryder and Smith 1989). Waterfowl are known carriers of *S. Montevideo B*, *Vibrio cholerae*, and Hepatitis A virus (Brock 1979) and *E. coli*, Norwalk virus, Coronavirus, Coxsackieviruses, Rotavirus, Astrovirus, and Cryptosporidium (WRc and Public Health Laboratory Service 1997).

Reservoirs with floating covers are susceptible to bacterial contamination and regrowth from untreated water that collects on the cover surface. Birds and animals are attracted to the water surface and may become trapped. Surface water collected on the floating cover of one storage reservoir contained fecal coliform bacteria counts as high as 13,000 per 100 mL and total coliform bacteria counts as high as 33,000 per 100 mL (Kirmeyer et al. 1999). If the cover rips or is otherwise damaged, any untreated water on the cover would mix with the stored water, potentially causing health problems. Floating covers on storage reservoirs are susceptible to rips and tears due to ice damage, vandalism, and/or changing operating water levels.

Based on surveys of professional tank inspection firms, State primacy agencies and utilities, Kirmeyer et al. (1999) concluded that many storage facilities are not being inspected at all. For facilities that are inspected, it is likely that prior to implementation of the Interim Enhanced Surface Water Treatment Rule (IESWTR) they were inspected less frequently than the three-year frequency recommended by AWWA (AWWA Manual M42, 1998). The survey of tank inspection firms indicated that the most frequently documented interval between inspections at that time was six to eight years. Information on inspection practices subsequent to implementation of the IESWTR, which included a prohibition on new uncovered finished water reservoirs, re-focused utility and state regulators on the issues surrounding uncovered reservoirs and floating covers.

The most common problems reported by commercial inspectors in survey responses are: no bug screens on vents and overflows, cathodic protection systems not operating or not adjusted properly, unlocked access hatches, presence of lead paint (interior and exterior), and the presence of paints not approved by NSF International (Kirmeyer et al. 1999). The most common coating problems reported by commercial tank inspectors that relate to water quality (Kirmeyer et al. 1999) are: chemical leaching from incompletely cured coating; corrosion product buildup from

excessive interior corrosion; turbidity events during tank filling due to excessive bottom sediment; unknown chemical leaching due to non NSF-61 Coatings; and lead leaching from lead based interior coatings.

The Total Coliform Rule (TCR) was promulgated specifically to identify public water systems that are contaminated or vulnerable to contamination. The total coliform group of organisms is used to indicate the possible presence or absence of pathogens and thus, provides a general indication of whether the water is contaminated. The presence of fecal coliforms or *E. coli* provides stronger evidence of fecal contamination than does a positive total coliform test and the likely presence of pathogens (Levy et al. 1999). The Total Coliform Rule does not specifically require monitoring at storage reservoirs, however, state primacy agencies have oversight of utility monitoring plans and may require selection of sample sites, such as reservoirs, when appropriate in TCR Monitoring Plans.

The Surface Water Treatment Rule establishes maximum contaminant level goals (MCLGs) for viruses, *Legionella*, HPC, and *Giardia lamblia*. It also includes treatment technique requirements for filtered and unfiltered systems that are specifically designed to protect against the adverse health effects of exposure to these microbial pathogens. The Surface Water Treatment Rule requires that a “detectable” disinfectant residual (or heterotrophic plate count (HPC) measurements not exceeding 500/mL) be maintained in at least 95% of samples collected throughout the distribution system on a monthly basis. A system that fails to comply with this requirement for any two consecutive months is in violation of the treatment technique requirement. Public water systems must monitor for the presence of a disinfectant residual (or HPC levels) at the same frequency and locations as total coliform measurements taken pursuant to the total coliform regulation described above.

The loss of disinfectant residual within a storage facility does not necessarily pose a direct public health threat (many systems throughout the world are operated without use of a disinfectant residual). However, disinfectant decay can contribute to microbiological problems such as growth of organisms within the bulk water or sediment. The rate of decay can be affected by external contamination, temperature, nitrification, exposure to ultraviolet light (sun), and amount and type of chlorine demanding compounds present such as organics and inorganics. Chlorine decay in storage facilities can normally be attributed to bulk water decay rather than wall effects due to the large volume-to-surface area ratio.

A long detention time can allow the disinfectant residual to be completely depleted thereby not protecting the finished water from additional microbial contaminants that may be present in the distribution system downstream of the storage facility. This problem is illustrated in a recent investigation of storage tanks in a large North American water utility’s distribution system (Gauthier et al. 2000). An estimation of stored water turnover rate using routine water quality data and hydraulic modeling results found that one tank had a turnover rate of 5.6 to 7.6 days which was probably responsible for the periodic loss of disinfectant residual in the surrounding distribution system and several occurrences of total coliform bacteria. The high residence time was caused by the hydraulic arrangement of the tank and pumping system where most water was pumped directly to consumers and the remaining water was fed to the tank. Water leaving the tank typically had a chlorine residual of 0.05 mg/L.

A detailed discussion of potential health issues associated with microbial growth and biofilms is provided in a separate White Paper.

2.1.3 Nitrification

Nitrification is a potential health concern in finished water storage facilities due to the formation of nitrite and nitrate. Nitrification may occur within storage facilities due to long hydraulic residence times. Under the Safe Drinking Water Act (SDWA), primary MCLs have been established for nitrite-N, nitrate-N, and the sum of nitrite-N plus nitrate-N. The MCLs are 1 mg/L for nitrite-N, 10 mg/L for nitrate-N, and 10 mg/L for nitrite + nitrate (as N). The nitrite and nitrate MCLs are applicable at the point-of-entry to the distribution system, not within the distribution system where nitrification is most likely to occur. Review of nitrification episodes and information gathered from the literature indicates that an MCL exceedence within the distribution system due to nitrification is unlikely, unless source water nitrate-N or nitrite-N levels are close to their applicable MCLs. Potential public health issues associated with nitrification are discussed in the Nitrification White Paper.

2.1.4 Chemical Contaminants

Coating materials are used to prevent corrosion of steel storage tanks and to prevent moisture migration in concrete tanks. Through the 1970's, coatings used in finished water storage facilities were primarily selected because of their corrosion resistance and ease of application. This led to the use of industrial products like coal tars, greases, waxes and lead paints as interior tank coatings. These products offered exceptional corrosion performance but unknowingly contributed significant toxic chemicals to the drinking water. Grease coatings can differ greatly in their composition from vegetable to petroleum based substances and can provide a good food source for bacteria, resulting in reduced chlorine residuals and objectionable tastes and odors in the finished water (Kirmeyer et al. 1999).

An old grease coating on a storage tank interior in the state of Florida was suspected of causing water quality problems in the distribution system such as taste and odor, high chlorine requirements and a black slime at the customers tap. The Wisconsin Avenue 500,000 gallon elevated tank was originally coated with a petroleum grease coating when it was built in 1925. In 1988, the storage facility was cleaned and the grease coating was reapplied. In 1993, a tank inspection revealed that the grease had sagged off the tank walls and deposited a thick accumulation of black loose ooze in the bottom bowl of the tank (6-8 inches deep). A thin film of grease continued to coat the upper shell surfaces. Although this material had performed well as a corrosion inhibitor, it was introducing debris into the distribution system as well as creating a possible food source and environment for bacteria. The City decided to completely remove the grease and reapply a polyamide epoxy system. This work was completed in 1996 (Kirmeyer et al. 1999). Since the tank was returned to service, water quality has markedly improved. The required chlorine dosage rate has decreased from 4.0-5.0 mg/L to 3.5 mg/L. The chlorine residual at the tank outlet has improved from <1.0 mg/L to 1.4 mg/L. No more "black slime" complaints have been received.

The East Bay Municipal Utility District used hot-mopped coal tar as the standard interior coating system for tanks through the 1960's then discontinued its use due to concerns over VOCs (Irias, 2000). When manufacturer's directions and AWWA standards are not followed correctly, these coatings can leach organics into the finished water. Volatile organic compounds could be introduced to the stored water if sufficient curing time is not allowed after coating application (Kirmeyer et al. 1999). Burlingame and Anselme (1995) cite examples of odiferous organic solvents leaching from reservoir linings. Elevated levels of alkyl benzenes and polycyclic aromatic hydrocarbons (PAHs) have been reported in reservoirs with new bituminous coatings and linings (Yoo et al, 1984; Krasner and Means, 1985; Alben, 1980).

Alben et al (1989) studied leaching of organic contaminants from flat steel panels lined with various coatings, including vinyl, chlorinated rubber, epoxy, asphalt, and coal tar. Emphasis was given to the rate of leachate production and leachate composition. The test water was GAC processed tap water with a pH of 8 to 9. Leaching rates (mg/m²-day or ug/L-day) were assessed over a period of 30 days. Organic contaminants were found at parts-per-billion levels in water compared to parts-per-thousand levels in the coating. Detailed findings of the leaching study are provided in the Permeation and Leaching White Paper.

Solvents, adhesives and other materials used to repair floating covers could potentially contaminate the drinking water as storage reservoirs are not always drained to accomplish the repair. For example, Philadelphia formerly used trichloroethylene as a solvent to clean areas to be repaired on a Hypalon cover prior to making repairs (Kirmeyer et al. 1999). In 1984, Philadelphia repaired one basin's Hypalon cover 200 times. This Hypalon cover has since been replaced with a more durable, polypropylene cover.

Improper installation procedures may result in worker and public exposure to chemicals. For example, odor complaints at a Duval County, Florida utility led to a discovery of ethyl benzene contamination of the distribution system water (Carter, Cohen, and Hilliard, 2001). The source of ethyl benzene was determined to be a polyamide solvent applied to a ground storage water tank prior to painting. It is likely that solvent vapors carried over to an adjacent on-line aeration tower and became dissolved in the water. Flushing was conducted immediately as a response to this incident, and no samples were analyzed prior to flushing. After flushing, a distribution system water sample contained 0.004 mg/L ethyl benzene. The MCL for ethyl benzene is 0.7 mg/L and the secondary standard MCL threshold for odor is 0.03 mg/L.

When volatile compounds have entered a water distribution system through source contamination or contamination within the distribution system, storage facilities with a free water surface and reservoir vents can serve as a pathway for volatilization to the atmosphere. Walski (1999) describes an analysis method for estimating the loss of volatiles at a storage facility.

The National Sanitation Foundation (NSF) International and Underwriters Laboratory (UL) certify coatings and other products against ANSI/NSF Standard 61 (NSF 1996b), a nationally accepted standard addressing the health effects of water contact materials. Details on the NSF certification procedure are provided in the Permeation and Leaching White Paper.

The following AWWA standards were developed to ensure that approved coatings function as intended:

- D102 Coating Steel Water Storage Tanks
- D104 Cathodic Protection for Interior of Steel Water Tanks
- D110 Wire- and Strand-Wound Circular Prestressed-Concrete Water Tanks
- D130 Flexible Membrane Lining and Floating Cover Materials for Potable Water Storage

Twenty-one volatile organic compounds (VOCs) and 33 synthetic organic compounds (SOCs) are currently regulated under the Safe Drinking Water Act Phase I, II, and V Rules based on health effects that may result from long-term exposures. Compliance is determined based on annual average exposure measured at the point of entry to the distribution system.

2.1.5 Disinfection By-Products

Storage facilities provide opportunities for increased hydraulic residence times, allowing more time for disinfection by-products (DBPs) to form. Rechlorination within storage facilities exposes the water to higher chlorine dosages, potentially increasing disinfection by-product formation. Higher water temperatures in steel tanks during summer seasons can increase disinfection by-products as the chemical reactions proceed faster and go further at higher temperatures. Storage facilities with new interior concrete surfaces often have elevated pH levels that can also increase trihalomethane formation.

The USEPA has identified the following potential adverse health effects associated with HAA5 and TTHMs:

“Some people who drink water containing haloacetic acids in excess of the MCL over many years may have an increased risk of getting cancer. Some people who drink water containing trihalomethanes in excess of the MCL over many years may experience problems with their liver, kidneys, or central nervous system, and may have an increased risk of getting cancer.”

The forthcoming Stage 2 Disinfectants and Disinfection By-Products Rule is expected to include a new monitoring and reporting approach. Compliance with TTHMs and HAA5 standards will be based on a locational running annual average using monitoring data gathered at new monitoring locations selected to capture representative high levels of occurrence. MCL violations could potentially occur at single locations such as a finished water storage facility due to site-specific situations, including excessive water age or chlorine addition at the storage facility.

3.0 Prevention/Mitigation Methods

3.1 Indicators of Water Quality Problems within Storage Facilities

There are several indicators that may suggest water quality problems are occurring within storage facilities. These include aesthetic considerations that may be identified by consumers, as well as the results of storage facility monitoring efforts. It should be noted that indicators can be triggered by factors other than water age, such as insufficient source water treatment, pipe materials, and condition/age of distribution system and storage facility.

Aesthetic Indicators

The following indicators may be identified during water consumption:

- Poor taste and odor – Aged, stale water provides an environment conducive to the growth and formation of taste and odor causing microorganisms and substances. Improperly cured coatings can impart taste and odor to the stored water.
- Sediment accumulation – Improperly applied coatings can slough off reservoirs and accumulate at the bottom. Sediment carried into the storage facility from the bulk water can accumulate within the reservoir if reservoir maintenance and cleaning are not routinely performed.
- Water temperature – Stagnant water will approach the ambient temperature. Temperature stratification within reservoirs will impede mixing. Turnover due to stratification can entrain accumulated sediment.

Monitoring Indicators

The following indicators require sample collection and analysis:

- Depressed disinfectant residual – Chlorine and chloramines undergo decay over time.
- Elevated DBP levels – The reaction between disinfectants and organic precursors occur over long periods.
- Elevated bacterial counts (i.e., heterotrophic plate count).
- Elevated nitrite/nitrate levels (nitrification) for chloraminating systems.

3.2 Water Quality Monitoring and Modeling

Water quality monitoring and modeling are useful tools to assess the impact storage may be having on water quality in a distribution system. Studies can be conducted to define current or potential water quality problems in storage facilities. Water quality monitoring at storage facilities is not required by any specific federal regulations.

Monitoring within a storage facility can supplement tank inlet or outlet monitoring where short-circuiting or lack of use may cause water quality to vary widely within the tank. When detailed

investigation of a storage facility's impact is warranted, the ideal sampling program would capture water quality conditions throughout the storage facility, both vertically and spatially. Kirmeyer et al. (1999) recommended the following monitoring parameters: free and total chlorine residual, temperature, HPC, total and fecal coliform bacteria, pH, turbidity, and total dissolved solids. Monitoring in storage facilities can often be a difficult task and can present a safety issue because sampling taps or access ports are often not installed during the initial construction and utility workers must generally climb the tank and collect grab samples through the roof access hatchways.

Direct monitoring may not detect all potential water quality problems. For example, tank effluent sampling can result in zero bacteria counts, but microorganisms can still be present as biofilms on tank surfaces, in tank sediment or in the water (Smith and Burlingame 1994).

According to Grayman and Kirmeyer (2002), modeling can provide information on what will happen in an existing, modified, or proposed facility under a range of operating situations. There are two primary types of models: physical scale models and mathematical models. Physical scale models are constructed from materials such as wood or plastic. Dyes or chemicals are used to trace the movement of water through the model. In mathematical models, equations are written to simulate the behavior of water in a tank or reservoir. These models range from detailed representations of the hydraulic mixing phenomena in the facility called computational fluid dynamics (CFD) models to simplified conceptual representations of the mixing behavior called systems models. Information collected during monitoring studies can be used to calibrate and confirm both types of models.

3.3 Tank Inspections

Like water quality monitoring, tank inspections provide information used to identify and evaluate current and potential water quality problems. Both interior and exterior inspections are employed to assure the tank's physical integrity, security, and high water quality. Inspection type and frequency are driven by many factors specific to each storage facility, including its type (i.e. standpipe, ground tank, etc), vandalism potential, age, condition, cleaning program or maintenance history, water quality history, funding, staffing, and other utility criteria. AWWA Manual M42, Steel Water Storage Tanks (1998) provides information regarding inspection during tank construction and periodic operator inspection of existing steel tanks. Specific guidance on the inspection of concrete tanks was not found in the literature. However, the former AWWA Standard D101 document may be used as a guide to inspect all appurtenances on concrete tanks. Concrete condition assessments should be performed with guidance from the tank manufacturer. Soft, low alkalinity, low pH waters may dissolve the cementitious materials in a concrete reservoir causing a rough surface and exposing the sand and gravel. The concern is that in extreme cases, the integrity of reinforcing bars may be compromised. Sand may collect on the bottom of the storage facility during this process.

Routine inspections typically monitor the exterior of the storage facility and grounds for evidence of intrusion, vandalism, coating failures, security, and operational readiness. Based on a literature review and project survey, Kirmeyer et al. (1999) suggested that routine inspections

be conducted on a daily to weekly basis. Where SCADA systems include electronic surveillance systems, alarm conditions may substitute for physical inspection.

Periodic inspections are designed to review areas of the storage facility not normally accessible from the ground and hence not evaluated by the routine inspections. These inspections usually require climbing the tank. Periodic inspections, like routine inspections, are principally a visual inspection of tank integrity and operational readiness. Based on a literature review and project survey, Kirmeyer et al. (1999) suggested that periodic inspections be conducted every 1 to 4 months.

Comprehensive inspections are performed to evaluate the current condition of storage facility components. These inspections often require the facility to be removed from service and drained unless robotic devices or divers are used. The need for comprehensive inspections is generally recognized by the water industry. AWWA Manual M42 (1998) recommends that tanks be drained and inspected at least once every 3 years or as required by state regulatory agencies. Most states do not recommend inspection frequencies thereby leaving it to the discretion of the utility. States that do have recommendations are Alabama (5 years), Arkansas (2 years), Missouri (5 years), New Hampshire (5 years), Ohio (5 years), Rhode Island (external once per year; internal, every five years), Texas (annually), and Wisconsin (5 years). Kirmeyer et al. (1999) recommend that comprehensive inspections be conducted every 3 to 5 years for structural condition and possibly more often for water quality purposes.

Uncovered finished water reservoirs have unique problems. Consequently, water utilities have ceased constructing such facilities. As noted previously, the IESWTR prohibits construction of new uncovered finished water reservoirs in the U.S. Under the LT2ESWTR, existing uncovered finished water reservoirs will be managed in accordance with a state approved plan, if the facility is not covered subsequent to the rule's implementation. Flexible membrane covers are one means of enclosing uncovered reservoirs and these types of facilities also require specific routine, periodic, and comprehensive inspections to ensure the cover's integrity.

3.4 Maintenance Activities

Storage facility maintenance activities include cleaning, painting, and repair to structures to maintain serviceability. Based on a utility survey conducted by Kirmeyer et al. (1999), it appears that most utilities that have regular tank cleaning programs employ a cleaning interval of 2 to 5 years. This survey also showed that most tanks are painted (exterior coating) on an interval of 10 to 15 years.

The following existing standards are relevant to disinfection procedures and approval of coatings:

- ANSI/NSF Standard 61, and
- Ten States Standards (Great Lakes...1997)
- AWWA Manuals

- AWWA M25 – Flexible-Membrane Covers and Linings for Potable-Water Reservoirs (1996)
- AWWA M42 – Steel Water-Storage Tanks (1998)
- AWWA Standards
 - AWWA Standard C652-92 Disinfection of Storage Facilities (AWWA 1992) provides guidance for disinfection when returning a storage facility to service.
 - AWWA Standard D102 recognizes general types of interior coating systems including:
 - Epoxy,
 - Vinyl,
 - Enamel, and
 - Coal-Tar

Each of the coating systems listed under AWWA Standard D102 has provided satisfactory service when correctly applied (AWWA 1998). Other coating systems have been successfully used including chlorinated rubber, plural-component urethanes, and metalizing with anodic material (AWWA 1998). Epoxy and solvent-less polyurethanes interior coating systems are most likely to meet strict environmental guidelines and AWWA and NSF Standards (Jacobs 2000). Spray metalizing using zinc, aluminum or a combination of both is also a promising alternative. Coal tar coating systems are not common in eastern U.S. as the coatings installed in the 1950s and 1960s have mostly been replaced or the tanks themselves have been removed from service. Coal tar is still in use in California where it is often applied over an epoxy system on tank floors (Lund, 2002).

ANSI/NSF 61 (National Sanitation Foundation 1996) is a nationally accepted standard that protects stored water from contamination via products which come into contact with water. Products covered by NSF 61 include pipes and piping appurtenances, nonmetallic potable water materials, coatings, joining and sealing materials (i.e. gaskets, adhesives, lubricants), mechanical devices (i.e. water meters, valves, filters), and mechanical plumbing devices. NSF 61 was reviewed and certified by the American National Institute of Standards (ANSI) which permitted the use of the standard by other independent testing agencies such as Underwriters Laboratories. With the development of this ANSI/NSF-61 Standard, the approval and reporting for tank coatings process is now standardized. State agencies that previously had independent coating approval programs discontinued these programs and adopted the ANSI/NSF 61 Standard. Details on the ANSI/NSF 61 certification procedure are provided in the Permeation and Leaching White Paper.

Coating manufacturers provide technical specifications for proper coating application and curing. Utilities or their consulting engineer provide technical specifications and drawings describing the specific project. Trained and certified coating inspectors provide quality control during coating application. The National Association of Corrosion Engineers has a certification program for coating inspectors.

Kirmeyer et al. (1999) recommended that covered facilities be cleaned every three to five years, or more often based on inspections and water quality monitoring, and that uncovered storage

facilities be cleaned once or twice per year. Commercial diving contractors can be used to clean and inspect storage facilities that cannot be removed from service. AWWA Standard C652-92 provides guidelines for disinfection of all equipment used to clean storage facilities.

Three finished water steel elevated spheroids at the City of Brookfield Water Utility in Brookfield, Wisconsin were the subject of a field study (Kirmeyer et al. 1999) conducted to document the underwater cleaning process and its water quality impacts. The time since last cleaning was 15 years for one tank and 7 years for the other two tanks. The tank with the longest cleaning interval contained the most accumulated sediment (28 inches maximum depth compared to 4-12 inches in the other two tanks), and the highest HPC bacteria levels before cleaning (1300/mL compared to 640 and 80/mL in the other two tanks). As a result of underwater cleaning, HPC bacteria and turbidity levels were significantly reduced.

Maintenance of the cathodic protection system is a component of controlling corrosion and degradation of the submerged coated surface of finished water storage facilities. AWWA Standard D104 (AWWA 1991) provides guidelines on system inspection and maintenance.

3.5 Operations Activities

As noted previously, water age is an important variable in managing water quality in finished water storage. Operationally, water age in these facilities is managed by routine turn over of the stored water and fluctuation of the water levels in storage facilities. Kirmeyer et al. (1999) recommended a 3 to 5 day complete water turnover as a starting point, but cautioned that each storage facility be evaluated individually and given its own turnover goal. Water storage management for water quality must take into account influent water quality, environmental conditions, retention of fire flow, and demand management, as well as factors specific to the design and operation of the tank such as velocity of influent water, operational level changes, and tank design. Consequently, water level fluctuations in a distribution system are managed as an integrated operation within pressure zones, demand service areas, and the system as a whole rather than on an individual tank basis. Available guidelines for water turnover rates are summarized in Table 2.

From a field perspective, the Philadelphia Water Department estimated mean residence time and turnover rate in several standpipes by measuring fluoride residual and water levels. Mean residence time of water in the standpipes was determined to be 50 percent longer than expected because “old” water re-entered the standpipes from the distribution system. One major conclusion from this work was that for water to get out into the distribution system and away from the standpipes, standpipe drawdown needs to correspond to peak demands or precede peak demands. (Burlingame, Korntreger and Lahann 1995).

Philadelphia also demonstrated how operational changes can reduce the hydraulic detention time needed to restore or maintain a disinfectant residual within the storage facility. During normal operation, the water levels in the storage facilities were allowed to drop an additional ten feet in elevation, decreasing the mean residence time by two to three days. As a result, disinfectant residuals were maintained at acceptable levels, even during the summer months (Burlingame and Brock 1985).

**Table 2
Guidelines on Water Turnover Rate**

Source	Guideline	Comments
Georgia Environmental Protection Division	Daily turnover goal equals 50% of storage facility volume; minimum desired turnover equals 30% of storage facility volume	As part of this project, state regulators were interviewed by telephone.
Virginia Department of Health, Water Supply Engineering Division, Richmond, VA	Complete turnover recommended every 72 hours	As part of this project, state regulators were interviewed by telephone.
Ohio EPA	Required daily turnover of 20%; recommended daily turnover of 25%	Code of state regulations; turnover should occur in one continuous period rather than periodic water level drops throughout the day.
Baur and Eisenbart 1988	Maximum 5 to 7 day turnover	German source, guideline for reservoirs with cement-based internal surface.
Braid 1994	50% reduction of water depth during a 24 hour cycle	Scottish source.
Houlmann 1992	Maximum 1 to 3 day turnover	Swiss source.

Source: Kirmeyer et al. (1999)

The Greater Vancouver Water District (GVWD) completed a field study of operational changes and their effects on stored water quality (Kirmeyer et al. 1999). Historical water quality monitoring indicated that finished water reservoirs often had chlorine residuals below 0.2 mg/L and HPC levels above 500 cfu/mL. At the Central Park Reservoir, chlorine residuals were low or non-detectable, and HPC levels were >10,000 cfu/mL. Operational practices for the Central Park Reservoir and the Vancouver Heights Reservoirs had resulted in time periods when the water would remain stagnant, with little or no exchange with water from the supply main (daily turnover rate between 0 and 10 percent). At the Vancouver Heights Reservoir, the average daily turnover was increased from 10% to more than 100% changing the reservoir from one that floated on the system to a flow through operation. Operational changes made at the Central Park Reservoir improved daily water turnover rate to 50 percent. Monitoring after these operational changes indicated that chlorine residual levels were above 0.2 mg/L and HPC bacteria counts were consistently less than 500 cfu per mL.

The Consumers New Jersey Water Company experimented with a new standpipe to improve its water turnover rate (Kirmeyer et al. 1999). This facility was underutilized and had a turnover rate greater than 8 days. Control of the booster pumps feeding the service area was changed from an older elevated tank's operating level to the new standpipe's operating level. Various operating water level ranges were tested under both summer and winter demand conditions. During the summer study period, the operational changes did not increase chlorine residuals in the new standpipe. It appeared that the newer water was being pumped directly to the customers, and the older water was being returned to the storage facilities. During the winter study period, chlorine residuals in the new standpipe increased minimally from 0.1 to 0.2 mg/L. The turnover rate was reduced from 8.3 days to 4.6 days. Equipment problems were encountered as a result of longer pumping periods. When the standpipe's operating range was changed, the booster pump feeding it cycled 1.5 times per day for a longer period instead of 6 times per day. The booster

pump motor became overheated and failed, causing damage to the pump starter and the main breaker. This field study illustrates that operational changes are not necessarily straightforward, and that water quality testing is important for evaluating proposed changes. To further improve mixing effects in new storage facilities, Consumers New Jersey is now using separate inlet and outlet piping arrangements.

The Eugene Water and Electric Board (EWEB) in Oregon had a difficult time maintaining chlorine residuals in their upper service levels, primarily due to chlorine decay in the bulk water over extended time periods. The EWEB operations staff determined that improved chlorine residuals could possibly be realized by changes in pump control. Historically, the pump station that fed each upper level reservoir pumped independently of each pump station in the service levels below it. By synchronizing pump station operations, EWEB found that water could be moved from the first level service area directly to any of the upper level service areas without first being discharged to an intermediate service level reservoir. The new pumping scheme decreased the water's residence time in the intermediate reservoirs and improved chlorine residuals throughout the upper service level storage and distribution system. Chlorine residual was not detectable in the upper level reservoirs before the operating change. Afterwards, the chlorine residual in the upper level reservoirs ranged from 0.1 to 0.4 mg/L.

Mixing processes within a storage facility should be controlled to minimize water age (Grayman et al. 2000). When mixing does not occur throughout the storage facility, stagnant zones can form where water age will exceed the overall average water age in the facility. Therefore, mixed flow is preferable to plug flow in distribution system storage. Mixing can be encouraged through the development of a turbulent jet. Mixing a fluid requires a source of energy input, and in a storage facility, this energy is normally introduced from the facility's inflow. As the water enters the facility, jet flow occurs and the ambient water is entrained into the jet and circulation patterns are formed, resulting in mixing. In order to have efficient mixing, the jet flow must be turbulent, and its path must be long enough to allow for the mixing process to develop. In order to assure turbulent jet flow, the following relationship between inflow (Q, in gallons per minute) and inlet diameter (d, in feet) must hold:

$$Q / d > 11.5 \text{ at } 20^{\circ} \text{ C}$$

$$Q / d > 17.3 \text{ at } 5^{\circ} \text{ C}$$

Temperature differences between the inflow and the ambient water temperature within the storage facility can cause the water to form stratified layers that do not mix together. Stratification is more common in tall tanks such as standpipes and tanks with large diameter inlets. It can be avoided by increasing the inflow rate. The critical temperature difference, $\cong T$ in $^{\circ}\text{C}$ which can lead to stratification, can be estimated based on the following equation:

$$\cong T = C Q^2 / (d^3 H^2)$$

Where:

C is a coefficient depending on inlet configuration, buoyancy type, and tank diameter
Q = inflow rate (cfs)
H = depth of water (feet)
d = inlet diameter (feet)

Booster disinfection may be required to restore disinfectant residuals at a storage facility. Either a continuous rechlorination system or a batch system can be employed depending on the need. Batch chlorination is used to restore the chlorine residual, to disinfect an existing biological population, or to destroy a taste and odor condition. Free chlorine is the most common secondary disinfectant. Disinfectant can be added at the reservoir inlet, outlet, or within the storage facility if it is equipped with a system to enhance circulation. Chlorine addition at the outlet is normally preferred over the inlet unless the residual is nearly depleted when entering the facility. Conventional rechlorination stations, whether controlled by on/off, flow pacing, or chlorine residual pacing may create a chlorine residual of unpredictable levels. Due to the dynamic nature of flow and chlorine demand in most water distribution systems, these methods of rechlorination can lead to periodic over- and under-feeding. Where rechlorination is in use, careful consideration must be given to storage facility operations. For example, seasonal changes in water demand and temperatures can directly impact rechlorination practices.

Operation of the rechlorination system must also consider the impacts on additional formation of disinfection by-products. A utility practicing chloramination for disinfection must carefully evaluate and monitor any rechlorination process. The mixing of free chlorine with chloramines can result in the loss of free chlorine residual if not conducted properly. If done correctly, chloramine levels can be increased with the addition of chlorine, depending on the level of residual ammonia present. If ammonia concentrations are insufficient, ammonia addition prior to chlorine addition may be required. Additional information related to rechlorination and blending of chlorinated and chloraminated waters is provided in the Nitrification White Paper. Batch chlorination can be accomplished by chlorine injection at the inlet pipe or by chlorine addition into the storage facility contents through hatches or a recirculation system.

Management of distribution systems requires appropriate skills and training. Public water systems employ systems operators that are properly trained and certified per EPA's operator certification guidelines (EPA 1999). These guidelines, required as part of the 1996 Amendments to the Safe Drinking Water Act, provide States with the minimum standards for developing, implementing and enforcing operator certification programs. The guidelines help to ensure that distribution systems, including finished water storage facilities, are operated in a proper manner.

3.6 Design of Storage Facilities

The sizing, number, and type of storage facilities affect a water system's ability to manage water quality while providing an adequate water supply with adequate pressure. Capital planning necessitates installation of facilities that have excess capacity for water storage and distribution. Standard design guidelines for hydraulic considerations in the planning and construction of tanks are available in:

- AWWA Manual M32 Distribution Network Analysis for Water Utilities (AWWA 1989)
- Modeling, Analysis and Design of Water Distribution Systems (AWWA 1995c)
- Hydraulic Design of Water Distribution Storage Tanks (Walski 2000)

These guidelines ensure adequate fire flow to meet applicable codes and rating systems as well as hydraulics of water storage. State regulations address design features related to tank sizing, siting, penetrations, coatings and linings through reference to industry recognized codes and manuals (i.e. AWWA, NSF International and 10 States Standards). A discussion relating fire flow requirements to storage volume and water age is provided in the Water Age White Paper. Findings suggest that volumetric increases are site-specific and cannot be generalized.

Design guidelines addressing water quality include:

- *Maintaining Water Quality in Finished Water Storage Facilities* (Kirmeyer et al. 1999)
- *Water Quality Modeling of Distribution System Storage Facilities* (Grayman et al. 2000)

Appurtenances on storage facilities, such as vents, hatches, drains, wash out piping, sampling taps, overflows, valves, catwalk, etc., can be critical to maintaining water quality. The Ten State Standards (Great Lakes...1997) provides recommended design practices for appurtenances.

Design considerations include mixing to preclude dead zones and to maintain a disinfectant residual. Guidelines for momentum-based mixing can be found in Grayman et al. (2000). Other types of mixings systems are described in Kirmeyer et al. (1999).

4.0 Summary

Microbiological, chemical, and physical water quality problems can occur in finished water reservoirs that are under-utilized or poorly mixed. Poor mixing can be a result of design and/or operational practices. Several guidance manuals have been developed to address design, operations, and maintenance of finished water reservoirs. Water quality issues that have the potential for impacting public health include DBP formation, nitrification, pathogen contamination, and increases in VOC/SOC concentrations. Elevated DBP levels within storage facilities could result in an MCL violation under the proposed Stage 2 Disinfectants and Disinfection Byproduct Rule, based on a locational running annual average approach. A separate White Paper on Nitrification indicates that nitrite and/or nitrate levels are unlikely to approach MCL concentrations within the distribution system due to nitrification unless finished water nitrate/nitrite levels are near their respective MCLs. Pathogen contamination from floating covers or unprotected hatches is possible. Recommended tank cleaning and inspection procedures have been developed by AWWA and AWWARF to address these issues. Elevated levels of VOCs and SOCs have been measured in finished water storage facilities. AWWA and NSF standards have been developed to ensure that approved coatings function as intended. Addition data and evaluation would be required to determine if there is a significant potential for coatings and other products used in distribution system construction and maintenance to cause an

MCL violation based on sampling within the distribution system rather than the currently required monitoring at the point of entry.

5.0 Secondary Considerations

5.1 Water Disposal Issues

When storage facilities are drained prior to cleaning or inspection, the water must be disposed of in accordance with local and State regulations. If the water contains a chlorine residual, dechlorination may be required. The National Pollution Discharge Elimination System is a Federal program established under the Clean Water Act, aimed at protecting the nation's waterways from point and non-point sources of pollution. Effluent limitations vary depending on receiving water characteristics (use classification, water quality standards, and flow characteristics) and discharge characteristics (flow, duration, frequency). Failure to comply with state regulations for such releases can result in legal action against the water utility including monetary compensation and punitive fines. AWWA Standard C652 describes dechlorination procedures for storage tanks.

5.2 Safety Issues

Safety is addressed primarily through referencing Occupational Safety and Health Administration (OSHA) regulations. OSHA regulations address confined space issues (entering the tanks), climbing the tanks, removing lead from tanks, and repainting. The 1994 OSHA Compliance Directive for the Interim Final Rule on Lead Exposure in Construction (29 CFR 1926.62) requires worker protective gear, compliance plans and monitoring equipment for any removal of lead-based coatings. OSHA's Fall Protection Standard applies to all construction sites where workers risk a fall of six feet or more. OSHA's Confined Space Rule (29 CFR 1910.146) requires employers to have written programs and permits for employees working in confined spaces including storage facilities.

EPA Title 10 regulations, issued in 1994, require training and certification of workers handling certain lead bearing materials. Special equipment has been developed for removing lead-based coatings, including vacuum blasting and power tools, and portable mini-containments for reservoirs and standpipes. The Structural Steel Painting Council (SSPC) has developed standards for containment equipment and for power and hand tools used in this application.

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