Optimizing Storage Tank Design for Efficient Potable Water Supply

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Abstract

Public water systems ensure the supply of safe drinking water, catering to consumer, industrial, and firefighting needs while adhering to state and federal regulations. To replace an aging tank serving 4,800 customers in New England, this project designed a 3 million gallon capacity prestressed concrete tank with a 60 ft radius, 8 ft height, and concrete dome, aligning with AWWA standards. Site selection considered topography, access, and excavation cost. Historical data and water quality reports were used to evaluate potential issues like stagnation, disinfection residual, and disinfection byproducts. A cost-effective mixing system was implemented to prevent stagnation and maintain water quality during storage.

Executive Summary

Public Water Systems (PWS) are defined as a network that delivers water for human consumption through pipes or conveyances to at least 15 connections or an average of 25 people for at least 60 days annually. Potable water storage tanks play a vital role in safeguarding consumer access to a dependable water supply. An appropriately sized tank or tanks guarantees a consistent water source for residential, commercial, agricultural, and firefighting purposes. There are four commonly used types of water storage tanks: elevated, standpipe, ground-level, and underground. Within water storage tanks, mixers, recirculating pumps, and chlorine are often used to maintain water quality by mitigating microbial growth, stratification, and disinfection byproducts (DBPs).

This project designed a potable water storage facility for a town in New England that wished to remain anonymous. The town water system had an existing water storage tank that was nearing the end of its useful life, and the town requested a new water storage tank with a 3 million gallon capacity to be built on the same plot of land as the existing tank. To achieve this goal, background research was conducted on public water systems, potable water storage tanks, and water quality. This information was then used to develop site, structural, and water quality designs that adhere to the standards set by the American Water Works Association (AWWA) and local governments.

The site design for the new water storage facility included determining the best location for a new tank based on accessibility, access to existing infrastructure (piping and power supply), base elevation, site preparations, and estimated cost. This process used Google Earth Pro to obtain satellite imagery and a topographic map of the site. A bid package from the utility was used to determine the location of the existing water storage tank, infrastructure and surrounding details. AutoCAD was utilized to draw and visualize the possible tank locations within the plot of land. Excel was the final software employed to estimate the excavation cost for each location based on values obtained from a senior level estimator at a construction company in Massachusetts. Based on these methods, the tank was sited southwest of the existing tank, directly attached to the existing access road, and 120 feet from the public road. The site has a base elevation of 449 feet and required 43,390 cubic feet of excavation. Site work was estimated at $42,000, compared to $165,000 at another viable location on the property, which required an additional 100 feet of piping to connect it to the PWS.

The tank was designed as a 3 million gallon, ground-level, precast concrete structure. To guarantee structural integrity the tank was designed to meet the following standards: (1) American Water Works Association Standard D110-13 on wire-wound, circular, prestressed concrete water storage tanks, (2) American Concrete Association Standard 372R-13 on the design of circular prestressed concrete structures for the purpose of bulk liquid storage, (3) American Concrete Association Standard 350R-20 on Environmental Engineering Concrete Structures, and (4) American Concrete Association Standard 314R-16 on the design of reinforced concrete buildings. The tank was designed with 5000 psi non-air-entrained concrete with a water reducing admixture. The dome had a thickness of 3.65 inches and reinforcement with #3 bars in both the radial and circumferential directions laid out like a grid. The core wall thickness was 4 inches with 210 gauge prestressing wire wrapped around the core wall with 13.82 inches squared on the bottom foot of the tank with less as the height increases. A 2-inch

shotcrete covering was put over the prestressing wire. The wall footing was designed with a 7-inch depth and #4 bars spaced 12 inches apart. The base of the tank was 19-inch depth and a top layer of reinforcement out of #6, 7, and 8 bars depending on distance from the wall. The bottom layer of reinforcement was designed with #6 bars in both directions all with 12 inch spacing.

Potential water quality issues in storage were evaluated. First, water quality data were obtained from the PWS including concentrations of coliform bacteria, chlorine, trihalomethanes, and haloacetic acids at four locations in the distribution system. Bacteria and chlorine levels met federal requirements, indicating effective disinfection practices. THMs and HAAs met maximum contaminant limits, calculated by locational running annual averages and operational evaluation levels. Research was focused on how to mitigate stratification through active and passive means. Active mixing using a Gridbee GS-12 was selected based on cost of installation and effectiveness. Also, should water quality concerns arise in the future, especially in relation to disinfectant concentrations, this mixer can add booster chlorination.

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We would like to thank our advisor Professor Dudle for her continuous help throughout this project. We would also like to thank Professor Albano for his guidance in the structural design portion of our project.

Authorship

All team members contributed various edits and drafts of sections in this report, however, everyone conducted thorough research into topics which interested them most. Bryce dedicated his time to working on-site location analysis, creating a topographical map with Google Earth Pro, and site drawings using AutoCAD. Christian led research on water quality concerns such as biofilm formations and stratification, along with comparing potential mixer systems to implement into our system. Marcella highlighted key information about public water systems in our communities, presented differences between water storage tank materials, and researched disinfection byproducts including their formation and removal within the storage tank. Robert composed sections relating to structural work and focused on concrete mix design and producing AutoCAD drawings of our proposed design.

1. Introduction

An estimated 286 million Americans receive their tap water from a combined 155,690 public water systems. Of these public water systems, 34% are community water systems, which serve water to the same population of people year-round (US EPA, 2007). These systems typically pull water from sources such as groundwater or surface water lakes and reservoirs. Most surface water systems treat water by filtration and disinfection; while groundwater systems may use treatment depending on the water quality. The water is then sent to one or more water storage facilities from where it is then distributed to the public taps within three days of disinfection.

Potable water storage facilities play a crucial part in safeguarding community water needs. An appropriately designed water storage facility has enough storage capacity to meet a community's peak water demand for domestic, agricultural, industrial, and firefighting practices. Potable water storage facilities also are the last line of defense against any contamination before its used for consumption. Therefore, utilities monitor water quality as the water enters and leaves the tank to confirm no issues are developing during storage.

New England has warm summers, with temperatures often exceeding 80 degrees Fahrenheit and harsh winters with high winds, snow, and temperatures below 20 degrees Fahrenheit. With such a drastic change in weather and a dense population, water storage facilities must be large enough to serve tens of thousands of people but also sturdy enough to endure the shifting weather conditions. Thus, concrete ground-level tanks are commonly found throughout the area. The thick outer shell of concrete tanks helps maintain water temperatures year-round while protecting the tank from weathering, erosion, and cracks throughout its life span.

The purpose of this project was to design a water storage facility that meets all American Water Works Association (AWWA) and local government standards in the New England area. To accomplish this objective, the team selected a water storage tank replacement project in an undisclosed town as a case study. Key components of the project include identifying a suitable tank location, a comprehensive structural design of the water tank, and implementing effective water quality maintenance techniques.

2. Background

Potable water systems (PWSs) consist of source water, treatment, storage, and distribution. These systems provide clean and drinkable water for an array of uses such as firefighting, consumption, gardening, household needs, and more. This chapter provides an overview of public water systems with a focus on design considerations for storage. The goal of this project was to design a water storage tank for a New England town taking into account population size, drinking water regulations, and suitable tank materials discussed in Chapters 3 and 4.

2.1 Public Water Systems (PWS)

Public water systems (PWS) provide safe drinking water to communities. The United States Environmental Protection Agency (US EPA) defines a public water system as a network which provides water for human consumption through pipes or other constructed conveyances to at least 15 service connections or serves an average of 25 people for at least 60 days a year. The US EPA (2014) classifies systems by service population, service connection size, water source (surface water, groundwater, or both) and frequency of service (year-round or occasional).

There are three categories of public water systems based on service population (US EPA, 2014). The first category is a Community Water System (CWS), which supplies water to the same population year-round. CWS populations could be municipalities, mobile home parks, or sub-divisions. The second category is Non-Transient Non-Community Water Systems (NTNCWS), which serve at least 25 of the same people at least six months per year. Examples of NTNCWS are schools, offices, factories, and hospitals that have their own supply of water. The third category is Transient Non-Community Water Systems (TNCWS), which are systems that provide water in places such as gas stations or campgrounds where people don't stay for long periods of time. The US EPA reports that in the United States, there were 155,611 active public water systems in 2021 (US EPA, 2021).

2.1.1 Drinking Water Regulations

According to the Centers for Disease Control and Prevention (2022), the Safe Drinking Water Act (SDWA) was passed by Congress in 1974, with amendments added in 1986 and 1996, to give the EPA the ability to regulate public water systems. The SDWA gives the US EPA the ability to set criteria for drinking water quality and maintain standard characteristics for all drinking water sources (US EPA, 2013). Under the SDWA, the US EPA requires all water systems to meet the National Primary Drinking Water Regulations (NPDWR) which set maximum contaminant levels for over 90 different contaminants potentially found in public drinking waters. The US EPA also can set requirements based on the source of raw water. For example, all PWSs using surface water as their source must treat the water using two treatment techniques: filtration and disinfection.

The US EPA (2015) also requires all PWS to meet strict water monitoring schedules and methods to measure contaminants in water. All water systems must report all contaminant levels of the pre-treated and treated water and specifications on the status of the current water systems; allowing for the US EPA to confirm if water systems are following the NPDWRs. Two specific pieces of legislation relating to the storage of water are the Total Coliform Rule which regulates the presence of coliforms in PWSs, and the Stage 2 DBPR rule which regulates the presence of disinfectant byproducts (DBPs) (US EPA, 2023). The Total Coliform Rule is discussed further in Section 2.4.4, and the DBPR Rule is discussed in Section 2.4.3.

2.1.2 Multiple Barrier Approach

Public water systems use a multibarrier approach to provide safe drinking water. The multibarrier approach is a series of strategies to safeguard against water contamination from the point of origin, through treatment, and through the point of consumption, ensuring a secure and clean drinking water supply for all users. The US EPA (2006) states the four-barrier approach includes the following:

- Risk Prevention: Risk prevention involves the highest quality of water to use as a source, and/or protecting that water from contamination.
- Risk Management: Risk Management is a multi-pronged approach that includes using appropriate treatment technologies, having certified operators for the treatment and distribution system, and having plans in place to respond to emergencies.
- Monitoring and Compliance: The purpose of monitoring and compliance is to identify issues in the source, treatment and distribution system, and fixing those issues in a timely manner. Reporting to state and federal agencies is part of compliance.
- Individual Action: Educating customers about water quality and improving their awareness of their water system and builds confidence.

2.2 Potable Water Storage Facilities

Public water systems utilize water storage facilities to provide a reliable and consistent water supply for communities, especially during peak demand or emergencies. These facilities serve as a buffer, enabling water utilities to manage fluctuations in demand, address seasonal variations, and handle unforeseen disruptions. Different types of storage facilities, such as elevated water tanks (water towers), standpipe tanks, ground-level reservoirs/tanks, and underground storage tanks, are employed based on factors such as local geography, available space, and community needs. Elevated tanks provide pressure for distribution while ground-level reservoirs hold large volumes in open or covered structures. Underground options offer flexibility in areas where above-ground structures may be impractical or aesthetically undesirable.

2.2.1 Sizing Storage Facilities

The size of a water storage facility is a crucial factor in providing communities with a high-quality water supply. A suitably sized water storage facility ensures a steady and reliable water source for households, businesses, and agricultural needs. Water storage facilities also play a vital role in firefighting capabilities, providing an essential reservoir of water for emergency response, particularly in areas prone to wildfires. While providing adequate capacity is essential for community well-being, an oversized tank should be avoided. An excess of volume can lead to water quality concerns, as stagnation and insufficient turnover can foster the growth of bacteria and algae, compromising the overall quality of the water.

According to the "Guidelines for Public Water Systems" published by the Massachusetts Department of Environmental Protection (MA DEP), the appropriate size for a community's water storage facility must meet several key regulations (MA DEP, 2009). The MA DEP states the minimum storage capacity for a water storage facility is that it must hold a community's peak daily water demand in million gallons per day (MGD) for domestic, agricultural, and industrial purposes (MA DEP, 2009). For a metered water supply, this demand is measured during the months in which the most amount of water is used.

For unmetered water supplies, MA DEP Policy #88-10 (MA DEP, 2009), is used to estimate demand. This policy states that the average citizen uses about 100 gal/day. Therefore, domestic use is calculated as:

$$\text{Daily Consumption} = \text{no. persons} * 100 \text{ gallons/(person}\bullet\text{day)}$$

Policy #88-10 considers consumption as: "kitchen, and laundry use (including automatic equipment), bathing, sanitary use, and other uses inside the building except indoor swimming pools". Demand from industrial and agricultural uses is then added to the estimated domestic use.

In addition to the MA DEP water storage requirements, water storage facilities must also meet the flow requirements outlined by the National Fire Protection Association (NFPA). According to the NFPA 22: Standard for Water Tanks for Fire Protection, all water tanks must be capable of the following (NFPA, 2022):

- "The water supply shall be capable of filling the minimum required fire protection volume within the tank in a maximum of 8 hours."
- "The tank shall be kept filled, and the water level shall never be more than 4 in. (102 mm) below the designated fire service level."
- "The net capacity shall be the number of gallons between the inlet of the overflow and the discharge outlet."

2.2.2 Projecting Future Storage Needs

When designing a water storage facility, it is essential to factor in the projected growth of the community over the estimated lifespan of the tank. According to Smart Water (2023), concrete water tanks have an average life span of 20-30 years and steel tanks can last upwards of 25 years. Therefore, water storage tanks being installed in 2023 should be designed to meet the estimated water demands until approximately 2050. AWWA (2013) says anticipating population expansion and increased water demands is vital to prevent potential shortages and ensure the water storage facility remains sufficient in meeting the evolving needs of the community. Taking these considerations into account ensures that the chosen tank size is not only adequate for current demands but also resilient enough to accommodate future requirements effectively. In addition to estimating the future water demand for a community, AWWA (2013) states, "this consideration is particularly important in water tank design, since they represent a large capital investment, and future enlargement of storage capacity is not always feasible. However, the sizing of a water storage tank must also allow for proper water turnover and circulation to ensure all water quality standards are met."

2.3 Types of Water Storage Tanks

The four most common types of water storage tanks are elevated, standpipe, ground-level, and underground tanks. Elevated storage typically consists of an elevated steel or glass fused tank raised above the ground by at least 20 feet, creating pressure due to the natural force of gravity. Standpipes are tall, cylindrical tanks that are usually made of steel, but can also be made of concrete. They are seen as a combination of elevated and ground-level storage tanks, providing pressure. Ground-level storage tanks are also cylindrical tanks made of concrete or steel, but the shell height is less than or equal to that of the diameter. Underground water tanks are often pre-made cylindrical tubes made of steel buried completely underground.

When choosing what type of water storage tank is appropriate for a PWS, the location, elevation, storage requirements, and local regulations must be considered. For example, the Connecticut Department of Public Health guidelines state that the bottom of reservoirs and standpipes should be placed at the normal ground surface and shall be above maximum flood level (CT Department of Public Health, 1999). Therefore, many tanks are built on elevated surfaces to meet this requirement, allowing for ground-level tanks to be built. However, when the site for a storage facility has a low elevation, standpipes or elevated tanks can be used to meet the flood level requirement. Appendix A further discusses the advantages and disadvantages of each type of tank and when their use is appropriate.

<u>2.3.1 Tank Coverings</u>

Tanks can be covered by a concrete, structural metal, or flexible material cover. Not all water tanks can be covered with the materials listed above. For example, steel tanks should not have concrete covers, while flexible covers should not be used on concrete tanks. While tanks may be uncovered, this increases the risk of contaminant entry into the system. Floating covers also are susceptible to contaminant risk. Birds and animals can become trapped in the cover and contaminate water. Rips and tears are also common in floating covers due to ice damage, vandalism, or water level change. This can combine untreated water collected on the cover with treated water in the tank, resulting in contamination. The US EPA prohibits the construction of new water tanks without covers because of these hazards. The Long Term 2 Enhanced Surface Water Treatment Rule states that all reservoirs for systems serving 10,000 or more people and using surface water or groundwater under the direct influence of surface water (GWUDI) constructed after February 16, 1999, be covered. Reservoirs constructed prior 1999 are not required to provide a retrofit cover (US EPA, 2009).

<u>2.3.2 Tank Materials</u>

This section provides material options for water storage tanks.

2.3.2.1 Steel

Steel is a common tank material. It is a strong material since the carbon atoms in the alloy prevent the iron atoms from dislocating. This material is resistant to corrosion, making it desirable for water treatment applications. Corrosion resistance increases tank lifespan and prevents cracking that other materials may be susceptible to. Typically, steel tanks have a lifespan of 10 to 30 years, with some facilities lasting 100 years with proper maintenance (Kris, 2018; Southern Cross Water, 2022). Steel tanks can be constructed in large volume capacities, making them sensible in areas with large demands. The cost per gallon of welded steel water tanks is about $0.25 to $0.29 per gallon (State of Michigan, 2023). Installations of steel tanks are rather quick, with no curing time, which can save on labor costs (Ironclad Environmental, 2023).

2.3.2.2 Fiberglass

Fiberglass is lightweight and durable enough to be considered for long-term storage applications. Fiberglass tanks last around 30 to 40 years (Belding Tank Technologies, 2020). While fiberglass is a cost-effective solution, it has the potential to crack. If the tank cracks below the water level, the entire tank will need to be drained for repair, which puts a hold on the delivery of water to homes and businesses. Another limitation of fiberglass is that it is the least durable material against changing weather conditions, making it less desirable in the Northeast states that experience harsh winters and unpredictable shifts in temperature.

2.3.2.3 Plastic

Polyethylene water tanks are a lightweight option when choosing material. Like fiberglass, it is quick to install plastic tanks. They can be easily moved to other locations if needed due to their weight and size. One source claims that if a plastic tank is crafted with high-quality polymer resins and manufactured properly, it can have a lifespan of over 30 years (Coerco Agriculture, 2019). These tanks are not typically used for large applications, holding anywhere from 300 to 100,000 gallons, making them ideal for small to medium storage needs (Ironclad Environmental, 2023).

2.3.2.4 Concrete

Concrete is a strong material, being able to withstand large, applied loads without deforming and tanks require little to no maintenance after construction. For a typical 100,000 gallon tank, the price is around $1.00 per gallon (Monolithic Dome, 2010). Due to its thermal mass and the ability to absorb and hold heat, concrete can keep the temperature of stored water stable regardless of external temperature (Cold Water Storage, 2019). Concrete also withstands rain, snow, and hot temperatures. It is important to choose a concrete mix that suits the area of the tank, as some mixes of concrete with water can freeze in low temperatures, leading to cracking that expands from excess moisture (Reozone, 2023).

2.4. Water Quality in Storage

The maintenance of water quality after treatment is necessary to ensure safety through the point of use. This section highlights the major water quality concerns throughout water storage and distribution. It also provides an overview of methods of treatment or prevention for each of these water quality concerns.

2.4.1 Stratification and Water Age

Water age is the time that treated water spends in a distribution system before use, including time in storage and in transport through pipes. This is an important metric as a higher water age means greater stagnation, which can lead to significant water quality issues. In storage tanks, water age can be reduced by increasing turnover, improving mixing, or reducing storage capacity (AWWA, 2013). Turnover represents the percentage of tank volume that is drawn out and replaced every day. As an example in New England, Connecticut guidelines state that water tanks should have complete turnover every 3-5 days, or 20-33 percent each day (CT.gov, 2006). Turnover can be improved by reducing the capacity to which tanks are filled, as full tanks can cause issues with mixing and circulation.

Even if a water storage tank has frequent turnover, stratification is still possible. In water that is poorly mixed, the layer that is not exchanged can see significant reductions in water quality because of higher water age and temperature. These conditions can lead to nitrification, disinfection byproducts, microbial regrowth, biofilm formation, and disinfectant decay. Stratification can be prevented on an as-needed basis by drawing down the volume within a storage tank to artificially increase circulation and decrease water age. Long term, recirculating pumps can be used to mix any potentially stratified layers. Mixing can further be improved by adjusting the inlet momentum and location. Inlet momentum can be increased by reducing the diameter of the inlet. Tanks that are operating on a fill-and-draw mode will primarily mix during the fill stage. If at the end of this stage the tank is well mixed, then mixing problems are unlikely to occur (AWWA, 2013). As such, it is important to minimize mixing time to maximize turnover during the fill and draw stages. The mixing time (t) can be evaluated using the following equation:

$$t = \frac{10.2V^{\frac{2}{3}}}{(U \cdot Q)^{\frac{1}{2}}}$$

Where:

- t= time in seconds
- V= water volume at the start of the fill period in cubic feet
- U= inlet flow velocity in ft/s
- Q= inflow rate in ft^3/s (Grayman *et al.*, 2004).

To achieve the best possible passive mixing, the mixing time should be less than the fill time.

2.4.2 Disinfectant Decay

Disinfectant decay is the gradual reduction in residual disinfectant throughout the water distribution system. The ability to maintain disinfectant residuals plays a significant role in the ability to protect water quality throughout storage and distribution systems. A system lacking residual disinfectant can face issues such as biofilm development, microbial regrowth, and nitrification. The US EPA regulates disinfectant concentrations in the distribution system of PWSs. The requirement is at least 0.2 mg/L of disinfectant throughout the distribution system, and a maximum average of 4.0 mg/L (EPA, 2008).

The metric that best predicts the ability to maintain disinfectant residuals is water age. A higher water age results in more time for residual disinfectants to react with microorganisms, sediment, and organic material. The result is a reduced disinfectant concentration. Increased water age can be caused by oversized pipes and infrastructure, decreases in water demand, incorrect valve positioning, stratification, poor mixing, and problems with system configuration (US EPA, 2021; AWWA, 2013a). In the design phase, these issues can be prevented with the addition of recirculating pumps, proper inlet location and diameter sizing, and proper capacity. The best methods for detecting these issues once the storage facility has been built are regular maintenance and monitoring for disinfectant residuals and temperature gradients (US EPA, 2022; AWWA, 2013b). Systems that are routinely monitored will detect configuration or operating issues that lead to disinfectant decay. Continual monitoring will also make it easier to identify decreases in demand or oversized infrastructure.

2.4.3 Disinfection Byproducts

Disinfection byproducts (DBPs) form as organic material within a body of water reacts with chlorine or other disinfectants. This most often happens in chlorine treated pools and drinking water (CDC, n.d). The DBPs that are regulated by the US EPA are trihalomethanes (THMs), haloacetic acids (HAAs), chlorite, and bromate. Disinfection byproducts can pose serious health risks. Consistent exposure may cause an increased risk of developing cancer, while individuals exposed to large quantities of DBPs can experience liver damage and decreased nervous system activity (CDC, 2022).

Regulation of DBPs is based on the U.S. EPA's Stage 2 Disinfectants and Disinfection Byproducts Rule. This rule sets maximum contaminant levels for THMs, HAAs, chlorite, and bromate through an average of measurements taken at each compliance monitoring station in the distribution system. The maximum contaminant levels allowed are 0.080 mg/L for THMs, 0.060 mg/L for HAAs, 1 mg/L for chlorite, and 0.010 mg/L for bromate (US EPA, n.d). In primary treatment, the formation of DBPs can be reduced by using a disinfectant other than chlorine, and by removing or reducing organic material before the disinfection stage of treatment. In the distribution system (including storage), the options for preventing the production of DBPs include reducing the contact time or concentration of chlorine in the water distribution system, ensuring adequate turnover of water in storage tanks and avoiding pools of stagnant water, reducing the water age, or using booster chlorination (disinfectant that is added throughout the distribution system to maintain residuals).

THMs are volatile compounds, meaning that they can be volatilized at room temperature. As such, it is possible to remove THMs from water storage tanks through aeration. By passing air through water, THMs are transferred from a liquid phase to a gaseous phase, which can then be vented to the atmosphere. The use of aerators has been shown to reduce volatile DBPs in storage by up to 60 percent (Water Research Foundation, 2015). For HAAs and chlorite, there is no effective system for removal in the storage tank. The best method for minimizing these compounds is to prevent their formation during treatment. Lastly, bromate only forms during ozone disinfection. Since the water treatment process for the municipality that is the focus of this project utilizes sodium hypochlorite (see Chapter 4), the formation of bromate is not a concern.

2.4.4 Microbial Regrowth

Microbial regrowth is a rebound in organism population after treatment. There are two main factors that contribute to increased microbial regrowth: the presence of biodegradable material, and microbial abundance. A significant factor that can exacerbate the issue is diminished disinfectant residuals, as there is less disinfectant present to inactivate microbes. As previously mentioned, the regulations for disinfectant residuals are a maximum annual average of 4.0 mg/L across the distribution system, and a minimum of 0.2 mg/L for each sample in the distribution system.

The most prominent microbes in water treatment are coliforms. Total coliforms are a group of related bacteria that are unharmful to humans (with some exceptions). A subset of total coliforms are fecal coliforms which originate in the gut of warm-blooded animals. The vast majority of fecal coliforms are *E. coli*. Most *E. coli* are harmless and play an important role in the digestive tract. However, some can cause diarrhea, urinary tract infections, respiratory illness, and bloodstream infections (CDC, n.d). Coliforms act as indicators for the potential presence of pathogenic organisms in the water. The Total Coliform Rules (U.S. EPA, 2023) regulate that no more than five percent of samples, taken throughout the distribution system, can be positive for coliforms.

To prevent microbial regrowth, the best strategy is to optimize organic carbon removal. This can be achieved through various methods including coagulation, precipitation, reverse osmosis, adsorption, ion exchange, and ozonation. In the storage and distribution system, the best methods for preventing this phenomenon are reducing the residence time in storage and maintaining disinfectant residuals.

2.4.5 Biofilm Formation

Biofilms are formed when microorganisms attach to surfaces that are in contact with water. These films can form in pipes, taps, showerheads, and water storage tanks. Biofilms pose significant public health risks. They can harbor potentially harmful bacteria and react with chlorine reducing the level of residual disinfectant (Shineh *et al.*, 2023). Some of the factors that promote the growth of biofilms are stagnation and elevated temperatures (with peak formation occurring near 30 degrees Celsius) (Lopez *et al.*, 2010). Once a biofilm forms, it is very difficult to completely remove, so the best method for the control of biofilms is prevention. The two best methods to prevent the formation of biofilms are maintaining a safe water temperature of below 20 degrees Celsius and maintaining free chlorine residuals. A safe water temperature will slow the growth of microorganisms, while free chlorine residuals will continue to inactivate them in storage and distribution.

2.4.6 Nitrification

Nitrification occurs when nitrogen compounds (ammonia, NH_3 or ammonium ion, NH_4^+) are oxidized to nitrite (NO_2^-) and nitrate (NO_3^-). Ammonia can be naturally found in source waters or can be added during disinfection. Free ammonia is metabolized by ammonia-oxidizing bacteria (Nitrosomonas) producing nitrite. That in turn is metabolized by nitrite-oxidizing bacteria (Nitrobacter) to produce nitrate. The reactions forming nitrite are as follows (AWWA, 2013):

$$NH_3 + \frac{3}{2}O_2 \rightarrow NO_2^- + H_2O + H^+$$

$$NH_4^+ + \frac{3}{2}O_2 \rightarrow NO_2^- + H_2O + H^+$$

The reaction for converting nitrite into nitrate is as follows (AWWA, 2013):

$$NO_2^- + \frac{1}{2}O_2 \rightarrow NO_3^-$$

For complete nitrification, the chemical reaction is shown below (AWWA, 2013):

$$NH_4^+ + 3.300\,O_2 + 6.708\,HCO_3^- \rightarrow 0.129\,C_5H_7O_2N + 3.373\,NO_3^- + 1.041\,H_2O + 6.463\,H_2CO_3$$

Nitrification is a concern because the ingestion of high concentrations of nitrate and nitrite can lead to methemoglobinemia, a condition which affects the blood's ability to carry oxygen (Michigan.gov, n.d). Nitrite can also dechlorinate the water through chemical reactions with free chlorine or chloramine. This is a major concern as the maintenance of disinfectant residuals is necessary to protect water quality in storage and distribution. The maximum contaminant levels for nitrate and nitrite are 10.0 mg/L for nitrate, 1.0 mg/L for nitrite, and 10 mg/L for total nitrate/nitrite (Water Quality Association, n.d). Some major factors that contribute to nitrification are stagnation and temperature. Warmer temperatures promote greater reproduction of the nitrifying bacteria. Nitrification events can be prevented by maintaining safe temperatures, consistently maintaining residual disinfectants, and monitoring for thermal stratification.

2.4.7 Tank Maintenance

Tank maintenance is a minor factor when it comes to water quality, but it is worth evaluating throughout the tank's operational life. The largest threats to physical and aesthetic water quality during storage are structural breaches (US EPA, 2022). There are many ways that the quality of a storage facility can be compromised such as vandalism, storm damage, animal entry, aging, or anything that changes the facility's structural stability. These breaches can lead to serious sanitary risks. The best methods for preventing breaches are exterior inspections and maintenance. By verifying the facility's physical integrity, issues can be identified and remedied quickly before they compromise the safety of the water and the general public (US EPA, 2022).

Cleaning is a necessary step in the care and upkeep of any water storage facility. This process can involve removing sediment and corrosion material from the floor, removing biofilm that has formed on the walls, and removing any other debris. A full cleaning of a water storage tank involves draining the entire facility. A partial cleaning involving the removal of sediment and corrosion materials can be performed using a diver or unmanned device (US EPA, 2022).

2.4.8 Aesthetic Quality of Water

Another concern for the water is taste and odor. The main causes of these issues are a buildup of organic material, excessive chlorine, or a combination of both. While these do not pose immediate health risks, taste and odor issues should still be avoided. The best method for preventing issues is the removal of organic material during primary treatment (Washington State Department of Health, 2018). Although residual chlorine is necessary for the prevention of several quality concerns, a concentration at or near the MCL (4.0 mg/L) will cause issues with taste and odor (US EPA, 2000).

3. Methodology

The design of the water storage facility used software, expert knowledge, calculations, data sources, and personal communications. This section provides the methods used to select the tank location; design the structural components of the tank; and select tank components necessary for maintenance of water quality. The public water system required the team to maintain their anonymity. Therefore, the exact location of the system is not disclosed in this report, and reference material that contained information on the site or water system is withheld.

3.1 Site Design

The site designs for the water storage tank can be found in Appendices B-F. Each of the drawings was created using Autodesk's software AutoCAD with data compiled from (a) a bid package for a new water storage facility in New England, (b) Google Earth Pro, and (c) Cisdem PDF Master.

3.1.1 Site Location and Dimensions

Information on the site's location and dimensions was provided through a bid package released by the town in New England. Using the information on the specific location provided from the bid package, Google Earth was used as a tool to provide satellite imagery of the site, as seen in Figure 1.

Image Captured on Google Earth © 2023 1/17/2023

Figure 1: Screenshot collected from Google Earth of the site location in the wintertime.

The site drawings from the bid package were then uploaded and scaled using the software Cisdem PDF Master. Cisdem has several dimension-oriented tools within the software which provide information on the reference geometry of the site. Using the information collected in Cisdem and the bid package, an outline of the location with accurate dimensions was created using the polygon tool within Google Earth (see Figure 5 in Section 4.2). This method defined the area, elevation, and proximity to surrounding structures using the measurement tools within

Google Earth. Results are shown in Sections 4.2 and 4.2.1.

3.1.1.1 Topographic Map of the Site

Appendix B is a drawing of the existing site details, providing dimensions accurate to the inch, and layered over a topographical map. The initial step in the creation of the topographical map was using Google Earth Pro's path feature to gather over 700 data points. These data points were then downloaded into a KML file and encompassed the longitude, latitude, and elevation of each data point collected.

The KML file was then uploaded and converted into a text file on the GPS Visualizer website, labeling each point with its respective longitude, latitude, or elevation. The resulting text file was then uploaded to Quick Grid, a software capable of converting a text file into a topographic map on a specific axis, complete with labeled elevations.

The map generated in Quick Grid (Figure 2) was uploaded to an AutoCAD drawing. In AutoCAD, the map underwent scaling and orientation adjustments based on the existing outline of the site. This process ensured the accurate representation of the site's topography with precision in dimensions and elevation details.

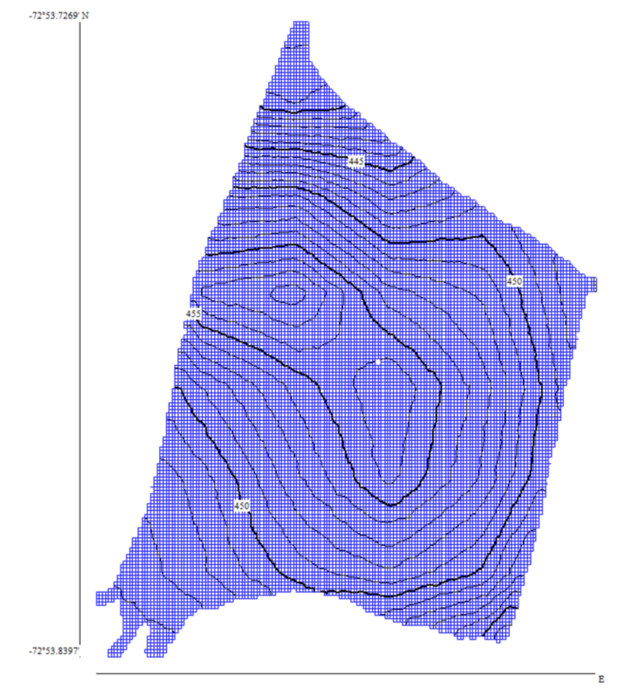


Figure 2: Contour map created within the program Quick Grid before it was uploaded to AutoCAD

3.1.1.2 Existing Site Details

Appendix C is a comprehensive drawing of the current details on the site, showing information on the existing water tank, access road, and residential structures. The creation of this drawing started with collecting satellite imagery from Google Earth. These images were utilized to identify all existing details on the site that may interfere with the construction of a water storage facility. The information collected from Google Earth was cross-referenced by aligning the bid package with the information extracted from the satellite imagery to determine the precise location of each structure within the land.

The information collected from Google Earth and the bid package was drawn over the topographic map previously created using AutoCAD. To ensure accuracy, the drawing was uploaded to Cisdem PDF Master. This step aimed to identify and address any conflicting information between the drawing and the bid package. Final adjustments to the AutoCAD drawing were then made based on the insights collected through Cisdem PDF Master, ensuring the coherence and reliability of the presented details found in Appendix C.

3.1.2 Water Tank Location

Appendix D illustrates two possible locations for the new water storage facility. These locations were determined based on state regulations on tank siting using the state of Connecticut as an example for this project. Section 19-13-B102 of the Regulations of Connecticut State Agencies (RCSA) provides rules and regulations for where a water storage facility can and cannot be placed. In accordance with these laws, the entire plot of land is suitable for a new water storage facility because it is located above the 100-year flood level and at least 50 feet away from a subsurface sewage disposal system, sanitary sewer, storm drain, watercourse, or other sources of pollution (CT DOPH, 2006). To ensure these requirements are met the new tank was placed at least 50 feet from the public road.

Since the entirety of the land is a viable option, the best locations for the new water storage facility considered several key factors: accessibility, access to existing infrastructure (piping and power supply), base elevation, site preparation and cost. Accessibility, access to existing infrastructure, and base elevation were determined using Google Earth pro and an analysis of the site drawings from the bid package. The site preparation cost calculations and methods are further discussed in Section 3.1.2.1 and 3.1.2.2. The information from these methods was compiled into a spreadsheet where the data was then compared to determine how each site benefited from the factors previously mentioned. The results of this analysis and the spreadsheet are further discussed in Section 4.2.1.

3.1.2.1 Excavation Calculations

To find the amount of land needed to be excavated (in cubic feet) for each location, AutoCAD was used with a trapezoidal step calculation. The first step for this process was to determine the total change in elevation of the given site. Then the area at each elevation was determined by tracing over the topographical map in AutoCAD for each elevation. Figures 3 and 4 show examples of two different outlines to calculate the area at a given elevation within site A.

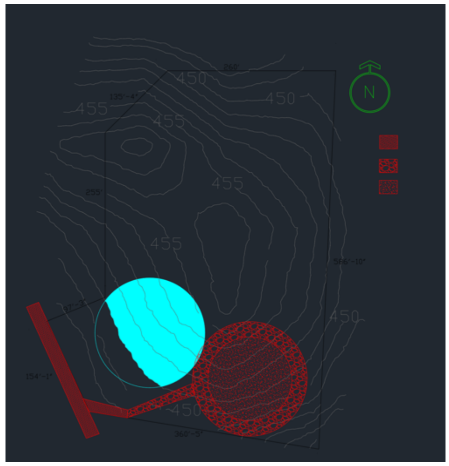


Figure 3: The circle partially highlighted in cyan represents the area of land needed to be excavated at 451 feet of elevation. AutoCAD calculated the highlighted section to be about 15,980 ft^2.

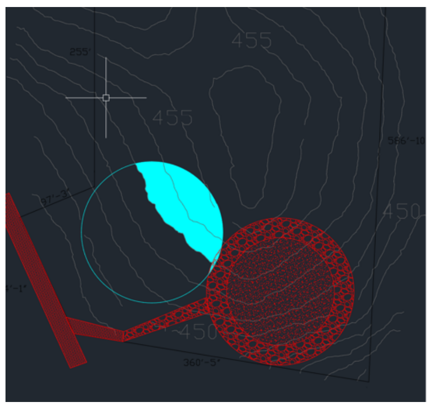


Figure 4: The circle partially highlighted in cyan represents the area of land needed to be excavated at 453 feet. AutoCAD calculated the highlighted section to be about 5,660 ft^2.

Once the area at each foot in elevation change was determined, the following equation was used to determine the total volume of land needed to be excavated.

$$Volume = D\left(\frac{A_o + A_n}{2}\right) + (A_1 + A_2 + \cdots + A_{n-1})$$

Where:

- D= difference between elevation steps (1 ft for both location A and B)
- A_o= total area of the tank
- A_n= area at the highest elevation
- A_1-A_n = areas at each respective elevation

This method of calculation gives an accurate representation of the total volume of excavation required for each location. The calculations can be found in Appendix E and the results are further discussed in Section 4.2.2.

3.1.2.2 Construction Cost Estimates

To produce an accurate estimation of the site work, a senior level estimator at a construction company in Massachusetts provided the rates for labor, equipment, and information on the estimated amount of time, people, and methods for each excavation. This information was then added into a spreadsheet where the rates were multiplied by the calculated site dimensions. The spreadsheet and total cost for each site can be found in Appendix F.

3.1.3 Final Location of the Water Tank

The final location of the tank was determined by comparing each of the key factors previously mentioned in section 3.1.2. In addition, the team consulted with several employees at a water storage tank construction company by analyzing their plans for other sites and determining what factors lead to new tank locations. The final location is discussed further in section 4.2.3 and can be seen in Appendix G.

3.2 Tank Design

The tank was designed in accordance with standards published by national organizations as follows:

- American Water Works Association Standard D110-13: standards on wire wound, circular, prestressed concrete water storage tanks; used for minimum design requirements for the dome, wall, and base design.
- American Concrete Institute Standard 372R-13: standards on the design of circular prestressed concrete structures for the purpose of bulk liquid storage.
- American Concrete Institute Standard 350R-20 on Environmental Engineering Concrete Structures: standards for general design requirements for the concrete structure.
- American Concrete Institute Standard 314R-16: standards on the design of reinforced concrete buildings; used for slab design.
- American Society of Civil Engineers Standard 7 used for general design loads.

First, the concrete was designed with which the structure would be built as described in Section 3.2.1. Then, the dome was designed followed by the tank wall design. Finally, the wall footing and the base were designed. The design procedures for these are described in Section 3.2.2.

3.2.1 Concrete Mix Design.

The concrete mix was designed based on the American Concrete Institute (ACI) Standard 211 for reinforced walls and footings. This standard provides tables used to determine the slump, aggregate size, water to cement ratio, and desired air content of the concrete. Slump is a measurement of the vertical displacement that freshly mixed concrete undergoes due to its own mass. The ACI Standard provides the minimum and maximum slump based on the construction type. Since the concrete water tank will have reinforced foundation walls and footings, the slump must be greater than 25 mm and less than 75 mm.

Table 1. Slump for reinforced foundation walls and footings adapted from ACI

Structure Type	Minimum Slump (mm)	Maximum Slump (mm)
Reinforced foundation walls and footings	25	75

ACI Standard 211 states that coarse aggregate shall not surpass 1/5 of the narrowest dimensions of sides, 1/3 the depth of slabs, and 3/4 of the minimum spacing between reinforcing bars. To meet this standard, the most common coarse aggregate size of 3/8 inches was applied for structural calculations.

ACI Standards also provides tables to determine the appropriate water to cement ratios. The water content in kg/m^3 was determined based on maximum nominal size of aggregate and desired slump previously mentioned.

Next, desired air content in the concrete was determined from a table detailing suggested air contents determined by exposure levels. After this was concluded, a water to cement ratio must be selected. This ratio was determined based on two components, compressive strength in psi after 28 days and whether the concrete is air entrained. Generally, concrete potable water tanks use a concrete strength of 5,000 psi. The value of 5,000 psi was chosen because building codes require 4,500 psi and industry standard dictates that as a precaution 5,000 psi concrete is designed for. Less air is desired in the mix to prevent leakage in the water storage tank. For this reason, non-air entrained concrete is desired.

ACI states that the maximum coarse aggregate size in any concrete mix design shall not surpass 1/5 of the narrowest dimensions of sides, 1/3 the depth of slabs, and 3/4 of the minimum spacing between reinforcing bars. The most common coarse aggregate size is 3/8 inch.

The water content in kg/m^3 is determined based on maximum nominal size of aggregate. This was determined from a table in ACI which details the amount of water required based on nominal size of aggregate and desired slump as seen in Table 2.

Table 2. Water content based on coarse aggregate size and desired slump adapted from ACI.

Slump	Water Content for 9.5 mm aggregate
25-50 mm	207 kg/m^3 water

The next step was to determine the desired air content in the concrete. This was determined from a table detailing suggested air contents determined by exposure levels.

After determining the air content, the required water cement ratio was found based on two components. The first one was the desired compressive strength after 28 days in psi. Generally, potable water concrete tanks use a concrete strength of 5,000 psi. The other consideration was whether the concrete was air entrained. Concrete water tanks are required to hold water therefore less air was desired in the concrete to prevent leakage. For this reason, non-air entrained concrete is desired. Table 3 shows the recommended water cement ratio based on a 5,000 psi compressive strength.

Table 3. Water-cement ratio for a compressive strength of 5000 psi adapted from ACI

Compressive strength after 28 days (psi)	Water-cement ratio for non-air entrained concrete	Water-cement ratio for air entrained concrete
5000	0.48:1.00	0.40:1.00

Based on the water content and the water to cement ratio, the cement content was calculated. This was done by taking the water content as determined above and dividing the water content by the ratio from Table 3.

After, the volume of coarse aggregate required per unit volume of concrete was calculated. This was done by determining the ratio of coarse aggregate to cement ratio. The maximum coarse aggregate size was known, and the fineness modulus of the fine aggregate was also known. Based on this, the ratio can be taken from an ACI table. The data based on the coarse aggregate size chosen is shown in Table 4.

Table 4. Aggregate-Cement ratio based on maximum aggregate size of 9.5 mm adapted from ACI.

Fineness Modulus	Coarse Aggregate to Cement Ratio
2.40	0.50:1.00
2.60	0.48:1.00
2.80	0.46:1.00
3.00	0.44:1.00

Lastly, the volume of fine aggregate was determined. This was done by taking the total volume of the concrete mixture and subtracting from that the volumes of the water, cement, air, and coarse aggregate. Adjustments to these values can then be made based on admixtures. For example, a water reducing admixture would allow the amount of water to be reduced in the final mix design. A water-reducing admixture was considered to allow a denser mixture which yields a less porous concrete. Less porous concrete is desired because the structure must hold water and a more porous concrete may lead to leaks.

3.2.2 Structural Design

The tank was designed by first finding the radius-to-height ratio, then drafting the tank dome, followed by design of tank walls and finishing with the fabrication of the membrane footing.

3.2.2.1 Radius to Height Ratio

The radius to height ratio was based on (1) the size of the tank, (2) the land area available, and (3) the API 650 Standard for tank sizing which recommends a 3 million gallon tank to have a 3:1 diameter to height ratio. The size of the tank was determined from the bid package, which specified a tank of 3 million gallons and from that finding a radius to height ratio that would not take up more land space than exists at the site as well as not being too tall which would require thicker walls.

3.2.2.2 Dome Design

The AWWA Standard D110-13 Section 3.6 recommends concrete domes have a radius that spans 8 feet for every 1 foot of rise. The standard also specifies that the minimum thickness of the dome is 3 inches. First, three load combinations are checked to determine which load combination will govern in terms of loads on the dome roof of the tank. The three load combinations are: (1) the dead load, (2) the dead load and the larger of the live load or the snow load, and (3) the dead load, the snow load, and the seismic load. AWWA Standard D110-13 Section 3.6 specifies that the maximum distributed load of the three loading conditions below must be used in determining the necessary thickness of the dome. The equations for the three load combinations are shown below.

$$Pu = 1.4 * D$$
$$Pu = 1.2 * D + 1.6(L + S)$$
$$Pu = 1.2 * D + 0.2S + 1.0Ev$$

Where:

- *Pu* = the maximum distributed load;
- *D* = the dead load from the self-weight of the dome in psf;
- *L* = the service roof live load determined from ASCE 7 in psf;
- *S* = the snow load on the roof determined from ASCE 7 in psf; and
- *Ev* = the vertical seismic load determined from a site-specific study in psf.

The dead load was found by finding the surface area of the dome using the equation below.

$$Surface\ Area = 2 * \pi * r * h$$

Where:

- r = the radius of the dome at the base in ft
- h = the height of the dome from the base to the top of the dome in ft.

The surface area was then multiplied by the minimum thickness of 3 inches specified by AWWA Standard D110-13 Section 3.6. The volume was then multiplied by a generally accepted density of reinforced concrete of 152.78 lb/ft^3. This value was then divided by the area of a circle with the same radius as the dome to determine the pounds per square foot for the dome self-weight. The roof service live load was determined from ASCE 7 which lists different live loads for many possible building types.

The snow load was found by first calculating the flat roof snow load based on site specific values. The equation below from ASCE 7 was used to calculate this.

$$pf = 0.7(Ce)(Ct)(Is)(Pg)$$

Where:

- *pf* = the flat roof snow load in psf
- *Ce* = the exposure factor
- *Ct* = the thermal factor
- *Is* = the importance factor
- *Pg* = the ground snow load from snow load map in psf.

The exposure factor is how covered the area is by other structures or trees. The thermal factor is how much heat is the structure radiating which would melt the snow. The importance factor is based off occupation. The ground snow load is based on a map that shows how much snow falls in that geographic location.

The following equation was then used to determine the sloped roof snow load.

$$Ps = Cs(pf)$$

Where:

- *Ps* = the sloped roof snow load
- *Cs* = the roof slope factor, which is found in ASCE-7 that is a multiplier for how sloped the roof is in degrees.

The vertical seismic load was determined by the equation below from the AWWA Standard 110-13 Section 3.6.

$$Ev = Av(D + 0.2S)$$

Where:

- *Ev* = the vertical seismic load in psf
- *Av* = the effective peak velocity
- *D* = dead load
- *S* = snow load.

The effective peak velocity was calculated using the equation below from the AWWA Standard 110-13 Section 3.6.

$$Av = \left(\frac{2}{3}\right)(Sds)$$

Where:

- Av = effective peak velocity
- Sds = the spectral response acceleration parameter at short periods

The Sds value was found using an online ASCE 7 map tool for determining seismic properties using specific geographic locations.

The values for the loads were input for each of the loading combinations to determine the maximum distributed load for the dome and that value was used to calculate the minimum thickness of the dome. The minimum thickness of the dome given the size of the dome was determined using the equation below.

$$\min t_d = r_d \sqrt{\frac{1.5P_u}{\phi \beta_i \beta_c E_c}}$$

Where:

- min t_d = minimum dome concrete thickness in inches
- r_d = mean radius of dome shell in ft
- P_u= maximum uniformly distributed load on dome shell in psf
- ϕ = buckling resistance factor
- β_i = buckling reduction factor for geometrical imperfections from a true spherical surface, such as local increases in radius
- β_c = buckling reduction factor for creep, nonlinearity, and cracking of concrete
- E_c = short-term modulus of elasticity of concrete or shotcrete in psi

These values were determined from accepted values listed in AWWA Standard 110-13 Section 3.6. The AWWA Standard 110-13 Section 3.6 provides the following equation to calculate the area of reinforcing steel required in the dome.

$$Area\ of\ reinforcing\ steel = 0.0025(btd)$$

Where:

- *btd* = concrete cross-sectional area.

The steel area was then calculated using the cross-sectional area of the concrete in the circumferential and radial directions. The calculation was performed using the maximum cross-sectional area in both directions meaning the area at the base of the dome in the circumferential direction and in the radial direction the cross-sectional area through the maximum height of the dome is used.

The area of prestressing wire required to resist the horizontal force of the dome pushing out from the center was then calculated. The area of prestressing wire was calculated using the equation below from AWWA Standard 110-13 Section 3.6.

$$Ads = \frac{(W\cot(w))}{2\pi(fse)}$$

Where:

- *Ads* = the total area of prestressing wires for dome ring area in square inches

- W = the total dead and live load on dome, exclusive of dome ring, in lb
- w = the half central angle of dome shell in degrees
- fse = the effective stress in prestressed reinforcement after losses in psi.

The total dead and live load on the dome (W) were found by multiplying the uniformly distributed load (Pu) by the area of a circle with the same radius (r). The total area of prestressing wire, Ads, was then divided by the circumference of the dome wall base to determine the amount of prestressing wire required by foot around the dome.

3.2.2.3 Wall Design

The AWWA standard 110-13 Section 3.5 states that the minimum core wall thickness is 4 inches and therefore a core wall thickness of 4 inches will be used for the water tank design. After this is determined, the hydrostatic pressure of the water in the tank acting on the wall is calculated using the equation below.

$$P = \mathrm{r}gh$$

Where:

- P = hydrostatic pressure
- ρ = the density of water (62.4lbs/ft^3)
- g = gravitational force (32.2 ft/s^2)
- h = the depth of the water in feet.

The amount of prestressing wire per vertical foot wrapped around the core wall was determined by calculating the hydrostatic pressure at each height. Then, the force of the water and the wall acting on the prestressing wire was calculated by multiplying the hydrostatic pressure by the area of the core wall. The total area of prestressing wire needed per foot was then determined by taking the force on the prestressing wire and dividing by the strength of the wire to ensure that the wire is not overstressed causing the wire to snap and the structure to fail. The AWWA standard states that the prestressing wire must then be covered by at least 2 inches of shotcrete to protect the wire from corrosion.

3.2.2.4 Footing and Base Design

Design of the wall footing was the final step in the structural design of the water tank. First, the vertical force of the self-weight of the dome in a one foot section of the wall was calculated. This is done using the equation below.

$$V = \frac{(Wu * L)}{2}$$

Where:

- V = vertical force of the self-weight of the dome in lbs/ft
- Wu = the factored dead and live loads of the dome in psf
- L = the length of the section in feet.

The self-weight of a one-foot section of the wall was calculated by taking the volume of concrete multiplied by the density of the concrete. Then the pressure from the dead loads of the dome and wall applied on the footing was calculated using the equation below.

$$Ps = \frac{(Total\ W)}{(Lf * 12")}$$

Where:

- *Ps* = the pressure of wall on the footing in psi
- Total W = the total unfactored weight of the concrete in the one-foot area in psf
- *Lf* = the length of the footing in inches.

The force of the backfill on the footing was calculated using the equation below.

$$W_s = 120\ pcf\ (d * w * x)$$

Where:

- W_s = the weight of the soil in kips
- *d* = the depth of the soil in feet
- *x* = the length of the footing in feet
- *w* = the width of the soil in feet

Next, the force of water on the footing was calculated through this equation.

$$W_w = 62.4\ pcf\ (d * w * x)$$

Where:

- W_w= the weight of the water in kips
- *d* = the depth of the water in feet
- *x* = the length of the footing in feet
- *w* = t he width of the water in feet.

In order to correct the footing length based on the factored loads, the equation below was applied based on previously determined values.

$$Pus = \frac{Wu}{(Lf * 12")}$$

Where:

- *Pus* = the pressure of the wall on the footing based on factored loads in psi
- *Wu* = the total weight of factored loads in psf
- *Lf* = the length of footing in inches.

The shear in the footing based on pressure is calculated using the equations below.

$$Vu = (Pus) * (x) * (12")$$

Where:

- *Vu* = the shear force in the wall footing in lbs
- *Pus* = the pressure of the wall on the footing based on factored loads in psi
- *X* = half of the length of the footing minus the thickness of the wall in inches.

The depth of the footing was then calculated using this equation.

$$d = \frac{(P_{us})}{(2\sqrt{f'_c}(12"))}$$

Where:

- *d* = the depth of the footing in inches
- P_{us} = the pressure of the wall on the footing based on factored loads in psi
- f'_c = the strength of concrete in psi.

Next, the bending moment in the footing was calculated using the equation below.

$$Mu = Pus * \left(\frac{x^2}{x}\right)$$

Where:

- *Mu* = the bending moment in the footing in pound-inches
- *Pus* = the pressure of the wall on the footing based on factored loads in psi
- *x* = half of the length of footing minus the thickness of the wall in inches.

The area of reinforcement in the footing was concluded. The rho value must be determined using the equation below.

$$Mu = \rho(fy) * (b) * (d^2) * (1 - 0.59\rho * \frac{fy}{f'c})$$

Where:

- *Mu* = the bending moment in the footing in pound-inches
- ρ = the steel ratio
- b = the width of the section in inches
- *d* = the depth of the section in inches
- *fy* = the strength of steel in psi
- *f'c* = the strength of concrete in psi.

The area of reinforcement in the footing was calculated through the equation below. A proper size of rebar was then selected based on the determined area

$$A_s = \rho bd$$

Where:

- A_s = the area of reinforcement in inches
- ρ = the steel ratio
- b = the width of the section in inches

- d = the depth of the section in inches

The force of the water on the base was calculated using the equation below.

$$W_w = 62.4\, pcf\ (d * w * l)$$

Where:

- W_w= the weight of water in kips
- d = the depth of water in feet
- l = the length of the base in feet
- w = the width of the water in feet

The footing length was corrected based on the factored loads using this equation.

$$Pus = \frac{Wu}{(Lb * 12")}$$

Where:

- *Pus* = the pressure of the wall on the base based on factored loads in psi
- *Wu* = the total weight of factored loads in psf
- *Lb* = the length of base in inches.

The depth of the footing based on pressure was then calculated using this equation.

$$d = \frac{(P_w)}{(2\sqrt{f'_c}(12")}$$

Where:

- *d* = the depth of the footing in inches
- P_w = the pressure of the wall on the footing based on factored loads in psi
- f'_c = the strength of concrete in psi.

The next step was to determine the area of reinforcement in the base of the tank. The maximum moment was calculated using the equation below.

$$\Phi Mn = \sqrt{\Phi Mnx^2 + \Phi Mny^2}$$

Where:

- Φ = 0.9
- M_n = maximum nominal moment in lb-ft
- M_{nx} = Maximum nominal moment in x direction in lb-ft
- M_{ny} = Maximum nominal moment in y direction in lb-ft

The bottom of the tank was laid out like a grid and the maximum moments were calculated throughout the base of the tank using a spreadsheet. Since the moments were the same in both the x and y direction the previous equation can be simplified to the following equation.

$$\Phi Mn = \Phi Mn\sqrt{2}$$

Where:

- $\Phi = 0.9$
- M_n = maximum nominal moment in lb-ft

The rho value was determined using the equation below.

$$M_n = \rho(fy)(b)(d^2)\left(1 - 0.59\rho\frac{fy}{f'c}\right)$$

Where:

- M_n = bending moment in the base in lb-in
- ρ = rho value which is the steel ratio
- b = the width of the section in inches
- d = the depth of the section in inches
- f_y = the strength of steel in psi
- f'_c = the strength of concrete in psi

The equation below was used to determine the area of reinforcement in the base.

$$A_s = \rho bd$$

Where:

- A_s = Area of reinforcement in inches
- ρ = rho value which is the steel ratio
- b = the width of the section in inches
- d = the depth of the section in inches

3.3 Water Quality

The following section contains information on the research and calculations necessary to evaluate water quality concerns and consider mixing needs.

3.3.1 Examining Local Water Quality

The most recent water quality report was obtained for the town in which the water tank was located. Upon reviewing the report, the team found no water quality concerns associated with the distribution system (see Section 4.3.3). However, it was decided that more data should be evaluated to investigate possible quality concerns. Through personal contact with an employee at the local water authority, data was obtained showing measured concentrations of various monitored parameters at four locations throughout the distribution system from 2020 to 2024. These parameters included THMs, HAAs, residual chlorine, and temperature. For chlorine residuals and coliforms, data were compared to regulatory limits which specify the minimum and maximum chlorine levels allowed in a distribution system, and the percentage of samples that can be coliform positive.

For the THMs and HAAs, LRAAs (Locational Running Annual Averages) and OELs (Operational Evaluation Levels) were evaluated for every grouping of four consecutive quarters for all the data that was available. To calculate the LRAAs, the following equation was used:

$$\text{LRAA} = \frac{PQ1+PQ2+PQ3+PQ4}{4}$$

Where:

- PQ1 through PQ4 each represent the THM or HAA concentration at a specific location for each of the previous four quarters.

Additionally, OELs were calculated using the following equation:

$$\text{OEL} = \frac{(PQ1+PQ2)+2CQ}{4}$$

Where:

- PQ1 and PQ2 represent THM or HAA concentrations in the two previous quarters
- CQ represents the THM or HAA concentration in the current quarter.

With this information, Table #7 was produced summarizing the LRAAs and OELs for disinfection byproducts throughout the distribution system. These values were compared to regulatory limits for the DBP groups.

3.3.2 Disinfection Byproducts

Research was conducted to determine how DBPs are formed during treatment, storage and distribution. Additionally, ways to reduce DBP formation and to remove DBPs after they are formed were investigated. Information was gathered for bromate, trihalomethanes, haloacetic acids, and chlorite as these are the four DBPs/DBP groups that are regulated by the U.S. EPA and can pose risks to consumer health. Information was gathered from journal publications and U.S. EPA guidance documents. A particular focus was on establishing ways to remove DBPs within the tank.

3.3.3 Stratification and Mixing

Research was conducted on other water quality issues that may occur in storage tanks, with a focus on preventing stratification. As mentioned in Section 2.4.1, the best method of preventing stratification is proper mixing, with the two predominant methods being the use of baffle walls and the use of active mixers. Since baffle walls have been the industry standard for tank mixing, information was readily available from tank manufacturers such as Preload and DN Tanks.

The use of mixers has been gaining traction; however, it is still a much more recent technology. First, information was gathered from websites of the companies that manufacture mixers. Next, the team read several engineering forums including ENG-TIPS and WaterWorld, to see how professional engineers feel about the effectiveness of mixers. The next objective was to obtain pricing information. Through personal contact with a professional engineer, pricing estimates were obtained for mixers produced by PAX, IXOM Gridbee, and Kasco. After focusing on the Gridbee GS series of mixers, pre-installation costs were obtained for the Gridbee GS-12 series of mixers from a subcontractor of IXOM. Lastly, the technical guides and warranties for all GS-12 mixers were consulted to provide installation and maintenance requirements for each product.

4. Results

The goal of this project was to design a water storage facility including siting the tank, completing a structural design, and assessing water quality concerns. The tank was designed for a town in New England. As requested by the water utility, the town, utility, and tank location are not to be disclosed. For this project's purpose, guidelines and regulations for Connecticut were used to represent New England when state-specific information was needed.

4.1 Water System Description

The PWS studied in this project was located in New England. While all public water systems in New England adhere to the US EPA federal regulations, states may impose stricter regulations for all or part of these regulations. The state of Connecticut was used as an example.

The PWS serves approximately 4,800 people in three different communities. This information was obtained from the public works website of the town that the PWS was located in (citation withheld for anonymity). Based on population served, this system was categorized by the US EPA as a medium sized system (population served ranging from 3,301 to 10,000 people). The system is supplied by water from groundwater wells.

Per the Ground Water Rule (US EPA 2008), systems using ground water as their source do not require filtration, and in accordance with that rule, this PWS does not filter their water. The state of Connecticut also does not require disinfectant for all groundwater supply systems. Rather, if there is a risk of fecal contamination within the PWS, the PWS is responsible for taking preventative measures to protect public health (portal.CT.gov, n.d). As noted previously, fecal contamination can cause diarrhea, urinary tract infections, respiratory illness, and bloodstream infections. Additionally, all active groundwater wells in Connecticut are rated on their susceptibility to contamination, considering potential microbial, and chemical contaminants. Based on CT standards, the wells in this system would range from low to high overall susceptibility. The PWS uses chlorine in the form of sodium hypochlorite as a primary and secondary disinfectant. No other treatment methods were specified for this PWS.

The PWS has one storage tank within the system. The existing water storage tank is above ground, cylindrical, and concrete with a concrete dome cap. The tank has a capacity of 3 million gallons. The tank is located on utility-owned land in a residential area (see Section 4.2). The tank was actively being used in 2024. However, its rising age and weathering have led to the development of a substantial crank spanning the entirety of the tank’s face, resulting in structural concerns. Therefore, the utility has commissioned the design of a new tank to be built in 2024.

The new tank will be located on the same plot of land as the existing tank. However, the existing tank will remain active throughout the construction process. Therefore, the new tank needs to be sited at a different location on the utility owned land. The utility has also requested the new tank be the same capacity as the existing tank (3 million gallons) and for the design to be cost effective without negatively affecting the tank's structural durability or water quality.

4.2 Site Location

As described in Section 4.1, the new water storage tank will provide storage for a PWS in New England. Figure 5 shows the plot of land owned by the utility, the location of the existing water storage tank on the land, and the area surrounding the land. As seen in this figure, the plot of land is located within a residential neighborhood with proximity to several single-family homes. This piece of land has a total area of 3.09 acres and perimeter of 1,950 ft. Within the land there is roughly 0.51 acres of unusable land because it is already occupied by the existing water storage facility.

Figure 5: Site location (outlined in yellow) for water storage tank and surrounding land.

This land sits on a hill overlooking a river and has a maximum elevation of 456 feet and a minimum elevation of 449 feet. Figure 6 shows topography from the U.S Geological Survey. The elevated terrain in comparison to the surrounding area makes this site an optimal location for generating pressure by gravity in the water distribution system. Appendix B shows the topography of the land available for use and Appendix C shows the land with the existing site details based on data collected from Google Earth Pro.

Image Captured from : U.S. Geological Survey, 2022, USGS Historical Topographic Map Collection: U.S. Geological Survey.

Figure 6: Topography of site (outlined in red) for water storage tank and surrounding land.

There is currently an access road on the site used to access the existing water storage facility. This internal access road connects to the public road on the southwest section of the land. Figure 7 shows a roadside view of the access road along with its location relative to the existing water storage facility. The access road spans 240 feet from the public road to the water tank, with 60 feet of paved road starting at the entrance and 180 feet of gravel up to the water tank.

Figure 7: Access road from public road to the tank: Aerial view with access road outlined in red (left) and street view (right).

4.2.1 Proposed Tank Locations

Based on the known information about the land and surrounding area, two possible sites for the new water storage tank were determined. Figure 4 shows the proposed locations (roughly) for the new water storage tank with blue circles labeled A and B. The circles are 160 ft in diameter, to accommodate the 120-foot diameter tank and an additional 40 feet surrounding the tank for access. Appendix D shows a more accurate representation of the proposed locations.

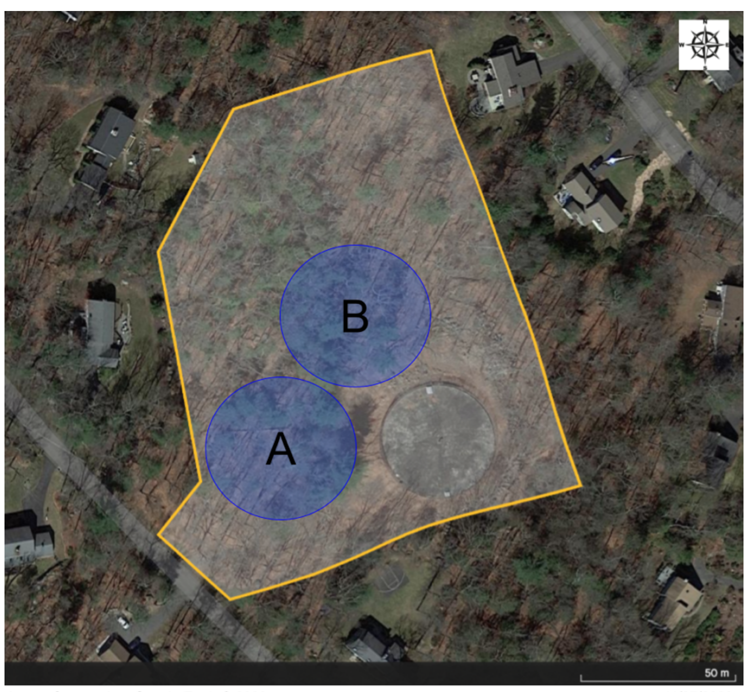


Figure 8: Satellite image with the proposed tank locations (roughly) highlighted in blue

Site A was chosen as a possible location due to its proximity to the public road and the existing access road. This location provides the advantage of being easily accessible for both construction and long-term operation. With an access road in place, little planning or sitework would be needed to start the construction process. Appendix G shows the exact location of this site, which has a minimum elevation of 449 feet and a maximum elevation of 454 feet. It was also determined using AutoCAD measurement tools that the tank is 12 feet away from the current PWS piping (see Appendix G). As explained in Section 3.1.2.3, a trapezoidal step method and AutoCAD area estimations were used to determine the excavation requirements for each site. Site A would require excavation of 43,390 ft^3 of land to flatten the land in preparation for construction (see calculations in Appendix E). Site A also has an elevation of 449 feet and would allow gravity to increase pipe pressure in distribution, lowering energy use.

Site B has the highest elevation out of the two locations, allowing for the most pressure created by gravity, leading to savings in long term energy cost. Appendix D also shows the exact location of this site on the plot of land and shows the minimum and maximum elevations of 453 and 456 feet, respectively. The distance from the proposed tank on Site B and the existing PWS piping is 135 feet (see Appendix D). Site B would require an estimated 32,110 ft^3 of excavation before construction begins (see calculations in Appendix E).

When choosing the optimal location within a plot of land for a new water storage facility, the most important criteria are elevation, accessibility, and cost. A higher elevation can decrease energy cost in the long term by lowering the amount of external pumping required through gravity. Site A and Site B have elevations within 7 feet of each other, and thus, the cost savings through pumping will be negligible between the locations. Accessibility is important during construction and throughout the lifespan of the water storage facility. Poor accessibility can lead to slower and more complicated construction based on the logistics of getting equipment in and out of the site. Furthermore, poor accessibility can hinder the ability to make repairs in a timely manner, possibly lowering the tank's lifespan. Site A and B are both easily accessible since they are next to the existing access road. Finally, the PWS desires a cost-effective tank that will not negatively affect water quality. In estimating the cost differences for each site, excavation requirements, extra site work, local grid connections, and PWS connections all must be considered.

4.2.2 New Site Location

Site A will require 35% more earthwork than Site B in preparation of the land for construction. However, the excavations costs are very similar for both sites: $39,000 for Site A versus $35,000 for site B. In addition to excavation cost, Site A is 123 feet closer than Site B from the estimated location of the existing PWS piping. Therefore, Site A would only require an additional 12 feet of piping, making construction costs much lower at Site A because the materials and earthwork costs for piping are close to $1000 per foot of pipe. Based on estimations from a senior level estimator at a construction company in the New England area the overall cost of the site work at location A is approximately $42,000 while Site B would cost approximately $168,000 (see calculations in Appendix F).

Based on the differences in cost and accessibility, Site A was a more suitable location for the tank. Site A will have less expensive site work, and ingress and egress will be optimized throughout the construction process and lifespan of the tank. As shown in Appendix D, the piping for the new tank was designed to overlap with existing pipes. In summary Site A is best suited for the utility because it meets the goal of constructing a water storage facility without any unnecessary costs. Table 5 shows a spreadsheet of each factor used to determine which site was a more suitable location for the new tank.

Table 5: Factors used to compare potential tanks sites (green = more desirable; red = less desirable).

Factor	Site A	Site B
Accessibility	120 feet from public road and directly attached to access road	260 feet from public road and 90 feet from to access road
Access to Existing Infrastructure	12 feet from existing PWS infrastructure	135 feet from existing PWS infrastructure
Base Elevation	449 feet	453 feet
Site Excavation	43,390 cubic feet	32,110 cubic feet
Additional Cost	$42,000	$168,000

4.3 Water Tank Design

The steps to design the structure of the water storage tank are detailed below. The type of tank was first decided, then, the general size of the tank. The concrete and shotcrete to be used during construction were designed. Following that, the load analysis and design of the dome roof, the walls and the footing were completed. Finally, the membrane between the wall and the footing was determined to ensure water tightness.

4.3.1 Tank Type

The required capacity of the tank being designed was 3 million gallons. Plastic tanks are not an option for projects of this size due to the holding capacity of plastic tanks ranging from 300 to 100,000 gallons. Due to the project's location being in New England, with significant temperature differences between winter and summer, fiberglass tanks do not provide temperature regulation or insulation. Comparing steel and concrete tanks, the two main benefits of a concrete tank over a steel tank are the lifespan as well as the maintenance needed. The average lifespan of a steel tank is 10 to 30 years while the average lifespan of a concrete tank is 20-30 years, as mentioned in sections 2.3.2.1 and 2.3.2.4. Steel tanks require coatings which add maintenance over time and without regular maintenance, the tank can have a reduced lifespan. Concrete tanks don’t require coatings due to the properties of concrete and therefore require less maintenance. Steel tanks overall cost less to build and are much quicker to make in large quantities. Concrete tanks take longer to build, which has an added labor cost. The group chose to design a concrete tank because of the longevity of the structure as well as the other benefits listed above for a concrete tank.

4.3.2 Dimensions of the Tank

The capacity of the tank was obtained from a bid package for this project. A preliminary height was selected based on an API 650 standard for a 3 million gallon tank and, from that, a radius was determined using the formula for the volume of a cylinder. The desired overflow height was added in accordance with AWWA D110-13 standards. The height of the dome was decided using AWWA D110-13 which states that the optimal ratio of span to rise off the water surface is 1:8. A radius of 60 ft on the interior of the tank yields a dome height of 7.5 ft, however, it was rounded to 8 ft for ease of calculation.

4.3.3 Concrete Mix Design

Wire-wrapped prestressed concrete structures require two types of concrete when being constructed. First, there is a core wall made from traditional concrete. The core wall is then wrapped with prestressing wire. A layer of shotcrete is then applied over the prestressing wire to protect it from corrosion and prolong the life of the structure.

The concrete mix design was designed using the following process. First, the desired slump of the concrete was determined from the type of structure that was to be built. Next, the coarse aggregate size was determined based on what is common in industry which in this case is a 3/8 inch coarse aggregate. After that, the water to cement ratio was determined from the required strength in the concrete and the fact that this type of construction requires non-air entrained concrete. The amount of water was determined based on the slump decided in the first step and from that the amount of cement was calculated. Following that, the aggregate to cement ratio was determined based on the size of the coarse aggregate. Finally, the volume of fine aggregate was determined using the volumes and densities of each material. The water content could then be adjusted due to the addition of water reducing admixture. This process can be found in greater detail in Section 3.2.1, and the results are shown in Table 6.

Table 6: Components and their amount within the mix

Component	**Amount per m^3 of concrete**
Cement	397.8 kg
Coarse Aggregate	1136 kg
Water	186.3 kg
Fine Aggregates	805.1 kg
Air	3%
Water reducing admixture	1.29 kg

4.3.4 Dome Design

The tank was designed in accordance with standards published by national organizations as mentioned in Section 3.2. Table 7 details the relevant values for each step of the structural design. The dome design was done by first calculating the dead load, the live load, the snow load, and the seismic load. These values were then put into the three loading conditions detailed in Section 3.2.2.2. After this, the minimum thickness of the dome was calculated. Then, the area of reinforcing steel was calculated in both the circumferential and radial directions. Finally, the required prestressing wire was calculated in order to prevent the base of the dome from moving away horizontally from the tank wall. A detailed explanation of this procedure can be found in

Section 3.2.2.2. and the calculations can be found in Appendix R.

Table 7. Dome design results

Variable	Important Considerations	Value
Dead Load	Self-weight of concrete	80 psf
Life Load	Roof live loads from ASCE-7	20 psf
Snow Load	Geographic location and curved roof factor	25.2 psf
Seismic Load	Geographic location	9.1 psf
Factored load condition 1	Dead Load	112 psf
Factored load condition 2	Dead Load, Snow Load	136.3 psf
Factored load condition 3	Dead Load, Snow Load, Seismic Load	110.14 psf
Minimum thickness of dome	Load condition 2	3.65 inches
Area of prestressing wire around dome base	Force of the dome pushing out on the wall horizontally, strength of prestressing wire	28.66 in^2
Area of prestressing wire around dome base per foot of circumference	Circumference of dome base	0.076 in^2
Area of reinforcement in the radial direction	Cross-sectional area of concrete	41.37 in^2
Area of reinforcement in the circumferential direction	Cross-sectional area of concrete	20.64 in^2
Area of reinforcement in the radial direction per foot	Length of section	0.11 in^2
Area of reinforcement in the circumferential direction per foot	Length of section	0.1 in^2
Rebar choice for radial direction	Area of reinforcement	#3 bars
Rebar choice of circumferential direction	Area of reinforcement	#3 bars

The required thickness of the dome is 3.65 inches which is only slightly more than the minimum specified in the standard of 3 inches. The shape of the dome can almost support the loads that are acting on the structure. Table 7 shows that #3 bars are required for reinforcement which is very little but sufficient due to the grid-like layout of the bars as well as the shape of the dome. Also, 28.66 inches squared of prestressing wire was required to resist the horizontal movement of the base of the dome which squeezes the dome together at the base forcing the base to be in compression.

4.3.5 Shell/Wall design

The tank wall was designed by taking the minimum core wall thickness of 4 inches then calculating the pressure that the water in the tank exerts on the wall. This was done by calculating the hydrostatic pressure and then comparing that to the amount of pressure the prestressing wire can exert on the wall from the outside. This was calculated as a gradient due to the hydrostatic pressure increasing with depth. A detailed explanation of this procedure can be found in Section 3.2.2.3. Table 8 shows the design requirements.

Table 8. Design requirements for wall design

Variable	**Important Considerations**	**Value with units**
Core wall thickness	AWWA Standard 110-13	4 inches
Water depth	Tank size	16 feet
Radius	Tank size	60.167 feet
Force in the prestressing wire	Strength after losses	140,000 psi
Shotcrete cover thickness	AWWA Standard 110-13	2 inches

Table 8 shows the height from the surface of the water in the first column. Then, the hydrostatic pressure is calculated from that. The force in the prestressing wire caused by the hydrostatic pressure is shown in the fourth column. Finally, the required prestressing wire is shows which was determined from the strength after losses of the chosen gauge wire.

Table 9. Prestressing wire as a function of hydrostatic pressure (60.2 foot radius)

Height of water (feet)	pgh (lbs/ft)	Force in prestressing wire (psi)	Prestressing required (in^2)
0	0	0	0
1	2009	121000	0.864
2	4018	242000	1.73
3	6027	363000	2.59
4	8037	484000	3.45
5	10046	604000	4.32
6	12055	725000	5.18
7	14064	846000	6.04
8	16074	967000	6.91
9	18083	1090000	7.77
10	20092	1210000	8.64
11	22102	1330000	9.50
12	24111	1450000	10.4
13	26120	1570000	11.2
14	28129	1690000	12.1
15	30139	1810000	13.0
16	32148	1930000	13.8

At the top of the water level no prestressing wire is required and as the depth increases, so does the amount of prestressing wire required. At the rough midpoint, approximately 7 inches squared of prestressing wire is required. At the bottom of the wall, approximately 14 inches squared of prestressing wire is required to resist the hydrostatic force.

4.3.6 Footing design

The wall footing was designed by determining the force on the footing from the dome, the wall, the backfill soil, and the water. After this, the sheer in the footing was calculated. Then, the required depth of the footing to resist the sheer was determined. Following that, the bending moment in the footing was calculated from the force from all the loads as well as the length of the footing. From that, the rho value could be calculated, then, the required area of prestressing wire determined. The base was designed in a similar method. The weight of the water in a unit width across the diameter of the base was calculated. After this, the sheer force was determined and, from that, the required depth of the section. The bending moment was then calculated. Then, the rho value was determined and the bottom layer of reinforcement for the base of the tank. The top layer of reinforcement was determined by taking the force of the dome, wall, and backfill on the edge of the base and multiplying by the distance away from the wall to get a moment gradient. From this, again, a rho value was calculated, and the required area of reinforcement determined. A detailed explanation of this procedure is shown in Section 3.2.2.4. Table 10 shows the relevant values from the design process as well as the final results.

The rebar chosen for the wall footing is #4 bars at a 12-inch spacing. The rebar chosen for the bottom layer of reinforcement in the base is #6 bars at a 12-inch spacing. The rebar choice for the top layer of reinforcement in the base is a gradient for which three bar sizes were chosen. The sizes were chosen based on feet from the edge of the base. For 0 to 39 feet from the edge, #6 bars were chosen at a 12-inch spacing. For 40-54 feet from the edge, #7 bars were chosen at a 12-inch spacing. From 55 feet from the edge to the center, #8 bars were chosen at a 12-inch spacing. Since the base is circular in shape, the rebar can be laid out like a grid where the reinforcement in one direction is the same as the rebar choice in the other direction given that they are the same distance from the edge of the tank.

Table 10. Wall footing and base design results

Variable	Important Considerations	Value with units
Factored Weight from Dome	Dome self-weight	5.8 kips
Factored weight from wall	Wall self-weight	3.6 kips
Factored weight of 4 feet of backfill	Weight of soil	1 kip
Factored weight of water above footing	Footing length of 2 feet	2 kips
Total factored load	All factored weights	12.4 kips
Total factored load over footing length	Size of footing	5952 lbs
Depth of footing	Factored load, strength of concrete	3.57 inches
Moment at edge of footing	Length of footing	5952 ft-lbs
Required area of reinforcement in footing	Bending moment	0.173 in^2
Rebar choice in footing	Area of reinforcement	#4 bars
Weight of water per 1 foot width	Weight of water	120 kips
Moment from weight of water	Length of section	7188 kip-ft
Depth of the base	Pressure on concrete from water	19 inches
Area of reinforcement in bottom of base	Moment from water	0.41in^2
Rebar choice for bottom of base	Area of reinforcement	#6 bars
Minimum Area of reinforcement for base	Depth of concrete	0.41 in^2
Rebar choice for base	Moment arm	
0-39 feet from edge		#6 bars
40-54 feet from edge		#7 bars
55-60 feet from edge		#8 bars

4.3.7 Analysis of membrane between wall and footing

Bearing Pads must be placed between the wall and the footing as well as between the dome and the top of the wall. These pads serve the purpose of preventing water leakage as well as avoiding the bending moment that would otherwise be produced if the wall was anchored to the footing. If the wall was anchored to the footing, a crack would form along the midpoint of the height of the wall allowing water to slowly leak out. All other voids or spaces between the bearing pads and the concrete will be filled with a closed-cell neoprene filler to further prevent any leakage out of the tank.

4.4 Water Quality

Maintenance of water quality throughout the storage and distribution system is critical for protecting public health. Failure to meet safety standards can cause quality concerns such as stratification, disinfectant byproducts (DBPs), microbial regrowth, biofilm formation, and nitrification.

4.4.1 Preventing Stratification

The leading cause of water quality concerns such as nitrification, DBPs, microbial regrowth, biofilm formation, and disinfectant decay is water stratification. As such, it is important to ensure proper mixing through passive and/or active means. There are three methods of preventing stratification that are used in the water storage industry. The first is mixers. Mixers utilize either impellers or a jet stream to create turbulence within the tank. This allows for any potentially stratified layers to be mixed with each other. The next system that can be used is aerators. Aerators use air bubbles to mix thermally stratified layers and volatilize compounds within the water. Aerators generate more uneven mixing compared to impeller mixers and are generally used when there is a concern about volatile compounds in the water such as THMs (Fisk, 2011). The third method is the use of baffle walls. Baffle walls are sets of c-shaped or straight walls that control the flow of water through the tank, resulting in mixing. Unlike mixers or aerators, baffle walls are part of the tank's design, rather than a mechanism added post-construction.

4.4.2 Disinfectants and Disinfectant Byproducts

Although DBPs can pose serious health risks, some are not anticipated to be a concern for this project. Bromate is a disinfection byproduct (DBP) that forms when naturally occurring bromide reacts with ozone treatment. In this project, chlorination was used for disinfection, therefore bromate will not form in the primary or secondary disinfection process. If a water tank is uncovered, bromate and chlorate can form as minor products in free chlorine treated systems if exposed to light (Zhang, 2023). This project was focused on covered water tank storage, so this was not of concern. Chlorine dioxide reacts with the organic and inorganic matter in water to produce the byproduct chlorite. There is an MCL of 1 mg/L of chlorite in drinking water (US EPA, 2004). Chlorite is not formed in systems that use free chlorine, so like bromate, it was not an issue for this project.

The first DBP group that was a source of concern for this project was trihalomethanes. Trihalomethanes can form as a product of a reaction between organic matter and chlorine when disinfecting water with free chlorine. The four THMs are chloroform, bromodichloromethane, dibromochloromethane, and bromoform. There are four approaches to control concentrations of THMs in potable water (Washington Department of Health, n.d.). The first three options minimize the formation of THMs. First is the optimization of chlorine dose. An appropriate concentration of chlorine is added to the system to achieve adequate disinfection. A second option is the use of alternative disinfectants. Using ultraviolet radiation and chlorine dioxide forms less or no THMs during the disinfection process. This is an advantage but with all disinfectants, they come with their own set of disadvantages such as daily monitoring, formation of additional DBPs, and reduced effectiveness in controlling viruses. A third approach for minimizing THMs is reducing the precursors before the application of disinfectant. This approach utilizes processes such as coagulation in conjunction with sedimentation and/or filtration; membrane filtration; or adsorption to remove natural organic matter (NOM) before disinfection. When NOM is removed or reduced, the reaction between NOM and inorganics won't proceed and produce DBPs like THM. The fourth option is adapting technologies to remove THMs after they are formed (Sinha, 2021). Aeration, mixing, and air stripping are treatment options to remove THMs. Aeration and mixing systems can be applied within the storage tank to encourage THMs to volatilize. In this project, there was a focus on the last approach since the project goal was to design a storage tank, and treatment plant design was outside the scope.

THMs are volatile compounds, meaning they can be evaporated at room temperature. Volatilization transfers the compound from the water phase to the air phase, removing it from the treated water. Henry's law provides a relationship between the concentration of a compound in liquid and the partial pressure of that compound in the gas phase. A high Henry's Law constant means the compound will transfer much easier from water to air than a compound with a smaller Henry's Law constant (Thurnau, 2020). Henry's Law can be expressed as shown in the equation below.

$$H = \frac{C_{gas}}{C_{aqueous}}$$

Where:

- H = Henry's Law Constant (dimensionless)
- C = VOC concentration (mole/m^3).

The Henry's Law constants for the four trihalomethane species is shown in Table 11.

Table 11. Henry's law constants for Trihalomethanes and Haloacetic Acids at 20°C (E. Brooke, M. Collins, n.d.)

DBP Group	Species	H at 20°C
THMs	Chloroform	0.127
	Bromodichloromethane	0.076
	Chlorodibromomethane	0.035
	Bromoform	0.018
HAAs	Monochloroacetic Acid	0.000000378
	Dichloroacetic Acid	0.000000343
	Trichloroacetic acid	0.000000553
	Monobromoacetic Acid	0.000000267
	Dibromoacetic Acid	0.000000181

The next DBP group of concern is Haloacetic Acids (HAAs). They are the result of the reaction that takes place between chlorine-based disinfection chemicals and the organic molecules in source water (NTP, 2021). There are five haloacetic acids potentially found in drinking water that are regulated: monochloroacetic acid, dichloroacetic acid (DCA), trichloroacetic acid (TCA), monobromoacetic acid, and dibromoacetic acid (NHDES, 2018). As shown in Table 6, the Henry's Law constants for HAAs are much smaller than those of THMs, meaning HAAs cannot be volatilized easily after they are formed. Therefore, control of HAA concentrations is achieved through preventative pre-treatment practices. These practices are the same as the ones to prevent formation of THMs.

To determine if THMs and/or HAAs were a concern in this project, data from the New England water distribution system were obtained, specifically quarterly concentrations for three years of THMs and HAAs at four locations in the distribution system. The raw data are not shown to maintain anonymity. As described in Section 3.2, the LRAAs and OELs were calculated at each location. The full results are shown in Appendices H-J, and a summary of the results are shown in Table 7.

The MCL for THMs is 0.080 mg/L, and the MCL for HAAs is 0.060 mg/L. For the OELs, if an OEL exceeds the MCL, the water system must perform an evaluation of their treatment and distribution system. As shown in Table 7, the LRAAs and OELs for both groups of disinfectants were below their respective MCLs for the three years of data. The maximum LRAA and OEL for THMs were 0.0583 and 0.0639 mg/L, respectively. For HAAs, the maximum LRAA and OEL were 0.0476 mg/L and 0.0548 mg/L. Thus, there are no current concerns with DBPs in this system and no preventative or removal techniques (such as aeration for THMs) necessary.

Table 12. Summary of LRAA and OEL data for 3 year period

DBP	**LRAA (mg/L)**		**OEL (mg/L)**	
	Range	Average	Range	Average
THMs	0.0202 - 0.0583	0.0396	0.0173 - 0.0639	0.0392
HAAs	0.0134 - 0.0476	0.0286	0.0111 - 0.0548	0.0285

4.4.3 Other Water Quality Concerns

In the case of microbial regrowth, biofilm formation, and nitrification, the best methods for preventing water quality concerns are mixing to prevent stratification, and the maintenance of disinfectant residuals. This section is focused on residual disinfectant concentrations. Quarterly concentrations over three years at four monitoring locations were provided from the New England water distribution system. These locations were the same locations as used for THM and HAA testing. The raw data are not shown to protect anonymity. The minimum, maximum, and average chlorine residuals measured in the distribution system were 0.05, 0.97, and 0.49 mg/L, respectively. The minimum level of chlorine required in a distribution system is that the chlorine concentration is detectable; and the maximum allowed is 4.0 mg/L (EPA 2023). Therefore, the system is currently in compliance with regulations. This means that the disinfectant requirements used to prevent microbial regrowth, biofilm formation, and nitrification are being met, and those issues should not be of concern in water that is properly mixed.

4.4.4 Water Quality Conclusions

The largest quality concern that needed to be addressed was stratification. This issue can be addressed through the use of baffle walls, mixers, and aerators. However, since past data has shown little to no problems with the formation of THMs and HAAs, and the formation of chlorite and bromate is impossible with the current treatment system, an aeration system can be eliminated from consideration. Although some mixers can add booster chlorination to the distribution system, this should not be a factor in deciding which method to use since previous data indicated that disinfectant decay is not a problem. As such, there should be little concern over microbial regrowth, biofilm formation, and nitrification.

4.5 Tank Mixing Design

As described in the previous section, the primary water quality concern in the tank is stratification. This can be addressed by providing mixing in the tank.

4.5.1 Tank Mixing Design

As described in section 4.3.2, aerators can be removed from consideration for the tank as there is little concern over DBPs. All information presented in this section is summarized in Table 8. There are many considerations to make when choosing a mixing system, including capital costs; operation and maintenance costs; lifespan; prevalence in the industry; and effectiveness.

The first aspect to consider is the cost of materials and installation. The mixer is a more cost-effective option compared to baffle walls. This is the case regardless of whether the baffle walls are precast, cast-in-place, masonry block, or fabric. According to a personal communication with a professional within the industry, a basic mixer costs around $20,000, whereas a basic baffle wall system costs around $75,000. The cost of installation is also lower for mixers because unlike baffle walls, a mixer is not a part of the tank's structure. The next criteria to consider is the cost of operation. Since baffle walls are passive, they are significantly easier to operate. Once they are installed, there is no energy cost, and they only receive maintenance during tank cleaning which should occur once every three to five years (KRWA, 2015). This contrasts with mixers. While some mixers are solar powered and do not have an energy cost, all mixers have maintenance costs as they have several moving parts.

The third criterion is lifespan. Again, baffle walls are the preferred option as they are not changed or replaced throughout the duration of the tank's lifespan. Mixers may need to be rebuilt or replaced over time. For example, mixers that operate using an electric motor may experience burnout, in which case the driving mechanism of the mixer needs to be replaced.

Another aspect that was evaluated is the prevalence of each method within the industry. Per personal communications with multiple professionals, baffle walls have been the industry standard in terms of water quality maintenance. Meanwhile, mixers are up-and-coming as an option for preventing stratification, as evidenced by the noticeably lesser information provided on them by water tank contractors compared to baffle walls.

The final and possibly most important factor to consider is effectiveness. Although baffle walls have been the industry standard for many years, they do have flaws. They cannot achieve complete mixing. No matter the design, there will always be some dead zones within the tank where mixing does not occur. Also, mixing only occurs when the tank is in its fill or draw stages. On the other hand, mixers are able to achieve more consistent mixing throughout the tank while running continuously. Overall, this means that although baffle walls have traditionally been the industry standard, the best choice for effectiveness is a mixer.

Table 13. Rankings of mixers and baffle walls

Type	**Cost (Materials and Installation)**	**Cost (Operation)**	**Lifespan**	**Effectiveness**
Mixers	Better	Worse	Worse	Better
Baffle Walls	Worse	Better	Better	Worse

4.5.2 Mixer Selection

The largest competitors in the mixing industry are Kasco, IXOM, and PAX. Each of these companies' products can thoroughly mix a 3 million gallon tank. Through personal contact with a professional who works in the area of water storage tank design, approximate costs for a mixer from each brand before installation are $20,000 for Kasco mixer, and $45,000 for IXOM and PAX mixers. However, by contacting a subcontractor of IXOM, it was determined that the cost could be as low as $18,000 pre-installation for their mixers.

Selection of a mixer brand was initially conducted based on capital costs, maintenance costs, and warranty. Based on capital costs, Kasco and IXOM offer lower priced mixers and therefore the choice was made not to consider PAX mixers which are approximately twice as expensive. With regard to maintenance, both Kasco Certisafe mixers and IXOM GS mixers are designed so they can sit on the floor of the tank and be removed using a retrieval chain for maintenance and inspections. This minimizes service costs as all maintenance work can be performed outside of the tank without the necessity of divers for service or retrieval of the mixer. Considering the warranty offered by each company, the standard warranty for Kasco mixers is three years, whereas the standard warranty for IXOM mixers is five years. As capital and operating costs are similar for both brands, the choice was made to explore options from IXOM based on the longer warranty.

IXOM offers mixers for various applications, including SN aeration systems for THM and VOC removal, and GS mixers for municipal water storage tanks, as well as grid-powered and solar-powered options. The GS mixers are appropriate for minimizing stratification. There are two categories of IXOM GS mixers: the GS-9 and GS-12. Although the maximum recommended tank volume for the GS-9 matches the tank volume in this project (3 million gallons), IXOM recommends using the GS-12 over the GS-9 when there is a concern over ice formation. Since this is a possible concern for tanks in New England, the GS-9 should not be considered.

There are three GS-12 models available: the Solarbee GS-12, the Gridbee GS-12, and the Gridbee GS-12 Air. Each of these units performs the same functions, with small differences in power usage and delivery. The Solarbee model is powered by a solar panel whereas Gridbee models receive grid power. Despite the energy savings that a Solarbee unit provides, the site is heavily wooded so access to solar energy is a significant concern. The difference between the Gridbee GS-12 and the Gridbee GS-12 Air is that the GS-12 is powered by an electric motor within the housing of the unit, whereas the GS-12 Air has a motor that is powered pneumatically, with an air compressor being placed outside of the storage tank. Pre-installation costs for each of the mixers including necessary hardware are $18,000 and $27,360 for the GS-12 and GS-12 Air, respectively. This makes the Gridbee GS-12 the ideal choice as it has similar energy costs to the GS-12 Air and fewer components resulting in easier maintenance.

5. Conclusions and Recommendations

This chapter summarizes the project findings, and provides recommendation for future consideration.

5.1 Conclusions

This project designed a replacement storage tank for a PWS in New England, with the guidelines and regulations of Connecticut as a representation of the area. The PWS is a medium sized system that uses a groundwater source and sodium hypochlorite for primary and secondary disinfection. The findings are as follows:

- The existing 3 million gallon tank was in need of replacement due to a crack, but needed to remain active through construction.
- The new tank was sited on the same plot of land as the existing tank, with the location selected based on accessibility, access to existing infrastructure, and site work costs. Site work was estimated to cost $42,000.
- A new 3 million gallon concrete tank was designed with material selection based on size, climate, maintenance, and lifespan. The tank was designed in accordance with national standards. The design included details on the concrete composition; dome thickness and reinforcement; wall thickness and prestressing wire; and shotcrete cover. The footing was also designed. All design components took into account daily fluctuating water levels in the tank.
- Evaluation of local water quality data showed little concern over DBPs, microbial regrowth, biofilm formation, and nitrification; however, stratification is always a concern in storage.
- The Gridbee GS-12 was chosen to actively mix the tank to prevent stratification and maintain water quality.

5.2 Recommendations

This project focused on the siting and design of a water storage tank. The following recommendations are made on water quality and the structural design:

- If DPBs are problematic in the future, the utility should consider reducing the formation of DBPs prior to storage. DBPs concentrations could increase based on changes in source water quality, or changes in treatment such as the type or dose of disinfectant.
- Regarding the structural design, some considerations fell outside of the project scope. Prior to construction, the following should be addressed: (1) methods of construction including method of prestressing the wire; (2) panel construction (cast in place or precast on site); and (3) deconstruction and disposal of the existing tank.

References

American Water Works Association, *Nitrification Prevention and Control in Drinking Water*, Second edition.; American Water Works Association, Ed.; AWWA manual, 2013.

American Water Works Association. *Standard D110 Wire- and Strand-Wound, Circular, Prestressed Concrete Water Tanks*, 2013.

American Concrete Institute, *Aggregates for Concrete*, 2007. https://www.concrete.org/Portals/0/Files/PDF/E1_07.PDF (Accessed on March 11, 2024)

American Concrete Institute, *Standard 314R Guide to Simplified Design for Reinforced Concrete Buildings*, 2016.

American Concrete Institute, *Standard 350R Code Requirements for Environmental Engineering Concrete Structures*, 2020.

American Concrete Institute, *Standard 372R Guide to Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures*, 2013.

American Society of Civil Engineers, *ASCE Hazard Tool*, 2024. https://ascehazardtool.org/. (Accessed on March 11, 2024)

American Society of Civil Engineers, *Standard 7 Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, 2022.

Belding Tank Technologies Inc., *How Long Do FRP Water Tanks Last?,* n.d. https://beldingtank.com/how-long-do-frp-tanks-last/. (Accessed on March 11, 2024)

SkyCiv*, Calculating Roof Snow Loads w/ ASCE 7.* https://skyciv.com/docs/tech-notes/loading/calculating-roof-snow-loads-w-asce-7-10/ (Accessed on March 11, 2024)

CDC/ATSDR, *Toxicological Profile for Haloacetic Acids,* 2002. https://www.atsdr.cdc.gov/ToxProfiles/tp160-c1-b.pdf (Accessed on March 11, 2024)

CDC, *E. coli and Food Safety*, 2023. https://www.cdc.gov/foodsafety/communication/ecoli-and-food-safety.html (Accessed on March 11, 2024)

CDC Department of Health and Human Services, *Public Health Statement Chlorine Dioxide and Chlorite*, 2004. https://www.atsdr.cdc.gov/ToxProfiles/tp160-c1-b.pdf (Accessed on March 11, 2024)

Coerco Agriculture, *Poly Water Tanks: Do They Break Down in the Sun?*, 2019. https://agriculture.coerco.com.au/agriculture-blog/poly-water-tanks-do-they-break-down-in-the-sun (Accessed on March 11, 2024)

CT.gov, *Chapter VI Potable Water Storage Facilities,* Guidelines for the Design and Operations of Public Water System Treatment Works and Sources, n.d. https://portal.ct.gov/-/media/Departments-and-Agencies/DPH/dph/drinking_water/pdf/chapter6pdf.pdf (Accessed on March 11, 2024)

Clark, R.; Thurnau, R. *The importance of temperature on Henry's-law solubility constants: Removing trihalomethanes by aeration*, 2020 https://awwa.onlinelibrary.wiley.com/doi/abs/10.1002/aws2.1168 (Accessed on March 11, 2024)

Cold Water Storage, *What Are Concrete Tanks Used For?*, 2022. https://www.coldwaterstorage.co.uk/blog/what-are-concrete-tanks-used-for/ (Accessed on March 11, 2024)

CT State Building Code, *2015 IBC portion of the 2018 CT State Building Code Structural Design*, 2015. https://up.codes/viewer/connecticut/ibc-2015/chapter/16/structural-design#1608 (Accessed on March 11, 2024)

Deese, P. *Daily Consumption Per Person*, 1989. https://www.mass.gov/files/documents/2016/08/wo/8810.pdf. (Accessed on March 11, 2024)

DES New Hampshire, *Haloacetic Acids (five) (HAA5): Health Information Summary*, 2012. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/ard-ehp-36.pdf (Accessed on March 11, 2024)

CDC, *Disinfection By-products (DBPs) Factsheet,* 2022. https://www.cdc.gov/biomonitoring/THM-DBP_FactSheet.html (Accessed on March 11, 2024)

CDC*, Drinking Water Standards and Regulations*, 2022. https://www.cdc.gov/healthywater/drinking/public/regulations.html (Accessed on March 11, 2024)

Earthquake Hazards Program, *Earthquake Hazards 201 – Technical Q&A*, 2019 . https://www.usgs.gov/programs/earthquake-hazards/science/earthquake-hazards-201-technical-qa (Accessed on March 11, 2024)

E. Brooke, M. Collins, *Assessing Post-Treatment Aeration Variables to Reduce Disinfection Byproducts (THMs) for Small Systems*, n.d.
https://www.unh.edu/wttac/Presentations/Ethan%20Brooke,%20Assessing%20Post%20Treatment%20DBP%20(THM)%20Aeration%20Variables.pdf (Accessed on March 11, 2024)

Fang, J.; Hua, Z.; Zhang, Y.; Zhang, X.; Guo, K. *Unexpected Trends for the Formation of Chlorate and Bromate during the Photolysis of Chlorine in Bromide-Containing Water*, 2023 https://www.sciencedirect.com/science/article/abs/pii/S0043135423005365 (Accessed on March 11, 2024)

Fresh Water Systems, *What Is Reverse Osmosis?,* 2018. https://www.freshwatersystems.com/blogs/blog/what-is-reverse-osmosis#2 (Accessed on March 11, 2024)

Ghosal, P., Gupta, A., Sinha, R., *A review on Trihalomethanes and Haloacetic acids in drinking water: Global status, health impact, insights of control and removal technologies*, 2011. https://www.sciencedirect.com/science/article/abs/pii/S2213343721014883?fr=RR-

2&ref=pdf_download&rr=84cdb56a6bb8820c (Accessed on March 11, 2024)

Ghosh, A.; Seidel, C.; Townsend, E.; Pacheco, R.; Corwin, C., *Reducing Volatile Disinfection By-Products in Treated Drinking Water Using Aeration Technologies*, 2015. http://www.aquametrologysystems.com/wp-content/uploads/2019/08/WERF_THM_May2015.pdf (Accessed on March 11, 2024)

Hamakareem, M., *ACI Method of Concrete Mix Design*, n.d. https://theconstructor.org/practical-guide/aci-method-concrete-mix-design/7196/ (Accessed on March 11, 2024)

The International Code Council, *International Building Code*, 2021 https://codes.iccsafe.org/content/IBC2021P1/chapter-16-structural-design (Accessed on March 11, 2024)

Jamal, H., *Simply Supported UDL Beam Formulas and Equations*, 2017. https://www.aboutcivil.org/simply-supported-UDL-beam-formulas-bending-moment-equations.html (Accessed on March 11, 2024)

López, D.; Vlamakis, H.; Kolter, R., *Cold Spring Harbor Perspectives in Biology: Biofilms*, 2010. https://doi.org/10.1101/cshperspect.a000398. (Accessed on March 11, 2024)

Massachusetts Water Resources Authority, *Water Supply and Demand*, 2023. https://www.mwra.com/04water/html/wsupdate.htm (Accessed on March 11, 2024)

Mass.gov, *Guidelines for Public Water Systems*, n.d. https://www.mass.gov/info-details/guidelines-for-public-water-systems. (Accessed on March 11, 2024)

Michigan Department of Health and Human Services, *Nitrate and Nitrite in Drinking Water for Well Owners*, 2019. https://www.michigan.gov/-/media/Project/Websites/mdhhs/Folder1/Folder29/Nitrate_Nitrite_in_Drinking_Water_09-12-2019_FINAL_ENGLISH.pdf?rev=e699a4f534ca4507b0b8d29ae728ec4f (Accessed on March 11, 2024)

Michigan Department of Treasury, *Aboveground Storage Tank Registration Data*, 2018. https://www.michigan.gov/-/media/Project/Websites/treasury/VOL/Vol235UIP11Tanks.pdf?rev=8da62f605b2b4001aa9a8c895db78b27 (Accessed on March 11, 2024)

Morse, K. *Is Concrete a Good Alternative to Steel for Above Ground Storage Tanks?*, 2018. https://blog.tbailey.com/is-concrete-a-good-alternative-to-steel-for-above-ground-storage-tanks (Accessed on March 11, 2024)

New Hampshire Department of Environmental Services. *Haloacetic Acids (five) (HAA5): Health Information Summary,* 2018 https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/ard-ehp-36.pdf. (Accessed on March 11, 2024)

NFPA -Free Access - NFPA 22: *Standard for Water Tanks for Private Fire Protection,* 2023. https://www.nfpa.org/product/nfpa-22-standard/p0022code?l=46 (Accessed on March 11, 2024)

NTP (National Toxicology Program), *Haloacetic Acids Found as Water Disinfection By-products (Selected)*, 2020. https://ntp.niehs.nih.gov/sites/default/files/ntp/roc/content/profiles/haloacetic_acids.pdf (Accessed on March 11, 2024)

Reozone, *What Causes Expansion in Concrete?*, n.d. https://www.reozone.com.au/what-causes-expansion-in-concrete/ (Accessed on March 11, 2024)

Rushing, D. *Choosing the Right Aboveground Water Storage Tanks for your Need*, 2023. https://ironcladenvironmental.com/2023/07/10/choosing-the-right-aboveground-water-storage-tanks-for-your-need/ (Accessed on March 11, 2024)

Shineh, G.; Mobaraki, M.; Perves Bappy, M. J.; Mills, D. K. *Biofilm Formation, and Related Impacts on Healthcare, Food Processing and Packaging, Industrial Manufacturing, Marine Industries, and Sanitation–A Review*, Applied Microbiology, 2023, 629–665. https://doi.org/10.3390/applmicrobiol3030044. (Accessed on March 11, 2024)

Sinha, R.; Gupta, A.; Ghosal, P. *A Review on Trihalomethanes and Haloacetic Acids in Drinking Water: Global Status, Health Impact, Insights of Control and Removal Technologies*, 2021 https://www.sciencedirect.com/science/article/abs/pii/S2213343721014883?fr=RR-2&ref=pdf_download&rr=83a55f5db87b4cfb (Accessed on March 11, 2024)

Engineers Edge, *Sloped Roof Snow Loads Calculations and Regional Design*, n.d. https://www.engineersedge.com/analysis/sloped_roof_snow_loads_9727.htm#:~:text=Roof%20Slope%20Factor%20for%20Curved%20Roofs.%20Portions%20of,determined%20from%20the%20appropriate%20curve%20in%20Fig.%20E-2 . (Accessed on March 11, 2024)

Smart Water Online, *How long will my water tank last?*, 2023. https://smartwateronline.com/news/how-long-will-my-water-tank-last (Accessed on March 11, 2024)

Smith, B.; Warner, J. W.; Inhofe, J. M.; Thomas, C.; Bond, C. S.; Voinovich, G. V.; Crapo, M. D.; Bennett, R. F.; Hutchison, K. B.; Chafee, L.; Baucus, M.; Moynihan, D. P.; Lautenberg, F. R.; Reid, H.; Graham, B.; Lieberman, J. I.; Boxer, B.; Wyden, R., *The Safe Water Drinking Act*. 1996. https://www.govinfo.gov/content/pkg/CPRT-106SPRT67528/pdf/CPRT-106SPRT67528.pdf (Accessed on March 11, 2024)

South, D. *Is there an alternative to concrete or steel water tanks?*, 2010. https://www.monolithic.org/airform/airforms-other/monolithic-permanent-fabric-water-tanks (Accessed on March 11, 2024)

Southern Cross Water, *How Long Does A Water Tank Last?,* 2022.

https://sxwater.com.au/how-long-does-a-water-tank-last/ (Accessed on March 11, 2024)

US EPA, *Distribution System Water Quality Protecting Water Quality Through Finished Water Storage Facility Inspection and Cleaning*, 2022 https://www.epa.gov/system/files/documents/2022-04/ds-toolbox-fact-sheets_sfi_final-508_revised.pdf (Accessed on March 11, 2024)

US EPA, *Drinking Water Storage Tank Assessment Study Protocol,* 2021. https://www.epa.gov/sites/default/files/2021-05/documents/storage-tank-spreadsheet-assessment-protocol.pdf (Accessed on March 11, 2024)

US EPA, *FACTOIDS: Drinking Water and Ground Water Statistics for 2007,* 2007. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100N2VG.PDF?Dockey=P100N2VG.PDF (Accessed on 02/11/2024)

US EPA, *How EPA Regulates Drinking Water Contaminants*, 2023 https://www.epa.gov/sdwa/how-epa-regulates-drinking-water-contaminants (Accessed on March 11, 2024)

US EPA, *Information about Public Water Systems*, 2023. https://www.epa.gov/dwreginfo/information-about-public-water-systems. (Accessed on March 11, 2024)

US EPA, *Long Term 2 Enhanced Surface Water Treatment Rule, Toolbox Guidance Manual Review Draft*. 2009. https://nepis.epa.gov/Exe/ZyPDF.cgi/P10045O1.PDF?Dockey=P10045O1.pdf (Accessed on March 11, 2024)

US EPA. *Multiple Barrier Approach to Public Health Protection*. National Service Center for Environmental Publications (NSCEP), 2006. https://nepis.epa.gov/Exe/ZyNET.exe/2000ZZBQ.txt?ZyActionD=ZyDocument&Client=EPA&Index=2006%20Thru%202010&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C06THRU10%5CTXT%5C00000000%5C2000ZZBQ.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=2 (Accessed on March 11, 2024)

US EPA, *Providing Safe Drinking Water in America: National Public Water Systems Compliance Report*, 2021 https://www.epa.gov/compliance/providing-safe-drinking-water-america-national-public-water-systems-compliance-report (Accessed on March 11, 2024)

US EPA, *Summary of the Safe Drinking Water Act*, 1974. https://www.epa.gov/laws-regulations/summary-safe-drinking-water-act (Accessed on March 11, 2024)

Washington State Department of Health, *Alternate Disinfectants,* 2016. https://doh.wa.gov/community-and-environment/drinking-water/disinfection/disinfection-byproducts/disinfectants-and-disinfection-byproducts/alternate-disinfectants (Accessed on March 11, 2024)

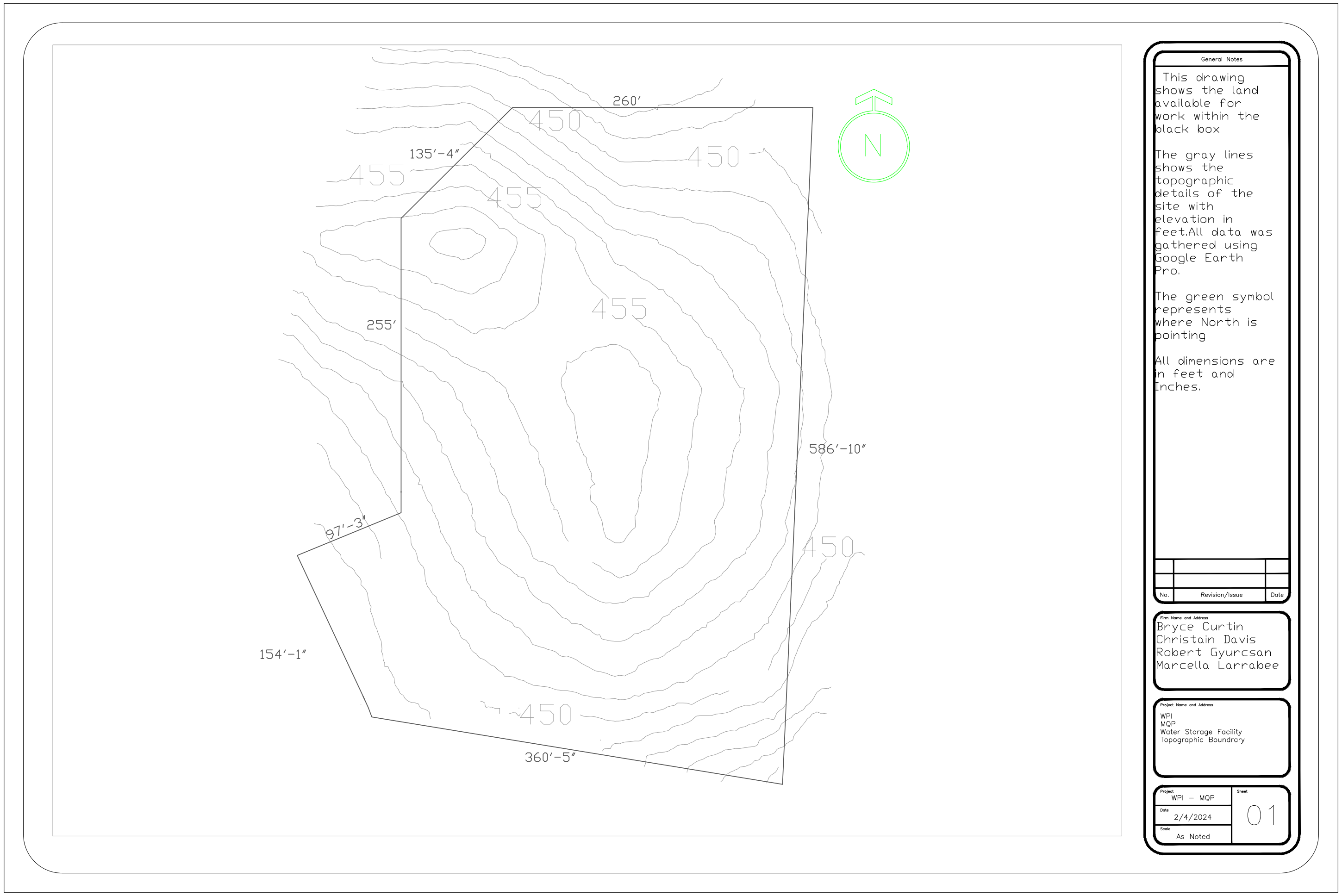
Washington State Department of Health. *Color, Taste and Odor Problems in Drinking Water*. 2018. https://doh.wa.gov/sites/default/files/legacy/Documents/Pubs//331-286.pdf (Accessed on March 11, 2024)

Woodard, J. *What Is a Reverse Osmosis System and How Does It Work?*, 2023 https://www.freshwatersystems.com/blogs/blog/what-is-reverse-osmosis#2 (Accessed on March 11, 2024)

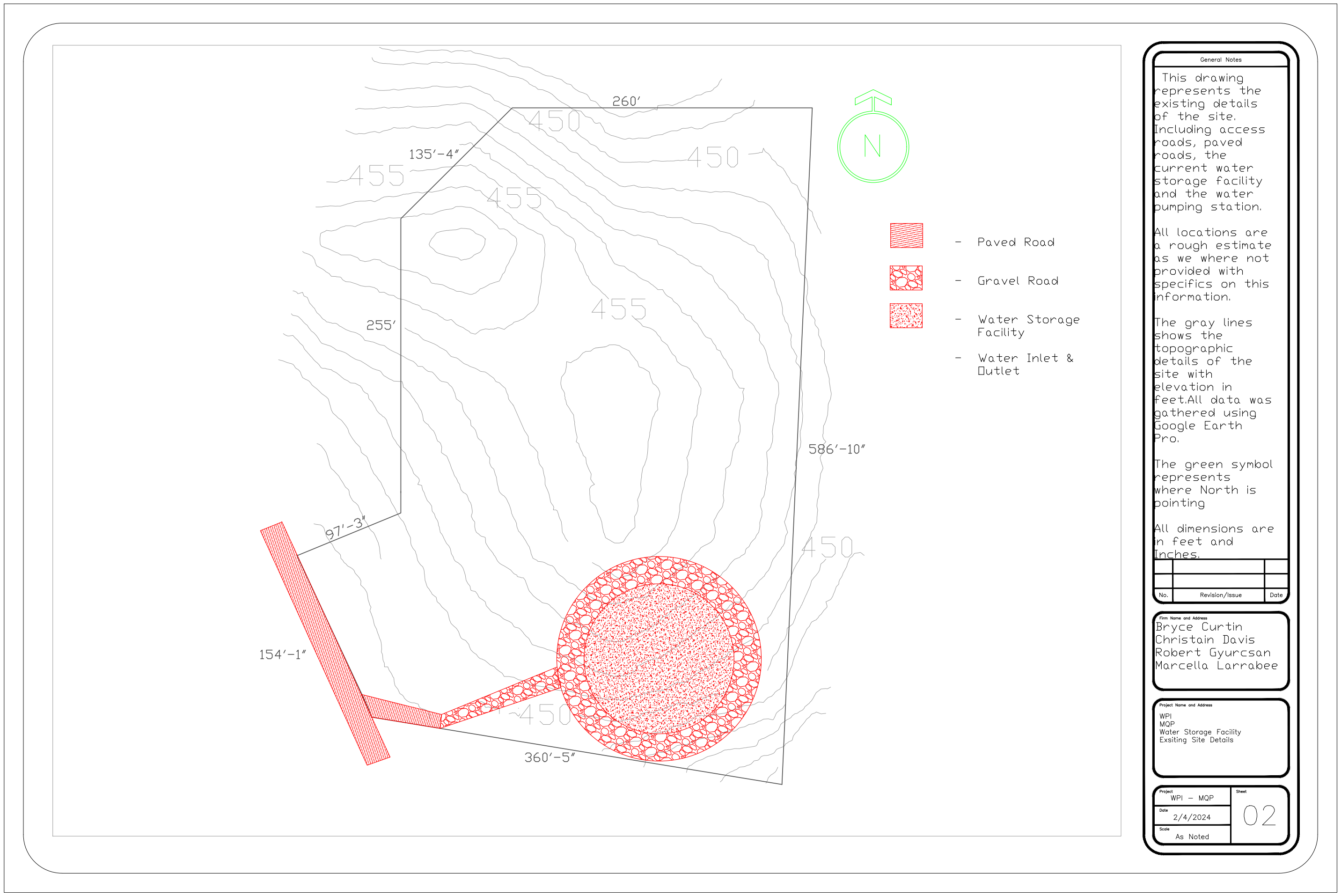
Appendix A – Advantages and disadvantages of different water storage facility types

Type of Water Tank	Description	Example	Advantages	Disadvantages
Above Ground - Elevated	Consists of tank and supporting structure. The supporting structure is typically built on a flat surface to elevate the storage tank in order to meet flow requirements.	 (Larry d. Moore, 2015)(Public Domain)	Small footprint	Smallest Storage Capacity
			Can be entirely pumped by gravity	Weather has a greater affect on its structure
			Gravity can lower the cost of pumping	
			Moderate cost	
			60 year life span	
			Limited maintence after construction	
Above Ground - Standpipe	Greater in height than diameter, blending the characteristics of elevated and ground level tanks, with a taller tank design creating gravity feed pressure.	 (Grillo, 2005) (Public Domain)	Small footprint	Shortest Life Span
			Gravity will lower the cost of pumping	Large standpipes are high in cost
			Widest variety of uses	Works best in smaller systems (200,000 gal or less)
			Small Standpipes have minimal cost	
Above Ground - Ground Level	Ground supported, flat bottom cylindrical tanks with shell height less than or equal to the diameter.	 (Photo by CEphoto, Uwe Aranas, 2012) (Public Domain)	Large Capacity	Elevation is usually required
			Extremely high weather and seismic resistance	High pumping cost
			Life span of 30+ years	Must be in a system with a high water turnover rate
			Able to support the most connections	
Underground	Commonly used for Non-Transient Non Community Water Systems. Typically a cylindrical tube made of steel stored completely underground.	 (Defense Visual Information Distribution Service, 2014) (Public Domain)	Unaffected by weather and seismic activity	External power and pumping is required
			Ground acts as natural temperature control	Restricted maintence
			Hidden from publics view	Not a viable option in areas where there is high ground water
				Limited use

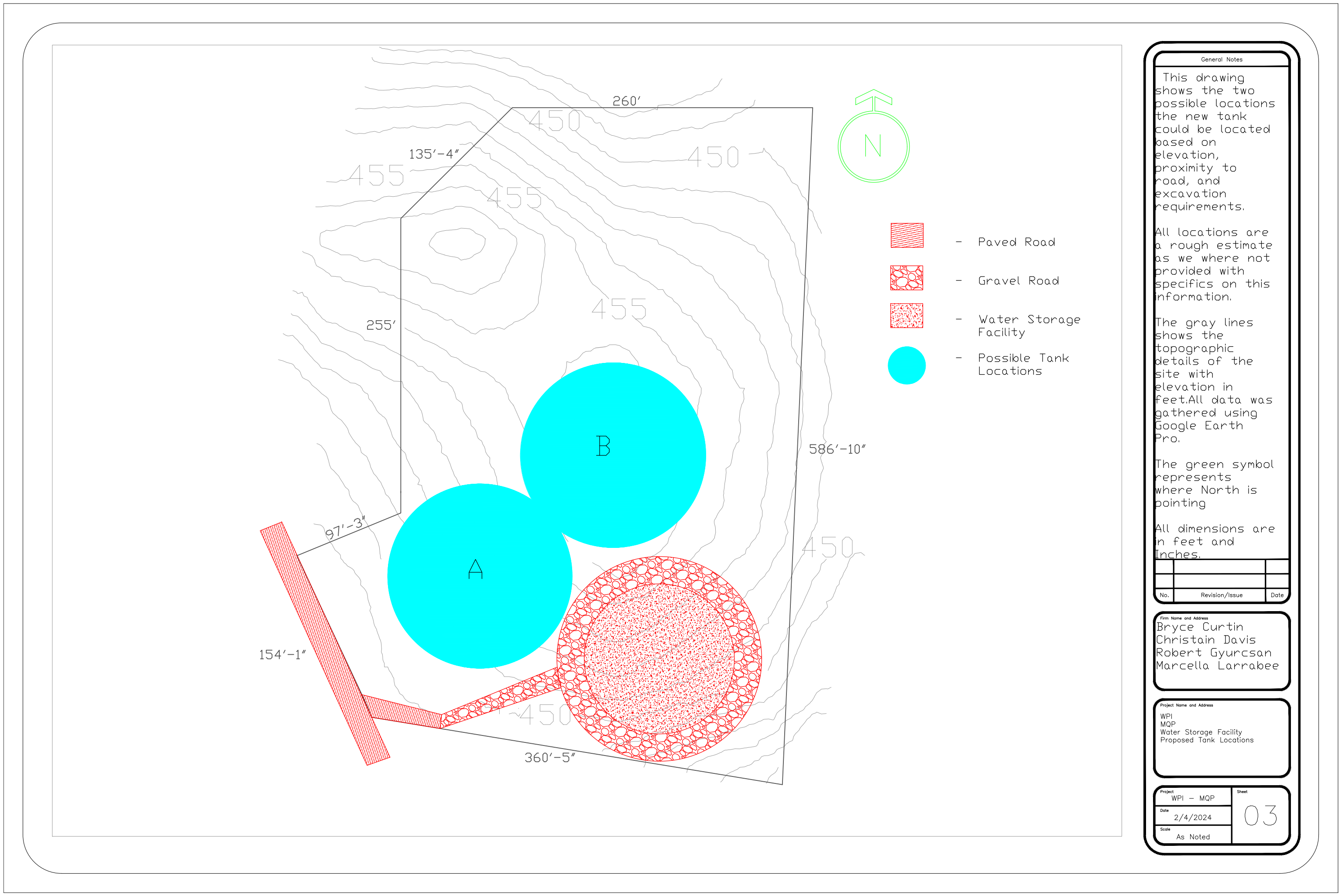
Appendix B – Site Outline and Elevation



Appendix C – Existing Site Details



Appendix D – Proposed Tank Locations



Appendix E – Excavation Calculations

Site A

Site Area = $\pi\left(\frac{d}{2}\right)^2 = \pi\left(\frac{160}{2}\right)^2 = 20{,}106.19\ ft^2$

Elevation Change = $454\ ft - 450\ ft = 4\ ft$

Volume of Earthwork Equation = $D\left(\frac{A_o+A_n}{2}\right) + (A_1 + A_2 + \cdots + A_{n-1})$

D = 1 *ft*

A_o= 20,106 ft^2

A_1 = 15,841 ft^2

A_2 = 10,695 ft^2

A_3 = 5762 ft^2

A_4 = 2076 ft^2

Volume of Earthwork = $1\left(\frac{20{,}106+2{,}076}{2}\right) + (15{,}841 + 10{,}695 + 5{,}762) = 43{,}389\ ft^3$

Site B

Site Area = $\pi\left(\frac{d}{2}\right)^2 = \pi\left(\frac{160}{2}\right)^2 = 20{,}106.19\ ft^2$

Elevation Change = $456\ ft - 454\ ft = 2\ ft$

Volume of Earthwork Equation = $D\left(\frac{A_o+A_n}{2}\right) + (A_1 + A_2 + \cdots + A_{n-1})$

D = 1 *ft*

A_o= 20,106 ft^2

A_1 = 17,879 ft^2

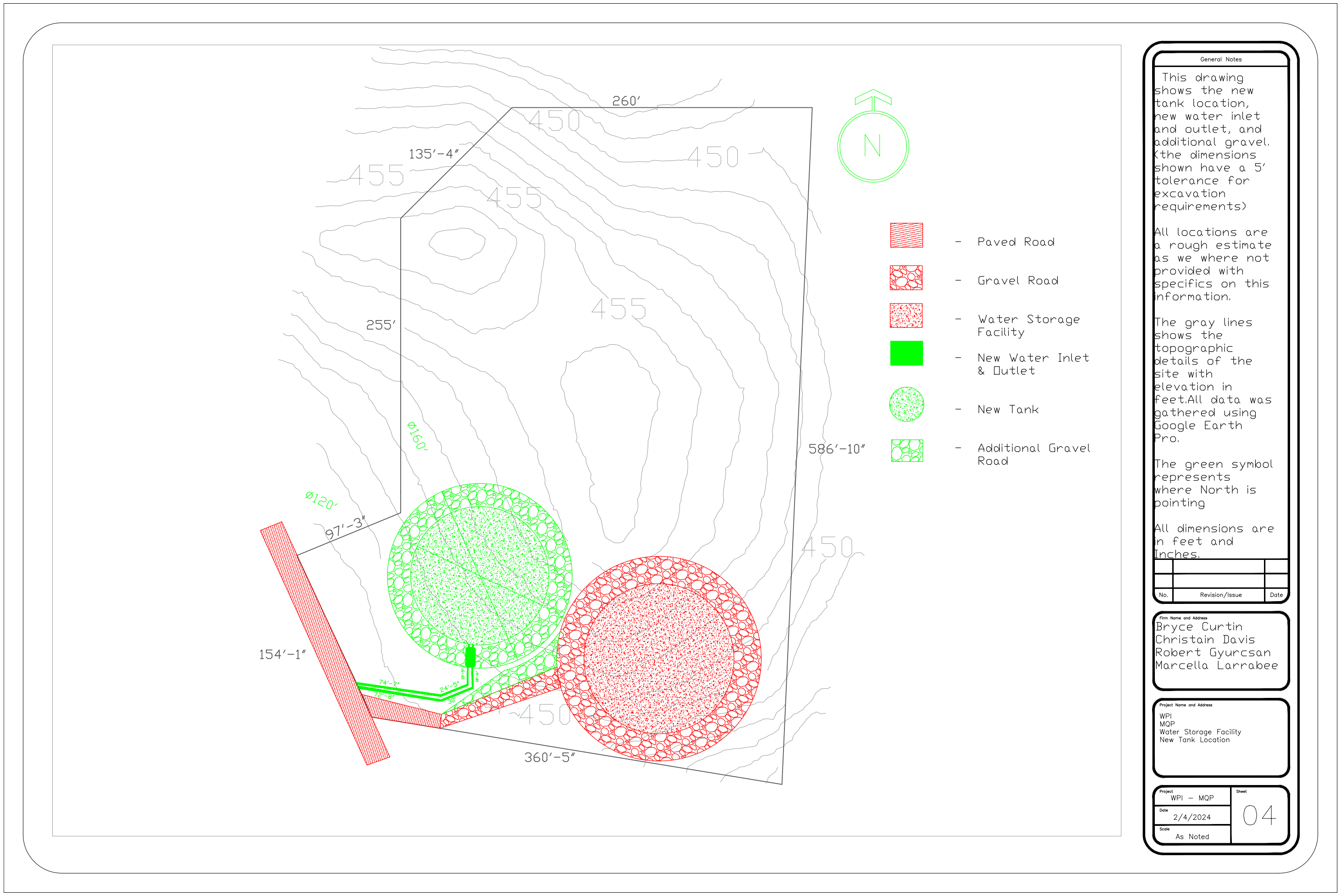
A_2 = 8,364 ft^2

Volume of Earthwork = $1\left(\frac{20{,}10664+8{,}364}{2}\right) + (17{,}879) = 32{,}114\ ft^3$

Appendix F – Site Work Estimation

Site A				Site B			
Excavation Cost Factor	Average Unit Price	Estimate Units	Cost	Excavation Cost Factor	Average Unit Price	Estimate Units	Cost
Excavator Rental	$1,210 per day	3 days	$ 3,630	Excavator Rental	$1,210 per day	3 days	$ 3,630
Compactor Rental	$567 per day	2 days	$ 1,134	Compactor Rental	$567 per day	2 days	$ 1,134
Dirt Hauling	$0.29 per cubic foot	43,389 cubic feet	$ 12,583	Dirt Hauling	$0.29 per cubic foot	32,114 cubic feet	$ 9,313
Labor (operator)	$21 per hour	24 hours x 1 man	$ 504	Labor (operator)	$21 per hour	20 hours x 1 man	$ 420
Labor (laborer)	$18 per hour	40 hours x 2 men	$ 1,440	Labor (laborer)	$18 per hour	40 hours x 2 men	$ 1,440
Soil Testing	$500 per job	N/A	$ 500	Soil Testing	$500 per job	N/A	$ 500
Surveying and Permits	$750 per job	N/A	$ 750	Surveying and Permits	$750 per job	N/A	$ 750
Miscellaneous Cost	$2000 per job	N/A	$ 2,000	Miscellaneous Cost	$2500 per job	N/A	$ 2,500
Total Excavation Cost =			$ 22,540	Total Excavation Cost			$ 19,690
Excavator Rental	$1,210 per day	1 days	$ 1,210	Excavator Rental	$1,210 per day	3 days	$ 3,630
12" Class 2 Concrete Pipe	$990 per foot	15 feet	$ 14,850	12" Class 2 Concrete Pip	$990 per foot	135 feet	$ 133,650
Dirt Hauling	$0.29 per cubic foot	60 cubic feet	$ 17	Dirt Hauling	$0.29 per cubic foot	810 cubic feet	$ 235
Labor (operator)	$21 per hour	4 hours x 1 man	$ 84	Labor (operator)	$21 per hour	24 hours x 1 man	$ 504
Labor (laborer)	$18 per hour	16 hours x 6 men	$ 1,728	Labor (laborer)	$18 per hour	60 hours x 6 men	$ 4,320
Surveying and Permits	$750 per job	N/A	$ 750	Surveying and Permits	$750 per job	N/A	$ 750
Miscellaneous Cost	$1000 per job	N/A	$ 1,000	Miscellaneous Cost	$5000 per job	N/A	$ 5,000
Total Piping Cost =			$ 19,640	Total Piping Cost =			$ 148,090
Final Cost =			$ 42,180	Final Cost =			$ 167,780

Appendix G – Final Tank Location



Appendix H - LRAA of trihalomethanes by location in mg/L

Dates and other identifying information are omitted to preserve anonymity by request of the PWS.

LRAA by Location (mg/L)			
A	B	C	D
0.0349	0.0314	0.0520	0.0307
0.0343	0.0245	0.0459	0.0260
0.0342	0.0202	0.0483	0.0256
0.0390	0.0365	0.0512	0.0308
0.0461	0.0482	0.0533	0.0386
0.0558	0.0473	0.0583	0.0464
0.0581	0.0424	0.0379	0.0434
0.0542	0.0285	0.0397	0.0427
0.0482	0.0261	0.0361	0.0406
0.0423	0.0264	0.0304	0.0343
0.0426	0.0300	0.0404	0.0361
0.0418	0.0395	0.0383	0.0337
0.0452	0.0404	0.0436	0.0357

Appendix I - OEL of trihalomethanes by location in mg/L

Dates and other identifying information are omitted to preserve anonymity by request of the PWS.

OEL by Location (mg/L)			
A	B	C	D
0.0385	0.0297	0.0495	0.0362
0.0353	0.0219	0.0451	0.0269
0.0327	0.0205	0.0368	0.0211
0.0310	0.0243	0.0631	0.0238
0.0475	0.0510	0.0517	0.0414
0.0543	0.0573	0.0545	0.0229
0.0639	0.0467	0.0518	0.0498
0.0524	0.0254	0.0293	0.0335
0.0516	0.0173	0.0400	0.0447
0.0408	0.0338	0.0287	0.0394
0.0422	0.0309	0.0386	0.0342
0.0410	0.0305	0.0399	0.0288
0.0445	0.0401	0.0401	0.0355

Appendix J - LRAA of haloacetic acids by location in mg/L

Dates and other identifying information are omitted to preserve anonymity by request of the PWS.

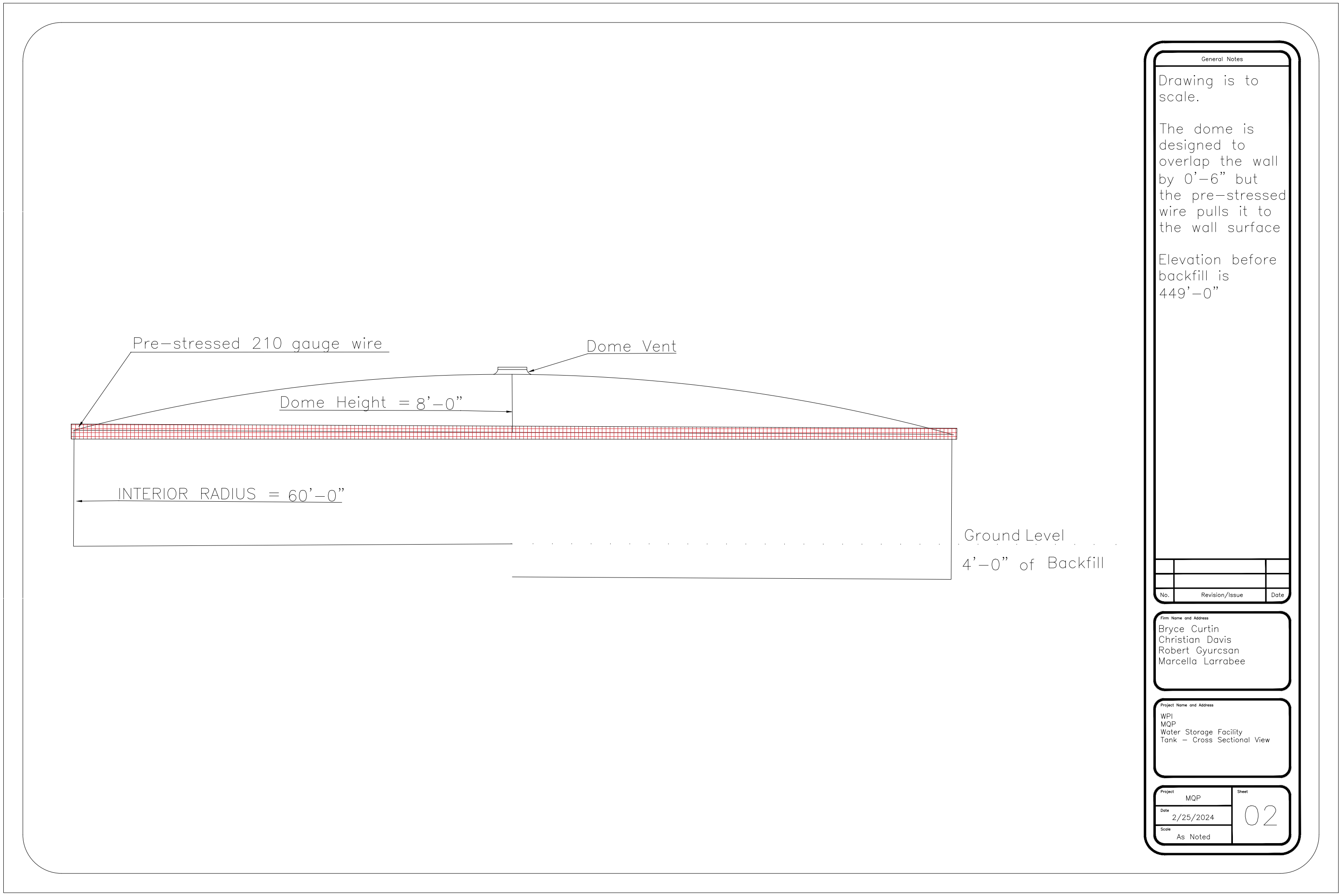
LRAA by Location (mg/L)			
A	B	C	D
0.0298	0.0175	0.0254	0.0269
0.0246	0.0159	0.0273	0.0208
0.0243	0.0134	0.0286	0.0199
0.0247	0.0234	0.0291	0.0168
0.0297	0.0326	0.0408	0.0253
0.0376	0.0333	0.0476	0.0344
0.0387	0.0278	0.0400	0.0313
0.0398	0.0194	0.0408	0.0342
0.0362	0.0147	0.0331	0.0308
0.0328	0.0147	0.0252	0.0228
0.0326	0.0172	0.0332	0.0237
0.0321	0.0253	0.0333	0.0257
0.0360	0.0296	0.0376	0.0275

Appendix K - OEL of haloacetic acids by location in mg/L

Dates and other identifying information are omitted to preserve anonymity by request of the PWS.

OEL by Location (mg/L)			
A	B	C	D
0.0325	0.0170	0.0309	0.0328
0.0248	0.0130	0.0210	0.0212
0.0213	0.0111	0.0291	0.0145
0.0244	0.0190	0.0290	0.0191
0.0278	0.0328	0.0351	0.0195
0.0348	0.0390	0.0462	0.0124
0.0425	0.0316	0.0548	0.0381
0.0395	0.0180	0.0323	0.0304
0.0391	0.0112	0.0359	0.0312
0.0299	0.0157	0.0239	0.0273
0.0331	0.0186	0.0322	0.0216
0.0321	0.0183	0.0327	0.0208
0.0345	0.0299	0.0362	0.0282

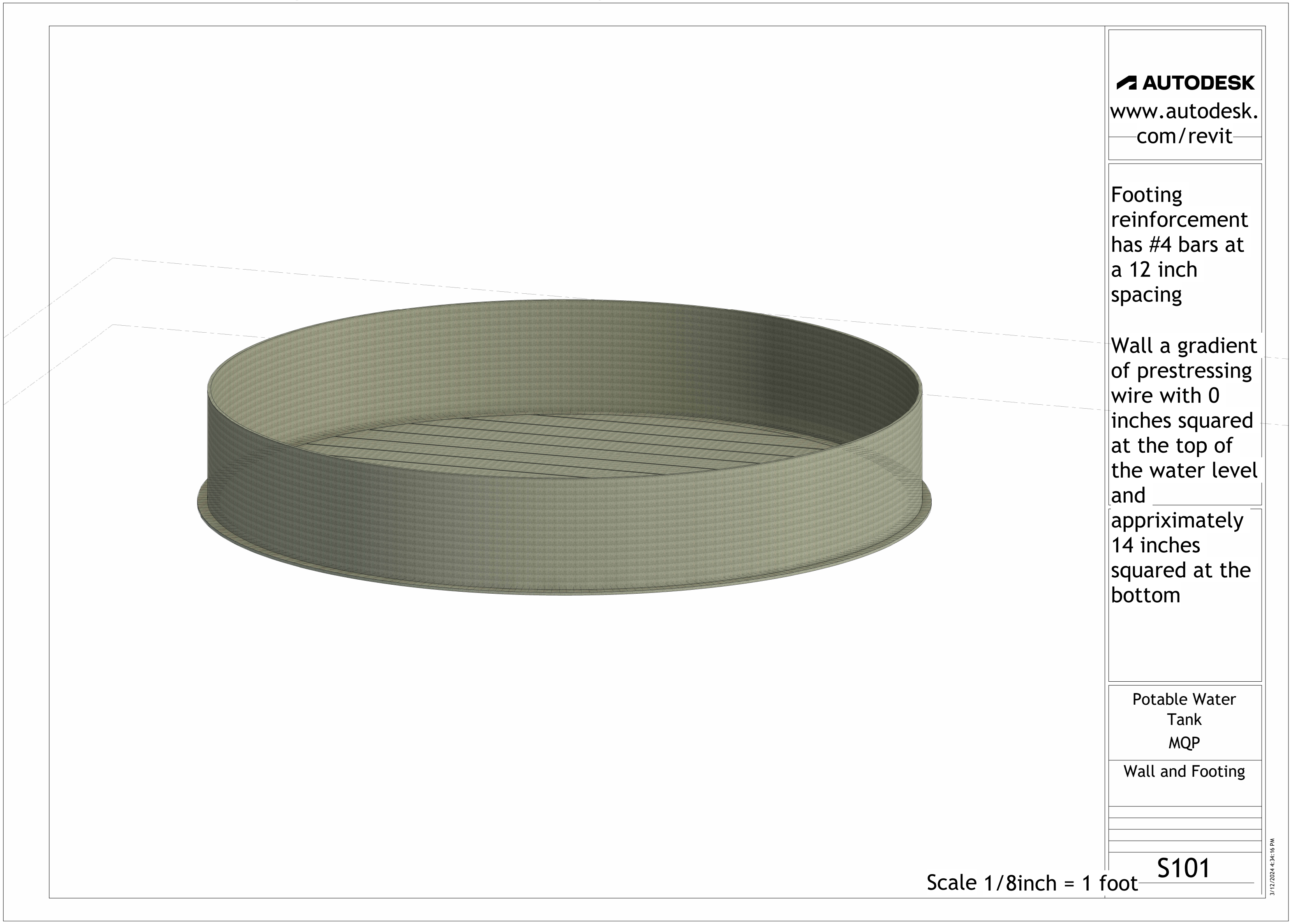
Appendix L – 2D Cross-sectional drawing of tank dome



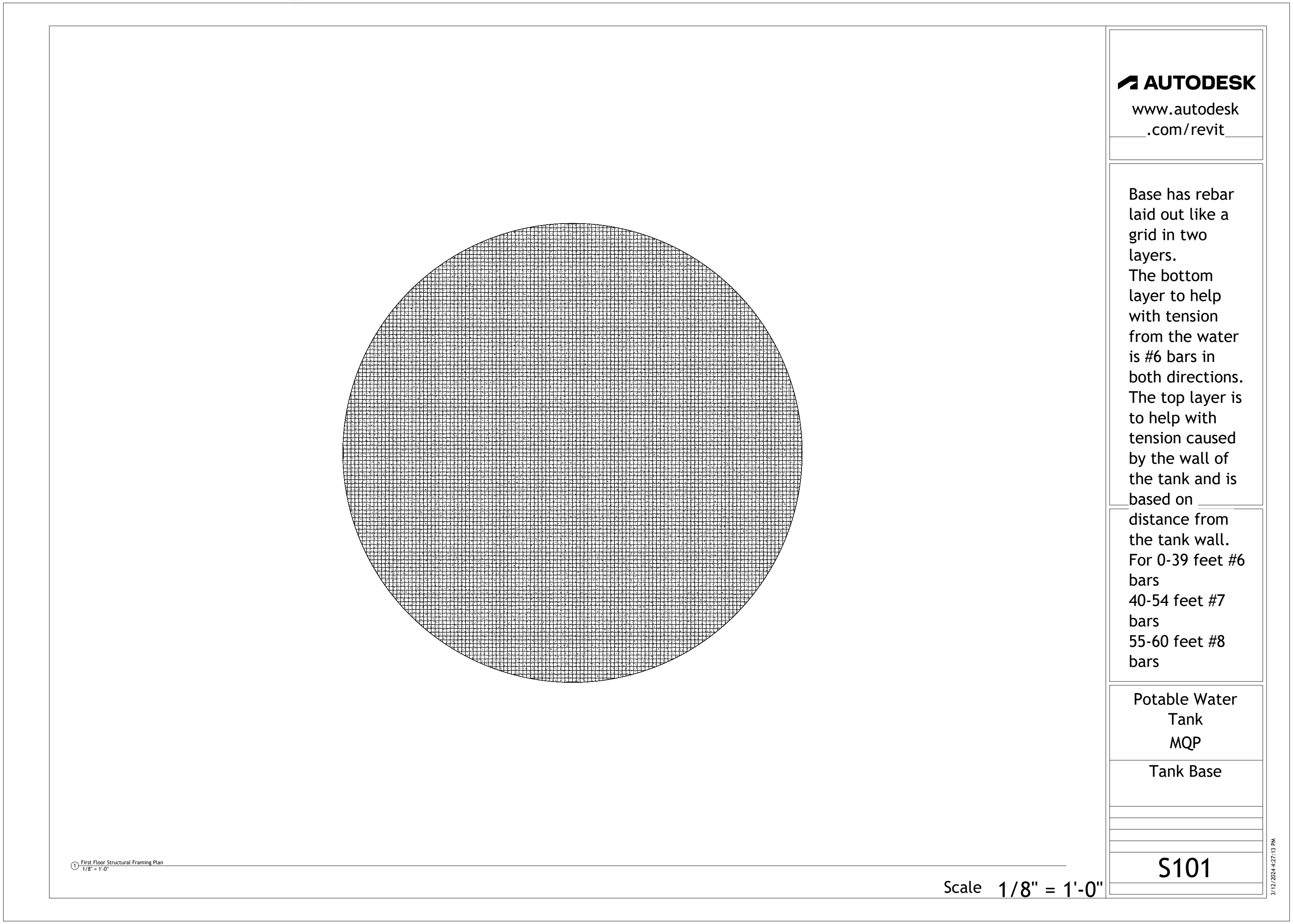
Appendix M – 2D Arial drawing of tank dome

Appendix N – 3D Drawing of tank dome

Appendix O – 3D Drawing of tank wall and footing



Appendix P – 3D Drawing of tank base



Appendix Q – 3D Full drawing of tank

Appendix R – Structural Design Calculations

Dead Load = $(\frac{2}{3})(\pi)(60^3)(152.78)$ = 867,600 lbs

Surface Area = 2 π (60) (8) = 3014.4 ft^2

Dead Load = 867,600 lbs / (3014.4 ft^2) = 80 psf

pf = 0.7(1.0)1.2)(1.0)(30) = 25.2 psf

Ps = 1.0(25.2) = 25.2 psf

Av = (2/3)(0.16) = 0.107

Ev = Av (80 + 0.2*25.2) = 9.1 psf

Pu = 1.2*80 + 0.2(25.2) + 1.0(9.1) = 110.14 psf

Pu = 1.2*80 + 1.6 (25.2) = 136.3 psf

Pu = 1.4*80 = 112 psf

$$\min, t_d = (34)\sqrt{\frac{1.5(136.3)}{0.6(0.5)(0.52)(57000(4^{0.5})}} = 3.65"$$

Area of reinforcing steel = 0.0025(8,256 in^2) = 20.64 in^2

Area of reinforcing steel = 0.0025(27,200 in^2) = 68 in^2

A_{ds} = ((2,690,600)cot(7.6))/2π(0.8)(140,000) = 28.66 in^2

P = (62.4)(32.2)(16) = 223.3 psi

V = (80psf*60ft)/2 = 5.8 kips

P_s = (total W)/(L_f*12")

W_s = 120 pcf (4')(1')(2') = 1 kip

W_w = 62.4 pcf (16')(1')(2') = 2 kips

12400 lbs/(5'*1') = 2480 psf

P_{us} =(1.2)(2480 psf)(2')(1') = 5952 lbs

d = (5952 lbs)(2)/(2 $\sqrt{(5000)}$(12") = 7"

M_u = 5952 lbs * $(\frac{2}{2})$ = 5952 ft-lbs

5952 ft-lbs = $\rho(60000)(12")(7"^2)\left(1 - 0.59\rho\frac{60000}{5000}\right)$

As = (0.0021)(12")(7") = 0.173 in^2

W_w = 62.4 pcf (1')(120')(16') = 119808 lbs

P_{us} = W_w/(120')(1') = 998.4 psf(1.2)(1')(60') = 71885 lbs

d = (71885 lbs)/(2 $\sqrt{(5000)}$(12") = 19"

$$\Phi Mn = \sqrt{\Phi Mnx^2 + \Phi Mny^2}$$

$$7{,}188{,}000 = \rho(60000)(12")(19^2)\left(1 - 0.59\rho\frac{60000}{5000}\right)$$

$A_{s,min}$ = 0.0018(12")(19")= 0.4104 in^2