DERRICK RESERVOIR 7.5 MG TANK REHABILITATION PROJECT

PRELIMINARY ENGINEERING REPORT

September 7, 2021

PREPARED FOR:

City of Coalinga

169 W Durian Ave, Coalinga, CA 93210

PREPARED BY:

MKN and Associates, Inc.
Henry Liang, PE – Principal-in-Charge and Project Manager
Tanner Bennett, PE – Technical Lead
Jon Hanlon, PE – Technical Advisor and Quality Control
Ammar Hanna, EIT – Engineering Support

WITH CONTRIBUTIONS BY:

CSI Services, Inc. – Coatings and Shell Thickness Testing
SSG Structural Engineers, LLP – Structural Evaluation

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1 BACKGROUND AND PROJECT UNDERSTANDING

1.1 Purpose and Scope of Evaluation

MKN and Associates, Inc. (MKN) was retained by the City of Coalinga (City) to evaluate the 7.5 MG welded steel Derrick Reservoir located at Jayne Avenue and S. Derrick Avenue in Coalinga, California. The purpose of this report is to assess current conditions, document findings and analysis, and to provide rehabilitation options to bring the existing tank into compliance with the current AWWA D100-11 standard while maintaining an operating level adequate to serve the City of Coalinga. The evaluation investigates tank coatings and other non-structural tank improvements that may improve the performance, operation, and useful life of the tank. The report also includes an alternative of replacing the existing tank with a new tank.

The documents provided to the project team for the evaluation of the Derrick Reservoir include as-built civil and structural drawings (Koebig & Koebig, Inc. dated 6/30/1970), a Maintenance Inspection Report including a dive inspection on 12/6/2019, historical photographs, field measurements (CSI Services dated 1/6/2020), and an "External Fixed Rood" inspection (Mistras Group dated 07/27/2021). MKN's evaluation of the structure was based on a review of provided documents and visual observations made by the MKN team during an on-site condition assessment conducted on 4/21/21. The structural and seismic evaluation was performed by SSG Structural Engineers in accordance with:

- American Water Works Association (AWWA) standard "Welded Carbon Steel Tanks for Water Storage" (AWWA D100-11)
- American Society of Civil Engineers Standard 7-16 "Minimum Design Loads and Associated Criteria for Buildings and Other Structures" (ASCE 7-16).

Based on our discussions with Coalinga staff, maintaining the storage capacity of the tank, to the extent possible, is desired by the City due to the reservoir's location for system optimization as well as for emergency storage. MKN's recommendations consider this objective and include improvements to maximize water storage capacity.

1.2 Tank Description

The following description was based on information collected during a visual observation of the reservoir and a review of drawings and documents provided by the City. Relevant structural parameters for evaluation of the tank are based on the past reports provided by the City. Where pertinent structural information could not be determined in the field, conservative assumptions were made based on the tank's age and our experience with similar structures.

Per the affixed name plate on the wall shell, the tank was built circa 1971, has a nominal diameter of 180'-0", a nominal wall height of 40'-6", and an overall capacity of 7,520,000 gallons. Seismic provisions for the design of steel storage tanks were developed and commonly implemented in 1978. Due the tank's age (Built 1971), it is not guaranteed and is unlikely that the tank was designed for seismic loading (See Figure 1 and Figure 2).

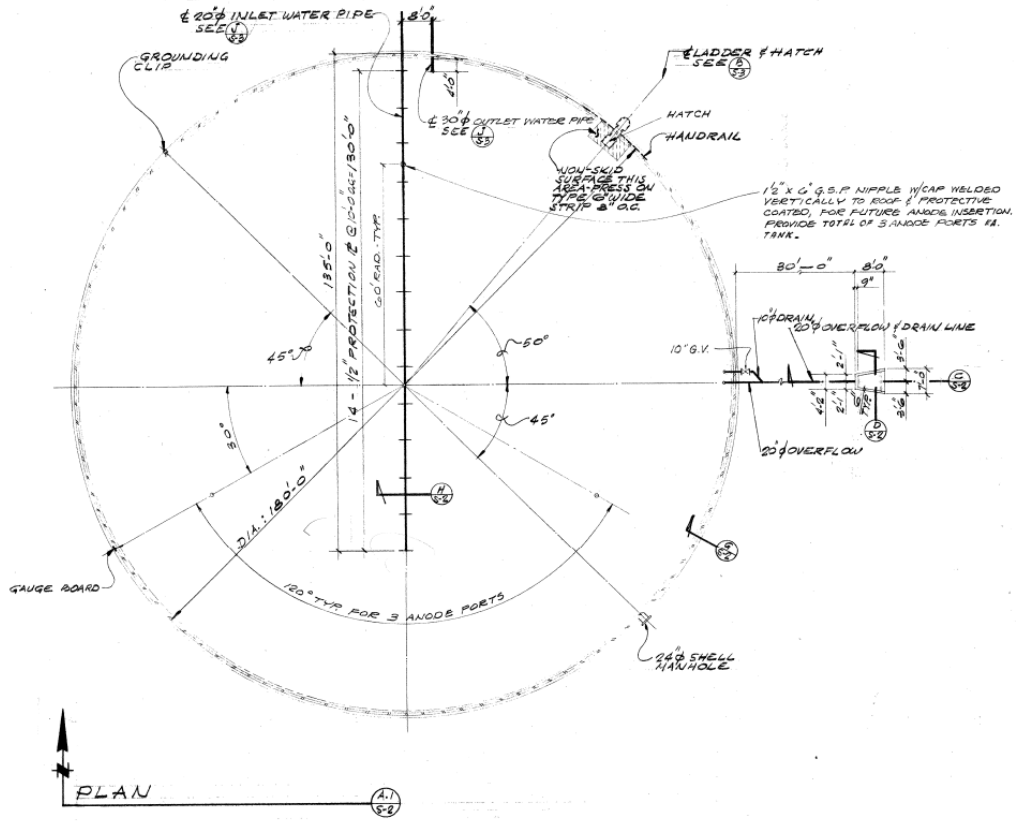

Figure 1: Site Plan (Sheet S-2 From Koebig and Koebig)

Figure 2: Aerial View (By MKN on 04/21/2021)

The tank wall has five shell courses leading to a conical roof with a drip edge. The tank has an internal radial framed roof support structure that is comprised of a dollar plate, rafter beams, girders, and columns. The tank has a caged external ladder that leads to the tank roof, which has handrails in the immediate vicinity of the ladder. The roof on the tank has one center vent, and there are various piping components throughout the tank. The tank is supported by a concrete ring wall that is surrounded by pavement. No anchors are present. The exterior of the tank has painted appurtenances that primarily involved piping. No cathodic protection system was identified.

1.3 Summary of Previous Reports and Information

1.3.1 Coatings Maintenance Report and Dive Inspection Report (2019-2020)

CSI Services, Inc. inspected Derrick Reservoir on December 16, 2019. Deficiencies in the tank are summarized in Table 1.

Table 1: Tank Coating Deficiencies

Item/Part	Deficiency Note
Exterior Walls	Mostly satisfactory condition with some minor isolated and fields of rust spots. The western shell had more rust spots that appeared to be the result of damage from gun fire.
Exterior Roof	The exterior paint on the roof is in poor condition and have heavy amount of chalking. Locations with advanced corrosion were noticed.
Interior Roof	The coating on the inside of the roof seems to have failed many years ago. Large pieces of coating have delaminated from the steel.
Interior Walls (above water line)	Shell was in poor condition with corrosion and fields of blisters.
Interior Walls (below water line)	Lower courses were in relatively better condition with some dark rust and shallow pitting.
Sediment	Not inspected
Drain	One rust tubercle on the bottom of the sump
Columns	In general, the roof support structure was in poor condition.

Overall, the tank's coatings are in poor condition, except for some exterior areas of the shell including some exterior appurtenances such as the ladder, manway, and piping. The most notable areas of rust are the interior roof, roof support structures, and walls of the tank. Seven of the roof beams have become loose and are no longer functional. One of these beams has fallen to the tank bottom. The inspection report also noted concerns regarding the ladder and handrail system. The tank was found to have areas that could benefit from an upgrade to its fall prevention system. The ladder and roof rail system should be upgraded and comply with current safety standards. The tank roof corrosion is extensive and although the City has attempted to repair holes in the past with fiberglass, many of these repairs have failed. Holes within the tank roof are still present.

CSI's dive inspection report noted concern for the interior ladder fall prevention cage on the internal access ladder because it presents an issue for emergency extraction. It is recommended to remove the cage and install a fall protection device suitable for submersion or replace the existing interior ladder with a ladder that does not have a cage at the next maintenance cycle. Personnel shall proceed with caution when accessing the ladder.

1.3.2 Photographic Documentation

Various photographs taken in early 2020 show signs of corrosion and vandalism. The tank shell has circular rust spots that appear to be the result of damage from gunfire (See Figure 3 and Figure 4).

Figure 3: Corrosion at Roof Hatch (By CSI on 01/06/20)

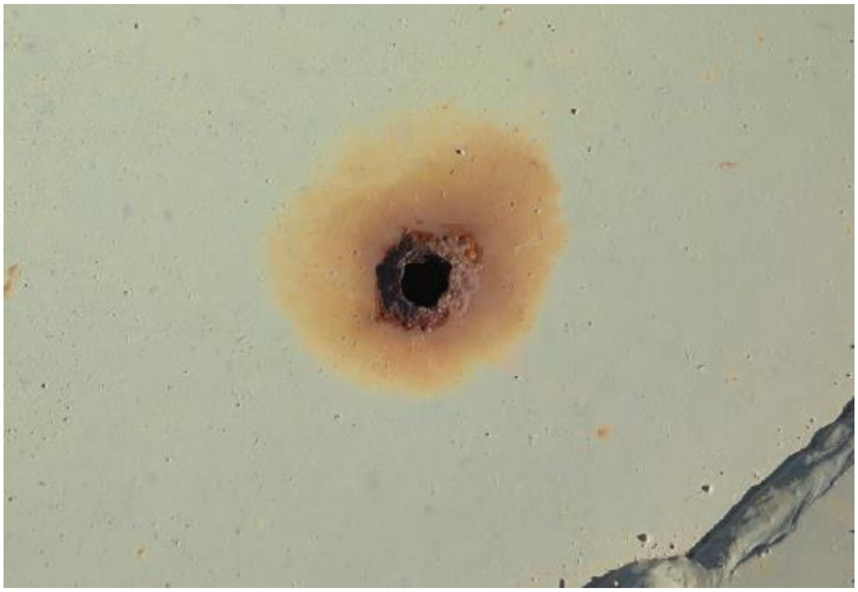

Figure 4: Gunfire Rust Spots (By CSI on 01/06/20)

2 COATING ASSESSMENT

This assessment included overall evaluation of the exterior coating and interior lining systems of the tank which remained in service during MKN's site visit. The evaluation involved visual observation, non-destructive testing, and destructive testing. Photographs were taken to further document the conditions observed.

2.1 General

The exterior paint system has a beige finish, while the interior lining is navy blue. The exterior appears to be painted with an alkyd-based system. The interior lining appeared to be coated with a bitumastic lining system and is likely the original coating applied. The lower part of the tank appears to have a hot-applied coal-tar enamel while the upper part appears to have a bitumastic cut-back (Supertank Solution).

Visual observations of the exterior coatings were limited to the lowest shell course, upper shell areas adjacent to the ladder, and the roof. The exterior paint on the tank is in poor condition on the roof and in overall fair conditions on the shell, with major chalking. Rust was present at various locations on the roof, and although the rust density was low, there were locations with advanced corrosion, mainly on the topside, the perimeter, and appurtenances on the roof. Figure 5 shows some of the corrosion found on top of the tank. The total amount of rust was rated to be 0.03% of the total area per ASTM D610.

Areas of minor, scattered corrosion on the tank shell were present, with the western quadrant of the shell having more rust spots that appeared to be the result of damage from gunfire. The shell's appurtenances including the ladder, piping, and manway were in a condition similar to the shell plate.

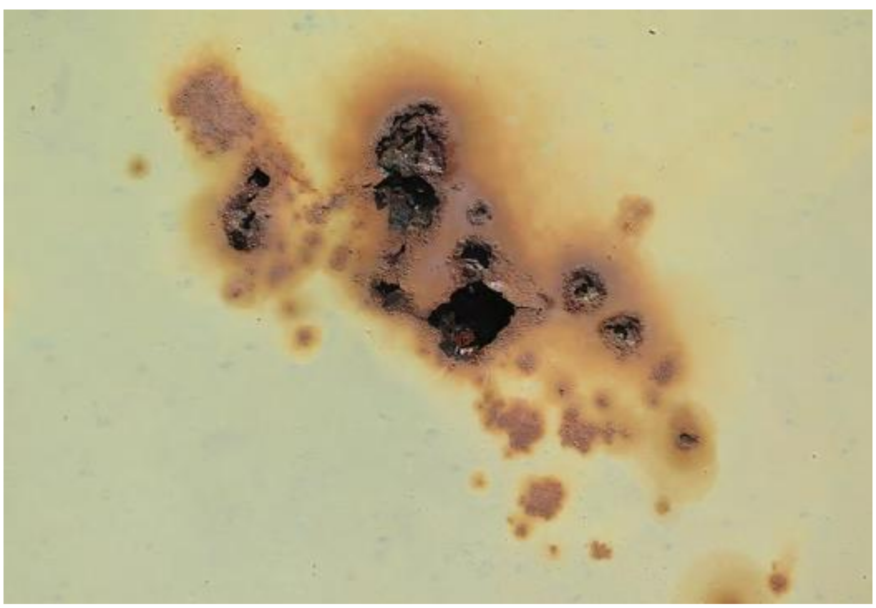

Figure 5: Typical Exterior Shell Corrosion (By CSI on 01/06/20)

The coating on the interior of the roof including all support structures was in poor condition. Most of the roof area had dark corrosion along with metal loss. One rafter beam was observed to have broken free and had fallen to the bottom of the tank. The interior wall liner of the shell was in a poor condition with observable corrosion. Figure 6 shows some of the corrosion found on the inside of the tank. Lower sections of the tank were in a relatively better condition in comparison with the top section. The floor lining was in mostly good condition, with some areas having dark rust and shallow pitting.

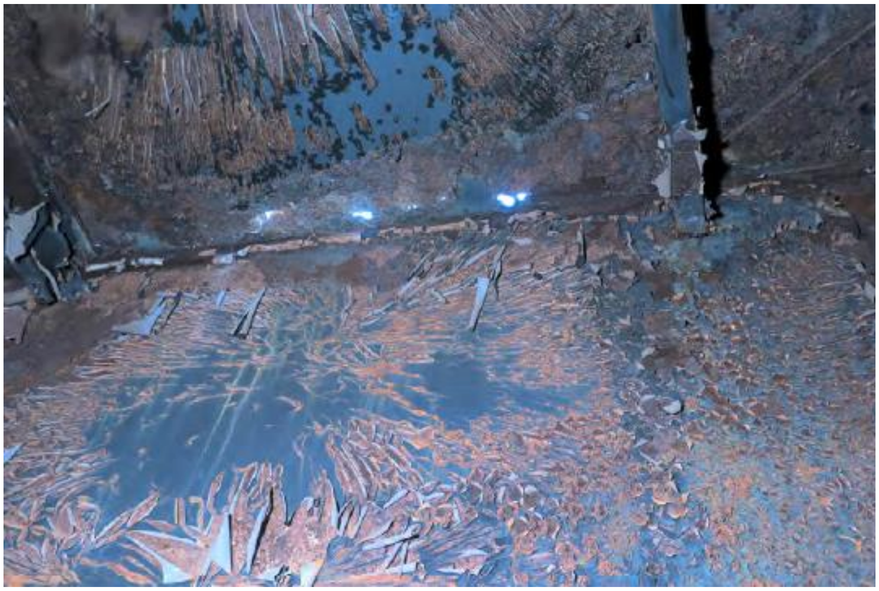

Figure 6: Typical Interior Shell Corrosion (By CSI on 01/06/20)

2.2 Tank Coating Thickness Testing

An inspection of the exterior shell coating was performed by CSI Services using a Positector 6000FN3 Type II dry film thickness gage (Serial No. 41071) in accordance with the requirements of ASTM D7091 and SSPC PA2. The paint dry film thickness on the exterior shell was measured to range between 7 and 16 mils. The fixed roof has coating failures with primer showing in certain areas, the 16-inch vent shows signs of internal corrosion, the autogauge tape guide is corroded, and there is significant sagging on the southwest side of the roof due to rafters failures.

2.3 Tank Exterior Coatings Testing for California Administrative Manual (CAM-17) Heavy Metals

A coating sample was collected from the tank exterior to determine the presence of heavy metals in the tank shell. The sample was sent to Schneider Laboratories in Richmond, VA for analysis of the seventeen CA Title 22 heavy metals (CAM-17) in accordance with EPA Method 2050B and EPA 7471A. Table 2 summarizes the results for all 17 metals which are reported in PPM (mg/kg).

Table 2: CAM-17 Heavy Metals Testing Results	
Parameter	Result (mg/kg)
Antimony	<6.46*
Arsenic	<6.46*
Barium	26,800
Beryllium	<6.46*
Cadmium	<6.46*
Chromium	99.1
Cobalt	141
Copper	18.3
Lead	1,940
Molybdenum	<6.46*
Nickel	12.2
Selenium	<6.46*
Silver	<6.46*
Thallium	<6.46*
Vanadium	<6.46*
Zinc	60.5
*6.46 is the Reporting Limit which is the lowest detectable concentration	

The presence of heavy metals results in additional costs associated with the proper removal and disposal of the coatings. EPA and CAL/OSHA regulations require appropriate worker and environmental protection measures (tenting full containment of the structure, and/or air monitoring may be required as determined by the contractor) to mitigate concerns associated with heavy metals present in coatings. Waste categorization is also required to determine landfill classification requirements for disposal. Disturbance or removal of the exterior tank coatings will require the Contractor to address worker safety and disposal requirements. Cost estimates included within this report include costs associated with mitigation of heavy metals. Specifications and requirements for heavy metal remediation should be included in future contract documents.

2.4 Coating Recommendations

There are multiple approaches available for the rehabilitation of exterior tank coatings ranging from spot repair, to spot repair and overcoat, to complete removal and replacement.

The first consideration is the coating's ability to withstand the added stresses of an additional coat(s). Film thickness and adhesion are primary elements to this determination. If an existing film is too thick or has poor adhesion, the tension from the curing stresses and/or the weight of the additional paint can cause the existing system to detach.

Another consideration is the amount of surface area requiring repair. An industry guideline is that if ten percent or less of the surface area requires repair, rehabilitation can be economically addressed by spot repair. Overcoating is generally feasible with up to ten percent rusting provided adhesion is better than fair, and in some cases top coating can be viable with greater than ten percent rusting if adhesion is satisfactory. However, once the amount of surface area exceeds approximately ten percent, the cost of surface preparation, cleaning, and coating the individual areas generally approaches or exceeds the cost of complete removal and replacement.

As noted above, shell paint was analyzed for heavy metal content (CAM-17 including lead, cadmium, and chromium) and found to contain low levels of Cadmium and relatively high levels of Chromium and Lead. Thus, mitigation of heavy metals will be required, particularly if coating removal and replacement is selected.

2.4.1 Exterior Coating Recommendation

To assess the existing coating's ability to be overcoated, CSI applied a test patch to the tank in conformance with ASTMD5062 and the manufacturer's recommendations. The evaluation of the test patch primarily included testing for film thickness and adhesion in accordance with ASTM D7091 and ASTM D3359A, respectively. The results of the test patch were unsatisfactory, and the existing paint was found to not be a candidate for overcoating (See Figure 7). A satisfactory test would have resulted in minimal lifting of the existing paint under the gray test patch. Figure 7 shows that a majority of the existing paint lifted. It is therefore recommended that the exterior tank coatings be removed by blasting and replaced.

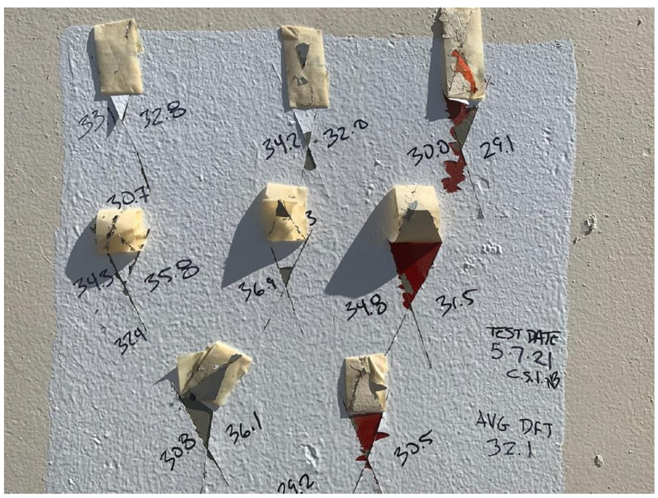

Figure 7: Paint Test Patch on the Shell of the Tank (By CSI on 01/06/20)

MKN recommends the following for replacement of exterior coating:

System 1, Epoxy Zinc, Polysiloxane

1. Description: Two step coating system consisting of a three-component epoxy zinc rich primer and polysiloxane finish coat applied to prepared surfaces. Epoxy zinc rich primer shall meet the performance requirement of SSPC Paint 20 and contain no less than 89% zinc pigment in the dried film. The polysiloxane finish coat shall be greater than 90% volume solids and exhibit excellent long-term color and gloss characteristics as defined by AWWA D102-20 OCS-5.
2. System:
    b. Prime Coat: Epoxy Zinc, 3 - 5 mils dft
        i. SW Zinc Clad 4100, or equal.
    c. Finish Coat: Polysiloxane, 4 - 6 mils dft

i. SW Sherloxane 800, or equal.

2.4.2 Interior Coating Recommendation

For the interior tank coating, it is recommended that the coating system be entirely removed and replaced. This includes that the interior be blasted to near white metal in preparation for recoating.

We recommend the following coatings for the interior surfaces:

A. System 1: Ultra High Solids Epoxy

1. Description: Single coat epoxy lining system consisting of a two-component epoxy finish coat applied directly steel surfaces. The epoxy shall be amine cured, two components, epoxy with greater than 96% volume solids, meet the performance characteristics of MIL PRF 23236 and AWWA C210 Epoxy Lining for Welded Steel Pipe, and be certified for potable water use per ANSI / NSF 61.

2. System:

   a. Stripe Coat: Epoxy or Ultra High Solids Epoxy, 3 – 8 mils dft

      i. SW Macropoxy 5500 or equal.

   b. Finish Coat: Ultra-high solids epoxy, 20 - 30 mils dft

      i. SW Duraplate UHS, Sherplate PW, or equal.

B. System 2: High Solids Epoxy

1. Description: Multiple coat epoxy lining system consisting of a two-component epoxy finish coat applied directly steel surfaces. The epoxy shall be amine cured, two components, epoxy with greater than 80% volume solids, meet the performance characteristics of AWWA C210 Epoxy Lining for Welded Steel Pipe, and be certified for potable water use per ANSI / NSF 61.

2. System:

   a. Prime Coat: High Solids Epoxy, 4 – 8 mils dft

      i. SW Tank Clad HS, or equal.

   b. Stripe Coat: High Solids Epoxy, 3 – 8 mils dft

      i. SW Tank Clad HS, or equal.

   c. Intermediate Coat: High Solids Epoxy, 4 – 8 mils dft

      i. SW Tank Clad HS, or equal.

3 STRUCTURAL ASSESSMENT

SSG Structural Engineers (SSG) conducted a limited structural assessment of the Derrick Reservoir to provide options to bring the existing tank into compliance with the current AWWA D100-11 Standard – Welded Carbon Steel Tanks for Water Storage, while maintaining an operating level adequate to serve the City of Coalinga's population. The analysis of the existing tank was performed using AMETank as developed by TechnoSoft. Calculations are provided in the Appendix for reference.

Evaluation of the tank focused on structural deficiencies identified in the 2019 dive inspection report by CSI and select structural elements identified by Mistras. The structural evaluation was based on a review of provided documents and information as well information that was able to be gathered during the on-site inspection. Structural elements not specifically referenced are outside the purview of this report.

3.1 General Assumptions

- Coordinates: 36.1414919, -120.3900433
- Year Built: 1971
- Tank Diameter: 180'-0"
- Tank Wall Height: 40'-6"
- Maximum Operating Water Level (MOL): 35'

3.2 Assumed Materials (Note original shop/fabrication drawings not available)

- Rafters: A36 (Fy= 36 ksi)
- Girders: A36 (Fy= 36 ksi)
- Steel Plates: A36 (Fy=36 ksi)
- Concrete: 2,500 psi

3.3 Seismic Design Values

- Maximum Considered Earthquake (period = 0.2 seconds) $S_S = 1.794$
- Maximum Considered Earthquake (period = 1.0 seconds) $S_1 = 0.593$
- Site-modified Spectral Acceleration Value $S_{MS} = 1.794$
- Site-modified Spectral Acceleration Value $S_{M1} = 0.890$
- Numeric Seismic Design Value at 0.2 sec $S_{DS} = 1.196$
- Numeric Seismic Design Value at 1.0 sec $S_{D1} = 0.596$

When assessing an existing tank for seismic loads, performance objectives should be determined based on the level of risk acceptable for the given tank. A description of performance levels and usage categories is provided below. This analysis assumes the Seismic Use Group of the tank is III, which is defined as a tank that provides direct service to facilities that are deemed essential for post-earthquake recovery and essential to the life, health, and safety of the public, including post-earthquake fire suppression. The Seismic Use Group III falls into the Essential Facilities Usage Category as the water can be used during post-earthquake fire suppression.

Table 3: Performance Objectives				
Usage Categories*	Expect Shell or Roof Damage	Maintain Confinement of Liquid	Maintain Storage Functions	Maintain Storage Seismic Risk
Low Risk Facilities	Yes	No[t]	No	Low
General Facilities	Yes	Yes	No	Medium
Essential Facilities	Minor	Yes	Yes	High

* Low-risk facilities are those that are remotely situated and, should a major spill or fire develop, would not pose serious health or life endangerment. General risk facilities are all others. Essential facilities are those that are used by public works departments during general emergency such as fire water tanks or potable water tanks for public emergencies.

[t] In this context, it is assumed that secondary containment is provided and would provide a localized confinement, or the tank contents should it rupture, preventing an environmental risk.

Information in table 3 above is obtained from Above Ground Storage Tanks by Philip E. Myers, (McGraw Hill, 1997)

3.4 Steel Ultrasonic Thickness Measurements

Spot steel thickness measurements were also collected from the roof plate and each shell course using a Krautkramer Braunston DMS ultrasonic thickness gage. The readings on the shell were taken from randomly selected locations a few inches in size, while the roof spot readings were collected from locations that had topside evidence of severe underside corrosion. These roof readings were continuously scanned perpendicular across a two-foot line that centered over lines of underside corrosion. Table 4 summarizes the results in inches.

Table 4: Steel Thickness Testing Results					
Roof Plate	5th (Upper) Shell Course	4th Shell Course	3rd Shell Course	2nd Shell Course	1st (Lowest) Shell Course
0.092” – 0.210”	0.350” – 0.354”	0.396” – 0.401”	0.594” – 0.601”	0.792”-0.806”	0.990”- 0.992”

3.5 Wall Shell

The following is a summary of the tank shell analysis. Calculations can be found in the appendix for reference. All shell courses are based on an allowable tensile hoop stress of 15,000-psi as defined in Table 5 of the AWWA D100. For seismic loads, a 1/3 increase in the allowable stress is used. A Utilization Ratio greater than 1.0 indicates the material is overstressed for the allowable loads as indicated in the AWWA D100.

All analysis was performed assuming that the existing tank is to remain self-anchored without any added mechanical anchors or modification to the existing ringwall foundation. The AWWA D100 outlines values for J as follows:

- J less than 0.785 indicates no uplift
- J less than 1.54, but greater than 0.785 indicates uplift, but a stable tank
- J greater than 1.54 indicates an unstable tank with anchors required.

As-built tank analysis indicated that the tank overturning ratio, J = 1.345, meaning that it is stable, but is subject to uplift. Table 5 is based on the tank shell performance for the as-built tank operating at the maximum capacity.

Table 5: As-built Tank Condition - Shell Analysis Summary

Course (1 Bottom, 5 Top)	Width [in.]	Min. Thickness, Hydrostatic	Min. Thickness, Seismic	Actual Thickness	Utilization Ratio
5	104	0.265	0.379	0.35	1.08
4	96	0.515	0.672	0.4	1.68
3	96	0.765	0.94	0.59	1.59
2	96	1.015	1.177	0.79	1.49
1	96	1.264	1.384	0.99	1.4

All tank shell courses have a thickness that is less than the minimum thickness that is required for seismic and hydrostatic purposes except for the top course which meets the minimum thickness for hydrostatic but not seismic. Therefore, shell courses 1 through 4 were determined to have a utilization ratio that is higher than one, meaning they are overstressed per current AWWA requirements for hydrostatic and seismic conditions.

3.6 Roof System

Magnetic Flux Leakage (MFL) scanning of the fixed roof revealed twenty-three (23) product side corrosion points with a remaining thickness below 0.09" or 35% of 0.250'' nominal thickness. The inspection found eighteen (18) sketch plates that have holes. API 653, Para. 4.2.1.2 states, "roof plates corroded to an average thickness of less than 0.09 inch in any 100 square inch area or roof plates with any holes through the roof plate shall be repaired or replaced". 15-foot exclusion zone barriers were installed due to holes on sketch plates and roof significant sagging due to rafters failures. An extension pole and manlift were used to perform Ultrasonic thickness readings within the exclusion zone. Approximately 65% of the roof plates were not scanned with MFL but were measured using UT means. There was no confirmation of the extent of underside corrosion that may be present in the areas that were not scanned using MFL.

Advanced corrosion was common to all roof surfaces including roof plate, rafters, girders, and ties. Multiple areas of daylight were visible through the roof, mostly in the southern half of the tank. Figure 8 shows holes in the fixed roof. All roof support structure fasteners are rusting. The corrosion has advanced to develop localized holes in both the plate and roof support structure. Six rafter beams are hanging and have become detached from one side as shown in figure 9, while a seventh beam had broken free and had fallen to the tank bottom. The original roof hatch has exfoliation and through holes. Based on the current conditions and without alteration, damage to the roof structure and/or partial structural collapse/failure of the tank may occur during an earthquake.

The level of corrosion on the tank interior above the shell has clearly advanced to where the existing steel likely cannot be cost-effectively repaired. However, the surfaces below the roof appear to be in a condition that can be rehabilitated. The tank roof and roof support structure require removal and replacement, while the lower surfaces can be repaired with some minor mechanical repairs and relining work. With respect to the exterior paint, a new roof will have new paint.

Figure 8: Fixed Roof Exterior Corrosion (By CSI on 01/06/20)

Figure 9: Failing Fixed Roof Rafters (By CSI on 01/06/20)

3.7 Seismic Evaluation Findings

3.7.1 Freeboard

AWWA D100 describes the freeboard height as the distance between the top of the overflow and bottom of the rafters. Based on the as-builts provided by the City, the existing over flow elevation is at 40-feet relative to bottom of tank providing 6-inches of freeboard. Per the design criteria discussed previously, SSG calculated the required freeboard for the as-built tank to be 7.38', which is exceeded by the current maximum operating level.

3.7.2 Overturning

The existing tank at a maximum operating level was analyzed to have an overturning ratio of J=1.345. Per AWWA D100, a J value less than 1.54, but greater than 0.785 indicates that the tank is stable, but that there is a potential for uplift.

3.7.3 Foundation/Anchorage

As previously mentioned, the tank was determined to be stable but subject to uplift per AWWA D100. As such, anchorage of the tank to the foundation is not required for alternatives presented in this report. Based on review of the as-built drawings the existing ringwall is 15-inches wide by 48-inches deep. Based on our understanding of the foundation geometry/construction and assuming an unconstrained slosh wave, the design bearing pressure on the foundation would be approximately 2,500 psf when considering design gravity loading.

3.7.4 Tank Wall Shells

The tank wall shells were analyzed for hydrostatic and seismic conditions considering the current maximum operating level and the measured wall shell thicknesses. Based on this analysis, the shells were determined to be overstressed and non-compliant per AWWA D-100 current code for both hydrostatic and seismic conditions.

3.8 Structural Recommendations

3.8.1 Recommendations for Fixed Rood

The roof structure consists of rafters supported by two girder lines and I-beam columns. Inspection reports noted extensive signs of corrosion at the tank roof structure. The roof structure and roof plate are both exposed to significant corrosion development. The underside corrosion of the steel plates immediately above roof rafter beams has developed to form through holes in the structure. All roof support structure fasteners are rusting. Most of the roof beams have become loose and are no longer functional.

Based on the level of deterioration and deficiencies observed of the fixed roof structure including rafters, girders, columns, and metal sheet plates, it is recommended that the roof be demolished and replaced with a new roof structure. Due to signs of major corrosion and damage, all rehabilitation options will include the requirement for replacement of the existing fixed roof structure.

MKN has explored the following three options as valid alternatives for roof demolition and replacement:

1. Demolition of the existing roof and installation of a new free-span aluminum dome roof:
   This alternative has the lowest cost compared to other roof replacement alternatives and might be the most suitable given the City's limited budget for this project. It is designed to meet the latest design codes including Eurocode, Aluminum Association's 2010 Aluminum Design Manual, IBC 2012, AWWA D108, and API 650G. This aluminum roof system is custom designed to meet the specific requirements of the project and is engineered for any snow, wind, or suspended load capacity as well as span-to-rise-ratio. The properties of this alternative include corrosion resistance, low maintenance cost, fast and low-cost construction, design flexibility, and Aluminum being

a recyclable material. The cost associated with this alternative, including prevailing wages, is expected to be approximately $830,000.

2. Demolition of the existing fixed roof and installation of a new Conventional Roof System:
   This alternative provides a roof plate thickness of 3/16" which is the AWWA D100 minimum requirement. Conventional roof systems are supported by a system of rafters that are placed underneath the roof plates' overlapping areas, creating inaccessible areas that are hard to coat. Conventional roof systems have a lower capital cost than other roof systems, but they have a higher ongoing maintenance cost because of the higher chance of rafters failures. The cost associated with this alternative is expected to be approximately $1,650,000.

3. Demolition of the existing roof and installation of a new Bent Plate Roof System:
   This alternative provides an increased roof plate thickness from the AWWA D100 3/16" minimum requirement to ¼", which gives the roof improved forming characteristics. This roof design reduces the inaccessible areas that are associated with a conventional roof system with rafters, eliminating a large percentage of the areas that are hard to coat. Rafters are impeded into each plate's design making it easier and more efficient to install and reducing the number of structural parts that might need to be fixed or replaced throughout the life cycle of the tank. The cost associated with this alternative is expected to be approximately $2,150,000.

3.8.2 Recommendations for Shell Overstressing

At the current overflow elevation and maximum operating level, the tank shell courses are overstressed. MKN has explored the following three options for addressing the overstressed bottom shell courses:

1. Reduce the Maximum Operating Level
   For this alternative, the maximum operating water level would be reduced to 29-feet to prevent overstressing the bottom courses of the tank. This will result in the loss of about 2.0 MG of water capacity resulting in a total storage volume of 5.5 MG. By reducing the operating water level, the overturning ratio decreases to J=0.6558 resulting in a stable tank. This alternative does not require any improvements to the shell.

   Table 6 summarizes the tank shell performance after reducing the maximum operating level.

Table 6: Reduce Operating Level - Shell Analysis Summary

Course (1 Bottom, 5 Top)	Width [in.]	Min Thickness, Hydrostatic	Min. Thickness Seismic	Actual Thickness	Utilization Ratio
5	104	0.25	0.25	0.35	0.714
4	96	0.25	0.25	0.40	0.625
3	96	0.406	0.533	0.59	0.903
2	96	0.655	0.785	0.79	0.994
1	96	0.905	0.996	0.99	1.006

2. Retrofitting the Lower Two Shell Course(s)

   This option would require that steel compression bands (“belly bands”) be installed on the outside of the existing lower two shells to provide additional support to the shell’s hydrostatic and hydrodynamic hoop stresses. Structural analysis has shown that retrofitting only the first bottom course would not allow the City to increase the operating level over 29-feet as the second bottom course would become overstressed. Therefore, the two bottom shell courses will have to be reinforced in order to increase the operating water level to 31-feet.

   The cost associated with this alternative is expected to be approximately $ 775,000.

3. Add a New 8-foot Course to Bottom of the Existing Tank
   For this alternative, a new bottom shell course would be installed, and the rest of the shell would be lifted and placed above the new course. The tank operating level could be maintained at 35-feet above the tank finish floor, which will keep the tank closer to its current capacity (About 0.8 MG less than existing) and the overturning ratio is lowered to J=0.7783 resulting in a stable tank. Adding an extra shell course to the top of the tank wall will not alleviate the overstressed conditions on the lower shell courses.

   Table 7 summarizes the tank shell performance after adding an 8-foot lower shell course.

Table 7: Increase Tank Height - Shell Analysis Summary

Course (1 Bottom, 5 Top)	Width [in.]	Min. Thickness, Hydrostatic	Min. Thickness, Seismic	Actual Thickness	Utilization Ratio
5	104	0.25	0.25	0.35	0.71
4	96	0.25	0.25	0.40	0.625
3	96	0.343	0.472	0.59	0.80
2	96	0.593	0.748	0.79	0.95
1	96	0.843	0.99	0.99	1.0
New Bottom Course	96	1.093	1.199	1.2	1.0

The cost associated with this alternative is expected to be approximately $ 1,715,000.

4 TANK APPURTENANCES

4.1 External Ladder and Roof Fall Protection

The external access ladder features a fall protection cage with a security gate as shown in Figure 10. The cage itself is attached securely and in good condition. A new fall protection system conforming to OSHA requirements is recommended. It is recommended to install a partial roof edge rail and a roof fall protection device anchored to the center of the top of roof.

Figure 10: External Access Ladder (By MKN on 04/21/21)

4.2 Internal Ladder

The interior ladder contains a safety cage and presents an access and safety challenge for maintenance dive inspections. The interior ladder fall prevention cage should be removed or a new cageless ladder with a fall prevention device meeting AWWA and OSHA standards should be installed in place of the existing one. A stainless steel or fiberglass reinforced polymer (FRP) interior ladder would eliminate the need for coating the ladder and is recommended during Tank Rehabilitation.

4.3 Manways

The Derrick Reservoir has one existing, 24-inch diameter shell manway. AWWA D100 recommends a minimum of two shell manways, with one being a minimum of 30 inches in diameter. MKN recommends adding a second 30-inch diameter manway in conformance with AWWA and industry standards.

4.4 Level Gauge

The tank is equipped with a standard level gauge with an interior float. The auto-gauge tape guide is corroded and the water level indicator is no longer operational. It is recommended that a new, manual level gauge system be installed.

4.5 Roof Hatches

The existing tank has two roof hatches. Both hatches are square openings. One is 24-inch by 24-inch, and the other is 48-inch by 48-inch. Dark corrosion with metal loss was also present. It is recommended that two new roof hatches be installed as part of the new roof.

4.6 Cathodic Protection

No cathodic protection system was present. It is recommended that impressed current cathodic protection system be added to the tank.

4.7 Tank Piping and Connections

The existing tank piping is consistent with tanks of this vintage. At the time, seismic flexibility was typically not part of the design. The inlet, outlet, overflow, and drain piping are all rigidly connected to the tank, either at the tank floor or the tank wall shell. Not having flexible connections can result in failures during a seismic event. To provide better protection against failures (leaks or loss of contents), MKN recommends installing flexible connections in accordance with AWWA D100.

4.7.1 Tank Inlet

From the as-builts, MKN observed that the tank inlet is a 20-inch welded steel pipe on the northern side of the tank. The inlet is below grade as it approaches the tank from the north, rises from below grade, turns horizontal via a fabricated 90-degree elbow, penetrates the tanks shell wall approximately 1.5' above the concrete ringwall. The inlet pipe then runs along the bottom of the tank for 135' heading south along the center line of the tank. The 90-degree elbow is coupled to the tank with mechanical joints and flanged connections. An approximate ¼-inch steel plate for reinforcement is present on the outer shell around the penetration and no flexible connection is present. Figure 11 shows the current inlet pipe configuration.

Figure 11: Inlet Piping (By CSI on 01/06/20)

Per AWWA D100, piping must be flexible enough to accommodate shell rotation and deflection due to elastic growth caused by hydrostatic pressure, seismic movements, and settlement in the tank or piping system. The minimum design displacement for piping connections is defined in Table 30 of AWWA D100. Considering that the City proceeds with an alternative presented in this report, the tank would be considered self-anchored and have an overturning ratio of J=0.7783 which is smaller than J=0.785, resulting in a minimum upward vertical displacement design of 1 inch and a minimum horizontal displacement design of 2 inch, relative to the foundation of the tank.

MKN evaluated two styles of flexible connections that can provide the required deflection: the double ball articulating joint (such as "Flex-Tend" by EBAA Iron shown in Figure 12); and the single-arch rubber expansion joint (such as Style 233 by Proco shown in Figure 13). The main benefit of the double ball joint is the large degree of flexibility that it provides. 20-inch Flex-tend flexible expansion joints deflect up to 15 degrees per ball, in any direction, and has a 12 inches of expansion or contraction. The disadvantages include size, and cost. The Flex-tend coupling is approximately 6-feet in length and has a list price of $16,500, not including tax or freight. Additionally, to accommodate this fitting, significant revisions to the buried 20-inch piping would be required.

Figure 12: Flex-Tend Flexible Expansion Joint

Comparatively, the Proco Style-233L 20-inch rubber expansion joints provide 4 inches of lateral deflection and 11.1 degrees of angular deflection, which is less than the Flex-tend, but is sufficient to meet the AWWA recommendations. The product is smaller in size than the double ball joint which makes it easier to install. The list price for the 20-inch NSF 61 Certified Proco style 233 is $5,040, which makes it relatively cheaper than the double ball joint option.

Figure 13: Proco Flexible Joint

MKN recommends installing a 20-inch rubber expansion joint on the tank inlet as part of the tank rehabilitation project. This flexible joint would be added above ground between the 90-degree elbow and the shell penetration. The existing inlet piping will have to be modified to accommodate the joint's 22-inch lay length.

4.7.2 Tank Overflow Piping

The tank's overflow consists of a 20-inch welded steel internal pipe at the eastern side of the tank. As seen in Figures 14 and Figure 15 the overflow pipe penetrates the sidewall of the tank with the centerline of the pipe about 1.5' above the bottom of the tank floor. On the interior of the tank, the pipe runs vertically approximately 2-feet from the tank shell to the overflow level of 40.0-feet. The overflow pipe is supported with side brackets and has a widened funnel overflow weir.

AWWA D-100 requires overflows to have a capacity of at least the specified inlet rate and gives it the option of being internal or external unless specified. The tank's overflow pipe is the same size of its inlet pipe, and with the funnel design it appears to comply with AWWA D100.

MKN recommends modifying the overflow elevation to align with the selected maximum operating level. The City may select to keep the overflow at a level higher than the recommended maximum operating level (29.0-feet) to allow for emergency storage, however, the City would be operating at a higher level than recommended at its own risk. In addition to this modification, MKN recommends moving the sidewall penetration higher above the tank floor which will allow for the design and installation of a 20-inch rubber expansion joint or an air gap on the vertical overflow piping. MKN recommends eliminating the below grade connection and installing an air gap with a duckbill type check valve to eliminate any connection to below grade piping. The City may elect to install a funnel piece on the overflow pipe that drops below grade to reduce spillage onto the surrounding asphalt in the event of an overflow. Cost estimates presented in this report reflect this recommendation. These modifications comply with Division of Drinking Water requirements and prevent backflow into the tank.

Figure 14: Overflow Pipe (By CSI on 01/06/20)

4.7.3 Tank Outlet and Drain

The tank outlet (Figure 16) consists of a 30-inch floor penetration located 8 feet to the east of the inlet pipe and about 4 feet from the shell wall. The tank also has a 10-inch drain that penetrates the tank floor approximately three feet to the north of the overflow pipe and two feet away from the shell wall (Figure 15). The drain line has a gate valve outside of the tank and connects to the tank's 20-inch overflow line below grade. Both the outlet and the drain pipes are welded steel.

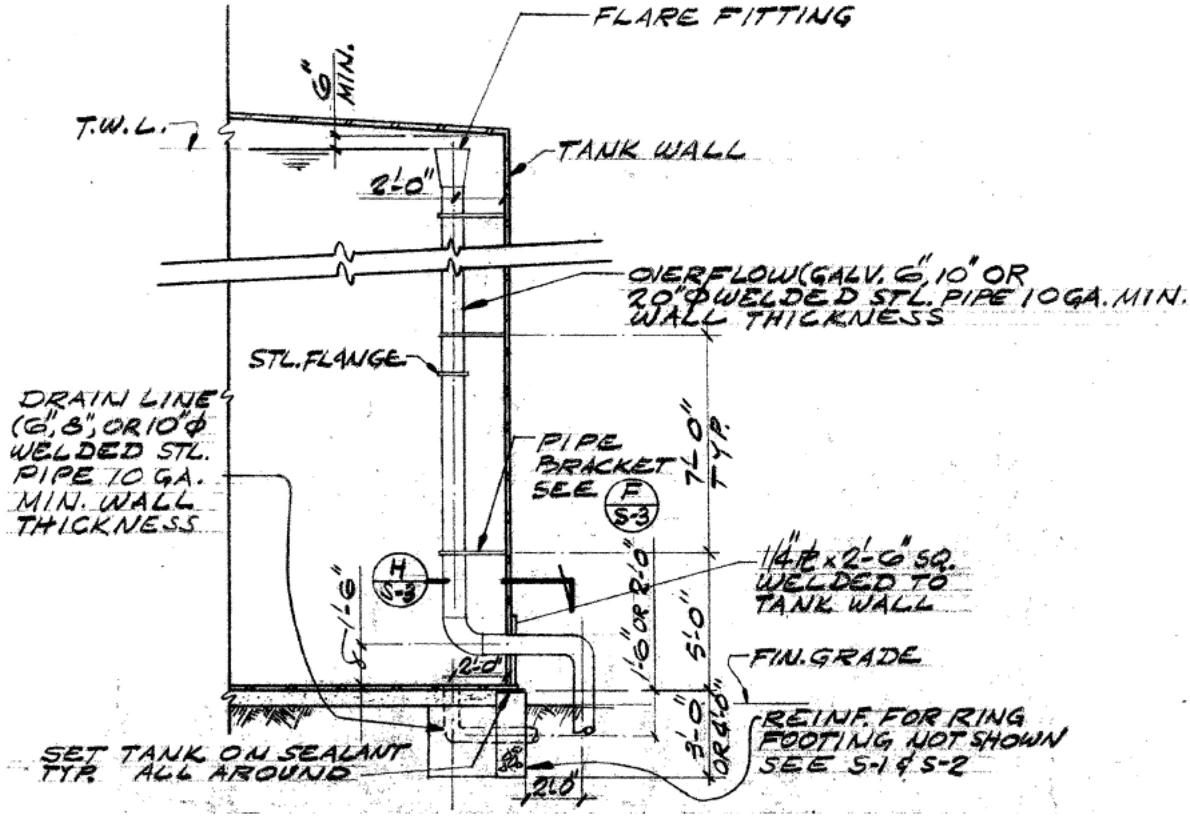

Figure 15: Tank Overflow and Drain Record Drawing

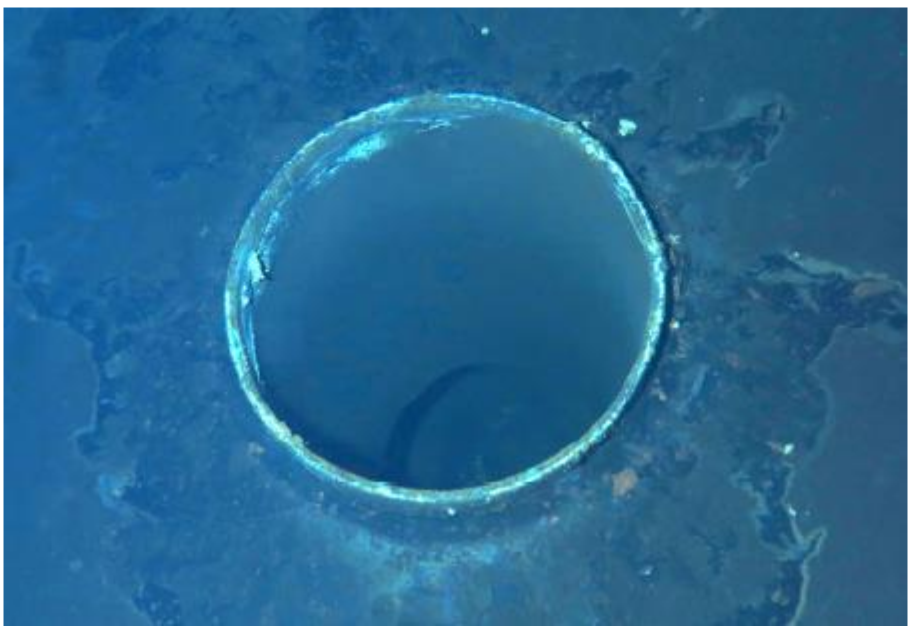

Figure 16: Tank Outlet (By CSI on 01/06/20)

AWWA guidelines determine the required minimum distance of floor connections from the shell wall. Assuming a ¼-inch thick floor plate, the edge of the drain and outlet should be at least 2.62 feet (1.62 feet + 1 foot) from the shell, based on equation 13-38 from AWWA D100. As stated previously, the tank outlet is four feet away from the shell wall and is compliant with AWWA standards while the drain does not meet the standard. The floor drain is only two feet away from the shell wall and is not compliant with AWWA standards. It is recommended that the City consider the relocation of the floor drain to comply with current AWWA standards.

There appears to be no existing flexible connections on the tank outlet or drain. MKN recommends that the City install double ball articulating joints beyond the tank footprint for both lines to provide adequate flexibility, provide some resistance to shear forces that can develop during a seismic event, and are suitable for buried applications.

5 SUMMARY OF RECOMMENDATIONS

5.1 Rehabilitation Alternatives

MKN has developed three main tank rehabilitation alternatives for the City's consideration. The alternatives developed include the "least cost" alternative (Alternative 1), which results in the loss of significant storage volume, and two solutions that require either raising of the roof and tank shell to maintain a storage capacity closer to the existing volume or strengthening the lower shell courses to optimize the maximum operating height.

5.1.1 Alternative 1 – Reduce Operating Level

The baseline, lowest cost alternative to bring the existing tank into compliance with the current AWWA D100 Standard is to reduce the operating level of the tank. This option minimizes the modifications required to the existing tank shell by reducing the forces on the shell by lowering the maximum operating level. To bring the tank utilization ratio to within 1.0, the tank maximum operating level must be reduced to 29-feet. The maximum operating capacity of the tank reduces to 5.519 MG with this option. Reducing the maximum operating level to 29-feet also addresses any freeboard concerns. The City may elect to modify the overflow elevation as is appropriate to accommodate infrequent emergency storage volume at its own risk, although the tank will not meet current AWWA requirements if operated above 29-feet.

5.1.2 Alternative 2 – Retrofitting Lower Two Shell Courses

This alternative allows the tank to have a maximum operating level of approximately 31-feet by strengthening the overstressed lower two shell courses fitting and welding on ½" thick steel sheets around the bottom two courses. Note that retrofitting only the lower course does not allow increasing the operating level.

5.1.3 Alternative 3 – Increase Tank Height, Add Course to Bottom of Existing Tank

This alternative keeps the tank near 7.5 MG of capacity by adding a thickened 8-foot steel shell course to the bottom of the existing tank. This option would require the existing tank to be detached from the existing tank floor, shored in place, and lifted 8-feet for the new steel to be installed. By adding an 8-foot course the tank can be operated at a maximum operating level of 35-feet and brings the total tank height to 48.5-feet. The maximum operating capacity of the tank is 6.662 MG with this option. Having the operating level at 35-feet and raising the overall tank height also meets freeboard requirements.

5.2 Recommendations Common to Alternatives 1 Through 3

The following improvements are recommended for all rehab alternatives and the associated costs of these improvements are included in the cost estimates presented in Table 9 of Section 5.4 below.

Table 8: Recommendation Summary		
Item	**Recommendation**	**Notes**
Demolition and Replacement of Existing Roof	Demolition and replacement of the existing roof with a new free-span aluminum dome roof system.	
Interior and Exterior Blasting and Coating	Remove interior and exterior coatings by abrasive blasting and coat.	• Include requirements in contract documents for contractor to prepare a plan to protect its workers and the environment from heavy metals. Proper Disposal will also be required.
Ladders, Appurtenances, and Safety Upgrades	Replace and add all recommended parts per the "Tank Appurtenances" section in the report.	• Add a fall prevention system to the exterior ladder. • Install a new interior cageless ladder with a fall prevention system. • Install a new level gauge system. • Install new roof hatches. • Add a second 30-inch diameter manway.
Flexible Connections	Add flexible connections to all tank connections to comply with AWWA Standards	• Single-arch rubber expansion joint shall be utilized on aboveground applications such as inlet and overflow and double-ball flexible couplings shall be utilized for below grade applications such as outlet and drain. • If airgap is provided on tank overflow, no flexible coupling is required.
Piping Modifications	Repair coatings and linings in the immediate vicinity of any piping modifications to accommodate adding the recommended flexible connections.	

5.3 Replacement Alternatives

MKN evaluated replacing the existing reservoir with an AWWA D110 Prestressed Concrete Tank and an AWWA D100 Welded Steel Tank.

MKN has developed two main tank replacement alternatives for the City of Coalinga's consideration, with Alternative 4 having a lower life cycle cost but a higher capital cost than Alternative 5:

5.3.1 Alternative 4 – Replace Existing Tank with a Prestressed Concrete Tank (AWWA D110 Type 1)

The existing steel tank would be replaced with a new, 7.0 MG, AWWA D110 Type 1 Circular prestressed concrete tank. Prestressed concrete tanks have a relatively lower total life-cycle cost of ownership when compared to other types of water tanks for multiple reasons. Unlike steel water tanks, they do not require coatings which is a significant recurring maintenance cost. Also, they allow for soil to be backfilled against the exterior walls of the tank and can be placed below grade, featuring a lower profile above finished grade. This alternative would be designed in accordance with ANSI/AWWA D110-13 standard which dictates the design for wire-wound and strand-wound circular, pre-stressed concrete water tanks.

If a “Column Supported Flat Slab Concrete” roof type is chosen, the capacity for this tank would be from the finished floor elevation to the top of the overflow at wall, along with a 180’ inside diameter, a 38’ side water depth, and a 5.5’ assumed freeboard. This takes into consideration a 2% floor slope and the existence of interior columns to support the roof. If a “Concrete Dome Roof” type is chosen, the capacity for this tank would be from the finished floor elevation to the top of the overflow at wall, along with a 178’ inside diameter, a 38’ side water depth, and a 5.5’ assumed freeboard. This takes into consideration a 0% floor slope and the absence of interior columns for the “Free Span Concrete Dome” roof type. This recommendation is provided based on the assumption that the tank is to be backfilled to an at-grade level, and that no excessive live load is present on the roof of the tank.

One disadvantage for having a prestressed concrete tank is the high capital cost. It is important to note that the replacement cost presented in this report account for favorable geotechnical conditions which would result in the use of an optimized 6-inch membrane floor slab. Further investigation would be required.

5.3.2 Alternative 5 – Replace Existing Tank with a Welded Steel Tank (AWWA D100)

The existing steel tank would be replaced with a new, 7.0 MG, AWWA D100 steel tank. Steel tanks are long-lasting, durable structures when properly maintained. With the right selection and application of coatings and cathodic protection, the structures are highly resistant to effects of corrosion. One of the key benefits to constructing a welded steel tank is the constructability. They do not require extensive equipment or laydown areas, as compared to prestressed concrete tanks. Also, welded steel tanks have a relatively lower capital cost than prestressed concrete tanks. This alternative would be designed in accordance with ANSI/AWWA D100 standard which dictates the design for welded carbon steel tanks.

The new steel tank would have a cone-shaped roof with 3/16” plate thickness and floor plates with a ¼” thickness. This alternative assumes the construction of a concrete ringwall foundation and the addition of an impressed current cathodic protection system to help mitigate corrosion of the tank metals. The new tank would be coated with a 12-mil epoxy coating system on the interior and a 6-mil epoxy urethane coating on the exterior. Shop and field painter is expected to have at least ten (10) years of field erected water tank abrasive blasting and coating experience. This alternative would also include installation of all necessary tank appurtenances.

A disadvantage of a welded steel tank is the higher life-cycle cost in comparison with a prestressed concrete tank. Steel corrodes and rusts if not well maintained. Also, steel tanks must be taken out of service for longer periods of time during interior recoating projects, while pre-stressed concrete tanks do not require interior coatings.

5.4 Alternatives Cost Comparison

Table 9 summarizes and compares the different cost opinions for the rehabilitation and replacement alternatives.

Table 9: Relative Cost Comparisons for Rehabilitation and Replacement Alternatives

Item	Description	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
1	Mobilization (10%)	$239,000	$317,000	$420,000	$410,000	$576,000
2	Interior Blasting and Coating	$813,000	$813,000	$858,000		
3	Exterior Blasting and Coating	$533,000	$533,000	$583,000		
4	Ladders, Appurtenances, Safety Upgrades	$60,000	$60,000	$60,000		
5	Demo and Replacement of Fixed Roof	$830,000	$830,000	$830,000		
6	Tank overflow	$12,500	$12,500	$12,500		
7	Tank Flex Joints	$70,000	$70,000	$70,000	$70,000	$70,000
8	Flex Joints Installation	$10,000	$10,000	$10,000	$10,000	$10,000
9	Piping Modifications	$40,000	$40,000	$40,000		
10	Cathodic Protection	$20,000	$20,000	$20,000		
11	Containment and Abrasive Disposal	$310,000	$310,000	$310,000		
12	Retrofitting First Bottom Course (8')					
13	Retrofitting Two Bottom Courses (16')		$775,000			
14	Adding 8' Lower Shell Course			$1,715,000		
15	New Welded Steel 7.0 MG Tank				$3,625,000	
16	New Prestressed Concrete 7.0 MG Tank					$5,100,000
17	Demolition of Existing Tank				$75,000	$75,000
18	Tank Appurtenances				$25,000	$100,000
19	Site Work and Mechanical				$286,000	$402,000
	Construction Subtotal	$2,937,500	$3,790,500	$4,928,500	$4,501,000	$6,333,000
	Contingency	$293,750[1]	$1,137,150[2]	$1,478,550[2]	$1,350,300[2]	$1,899,900[2]
	Total	$3,232,000	$4,928,000	$6,408,000	$5,852,000	$8,233,000

[1] Contingency is taken as 10% of the Construction Total
[2] Contingency is taken as 30% of the Construction Total

5.5 Welded Steel Vs. Prestressed Concrete Tank Life Cycle Cost Analysis

Typically, pre-stressed concrete tanks have a higher construction capital cost than welded steel tanks. However, pre-stressed concrete tanks have a lower maintenance cost than welded steel tanks. Welded steel tanks require periodic inspection and exterior and interior re-coating application that contain associated engineering, inspection, and construction management costs. Pre-stressed concrete tanks require power washing and inspection as part of their routine maintenance, but the cost is significantly less than welded steel tanks.

The life cycle cost analysis is based on the following assumptions:

- Initial cost based on vendor quotes for at-grade 7 MG tank on an ideal site.
- Coating period for steel tank is 20 years, totaling $1,804,354.50 per period based on $10/square foot for exterior recoating and $11/square foot for interior coating.
- Maintenance period for pre-stressed concrete option is 20 years, totaling $100,000.00 per period consisting of power washing, routine maintenance, and inspection.

The results of the life cycle cost analysis are provided as Figure 17. As illustrated in the figure, while the steel tank option has a higher 100-year life cycle cost by approximately 66%, the breakeven point is at approximately 30 years.

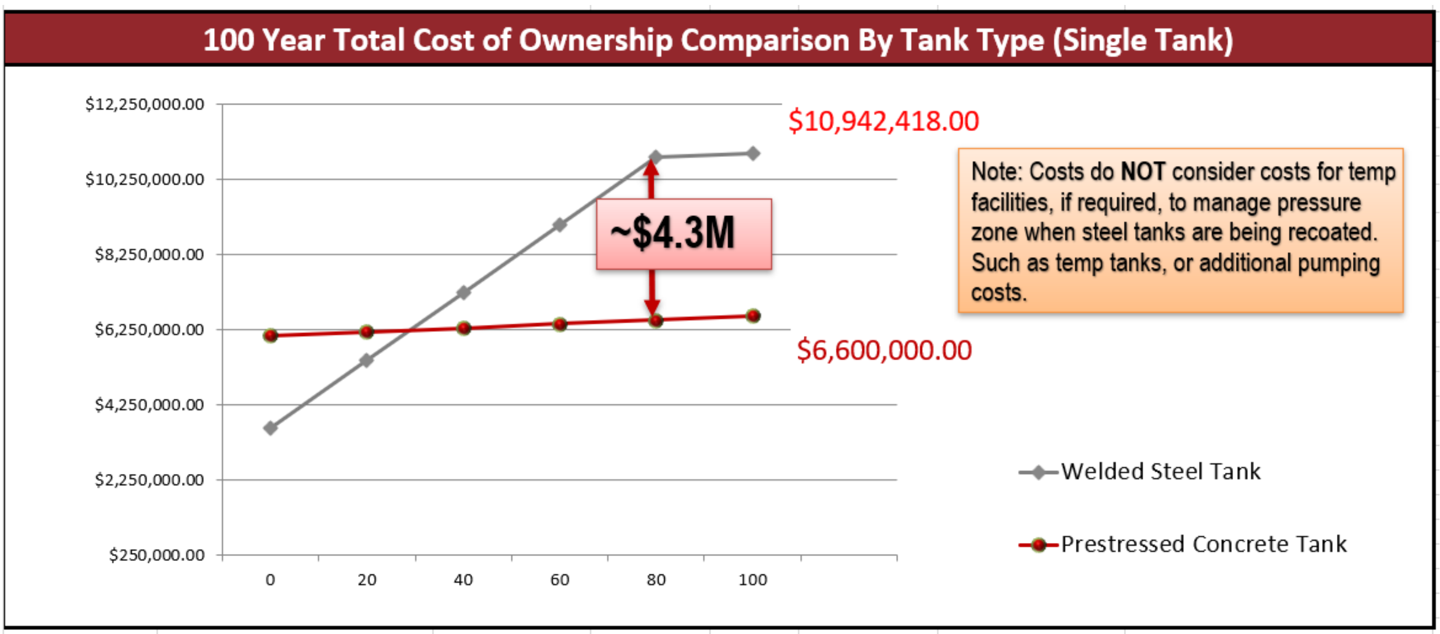

Figure 17: 100 Year Total Cost of Ownership Comparison by Tank Type (By DN Tanks)

ATTACHMENTS

Attachment 1: Preliminary Opinion of Construction Cost

Attachment 2: Structural Calculations By SSG Structural Engineers, LLP

ATTACHMENT 1

Preliminary Opinion of Construction Cost

City of Coalinga
7.5 MILLION GALLON WATER TANK REHABILITATION
DRAFT OPINION OF PROBABLE CONSTRUCTION COST
ALTERNATIVE 1
July 2021

Item	Description	Quantity	Unit	Unit Price	Amount
1	Mobilization (10%)	1	LS	$238,850	$239,000
2	Interior Blasting and Coating	81232	SF	$10	$813,000
3	Exterior Blasting and Coating	48400	SF	$11	$533,000
4	Ladders, Appurtenances, Safety Upgrades	1	EA	$60,000	$60,000
5	Demo and Replacement of Fixed Roof	1	EA	$830,000	$830,000
6	Tank overflow	1	EA	$12,500	$12,500
7	Tank Flex Joints	1	EA	$69,982	$70,000
8	Flex Joints Installation	1	LS	$10,000	$10,000
9	Piping Modifications	1	LS	$40,000	$40,000
10	Cathodic Protection	1	EA	$20,000	$20,000
11	Containment and Abrasive Disposal	1	EA	$310,000	$310,000

Subtotal (not including optional items)	$2,937,500
Contingency 10%	$293,750
Total	$3,232,000

Prepared By: Ammar Hanna, EIT
Prepared on: 8/2/2021

The opinion of probable construction cost presented here is only an opinion of possible construction costs for budgeting purposes. This opinion is limited to the conditions existing at issuance and is not a guaranty of actual price or cost. Uncertain market conditions such as, but not limited to, local labor or contractor availability, wages, other work, material market fluctuations, price escalations, force majeure events and developing bidding conditions, etc. may affect the accuracy of this estimate. MKN & Associates, Inc., is not responsible for any variance from this budgetary opinion of construction cost or actual prices and conditions obtained. The opinion of probable construction cost is based on the draft design plans prepared for the City; addition or subtraction of design elements will impact the final project cost.

City of Coalinga
7.5 MILLION GALLON WATER TANK REHABILITATION
DRAFT OPINION OF PROBABLE CONSTRUCTION COST
ALTERNATIVE 2
July 2021

Item	Description	Quantity	Unit	Unit Price	Amount
1	Mobilization (10%)	1	LS	$316,350	$317,000
2	Interior Blasting and Coating	81232	SF	$10	$813,000
3	Exterior Blasting and Coating	48400	SF	$11	$533,000
4	Retrofitting Two Bottom Courses (16')	1	EA	$775,000	$775,000
5	Ladders, Appurtenances, Safety Upgrades	1	EA	$60,000	$60,000
6	Demo and Replacement of Fixed Roof	1	EA	$830,000	$830,000
7	Tank overflow	1	EA	$12,500	$12,500
8	Tank Flex Joints	1	EA	$69,982	$70,000
9	Flex Joints Installation	1	LS	$10,000	$10,000
10	Piping Modifications	1	LS	$40,000	$40,000
11	Cathodic Protection	1	EA	$20,000	$20,000
12	Containment and Abrasive Disposal	1	EA	$310,000	$310,000

Subtotal (not including optional items)	$3,790,500
Contingency 30%	$1,137,150
Total	$4,928,000

Prepared By: Ammar Hanna, EIT
Prepared on: 8/2/2021

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City of Coalinga
7.5 MILLION GALLON WATER TANK REHABILITATION
DRAFT OPINION OF PROBABLE CONSTRUCTION COST
ALTERNATIVE 3
July 2021

Item	Description	Quantity	Unit	Unit Price	Amount
1	Mobilization (10%)	1	LS	$419,850	$420,000
2	Interior Blasting and Coating	85756	SF	$10	$858,000
3	Exterior Blasting and Coating	52924	SF	$11	$583,000
4	Adding 8' Lower Shell Course	1	EA	$1,714,286	$1,715,000
5	Ladders, Appurtenances, Safety Upgrades	1	EA	$60,000	$60,000
6	Demo and Replacement of Fixed Roof	1	EA	$830,000	$830,000
7	Tank overflow	1	EA	$12,500	$12,500
8	Tank Flex Joints	1	EA	$69,982	$70,000
9	Flex Joints Installation	1	LS	$10,000	$10,000
10	Piping Modifications	1	LS	$40,000	$40,000
11	Cathodic Protection	1	EA	$20,000	$20,000
12	Containment and Abrasive Disposal	1	EA	$310,000	$310,000

Subtotal (not including optional items)	$4,928,500
Contingency 30%	$1,478,550
Total	$6,408,000

Prepared By: Ammar Hanna, EIT
Prepared on: 8/2/2021

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City of Coalinga
7.5 MILLION GALLON WATER TANK REHABILITATION
DRAFT OPINION OF PROBABLE CONSTRUCTION COST
ALTERNATIVE 4
July 2021

Item	Description	Quantity	Unit	Unit Price	Amount
1	Mobilization (10%)	1	LS	$409,100	$410,000
4	New Welded Steel 7.0 MG Tank	1	EA	$3,625,000	$3,625,000
5	Demolition of Existing Tank	1	EA	$75,000	$75,000
7	Tank Flex Joints	1	EA	$69,982	$70,000
8	Flex Joints Installation	1	LS	$10,000	$10,000
9	Tank Appurtenances	1	EA	$25,000	$25,000
10	Site Work and Mechanical	1	LS	$286,000	$286,000

Subtotal (not including optional items)	$4,501,000
Contingency 30%	$1,350,300
Total	$5,852,000

Prepared By: Ammar Hanna, EIT
Prepared on: 8/2/2021

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City of Coalinga
7.5 MILLION GALLON WATER TANK REHABILITATION
DRAFT OPINION OF PROBABLE CONSTRUCTION COST
ALTERNATIVE 5
July 2021

Item	Description	Quantity	Unit	Unit Price	Amount
1	Mobilization (10%)	1	LS	$575,700	$576,000
4	New Prestressed Concrete 7.0 MG Tank	1	EA	$5,100,000	$5,100,000
5	Demolition of Existing Tank	1	EA	$75,000	$75,000
7	Tank Flex Joints	1	EA	$69,982	$70,000
8	Flex Joints Installation	1	LS	$10,000	$10,000
9	Tank Appurtenances	1	EA	$100,000	$100,000
10	Site Work and Mechanical	1	LS	$402,000	$402,000

Subtotal (not including optional items)	$6,333,000
Contingency 30%	$1,899,900
Total	$8,233,000

Prepared By: Ammar Hanna, EIT
Prepared on: 8/2/2021

The opinion of probable construction cost presented here is only an opinion of possible construction costs for budgeting purposes. This opinion is limited to the conditions existing at issuance and is not a guaranty of actual price or cost. Uncertain market conditions such as, but not limited to, local labor or contractor availability, wages, other work, material market fluctuations, price escalations, force majeure events and developing bidding conditions, etc. may affect the accuracy of this estimate. MKN & Associates, Inc., is not responsible for any variance from this budgetary opinion of construction cost or actual prices and conditions obtained. The opinion of probable construction cost is based on the draft design plans prepared for the City; addition or subtraction of design elements will impact the final project cost.

ATTACHMENT 2

Structural Calculations By SSG Structural Engineers, LLP

Existing Tank Condition
Seismic and Shell Analysis

Seismic Design Calculations

Site Ground Motion Design

Ac = Compute Impulsive Design Response Spectrum Acceleration Coefficient per AWWA D100-11 13.2.9.2
Af = Compute Acceleration Coefficient for Sloshing Wave Height per AWWA D100-11 13.5.4.4
Ai = Compute Impulsive Design Response Spectrum Acceleration Coefficient per AWWA D100-11 13.2.9.2
Anchorage_System = Anchorage System
Av = Vertical Ground Acceleration Coefficient per AWWA D100-11 13.5.4.1 and 13.5.4.3
D = Nominal Tank Diameter (ft)
Fa = Site Acceleration Coefficient
Fv = Site Velocity Coefficient
I = Importance Factor
K = Spectral Acceleration Adjustment Coefficient
Lmax = Maximum Design Product Level (ft)
Rwc = Convective Force Reduction Factor
Rwi = Impulsive Force Reduction Factor
S1 = Spectral Response Acceleration at a Period of One Second
SD1 = Compute Design Spectral Response Acceleration at a Period of One Second per AWWA D100-11 13.2.7.3
SDS = Compute Design Spectral Response Acceleration at Short Period per AWWA D100-11 13.2.7.3
SM1 = Compute Maximum Considered Earthquake Spectral Response Acceleration at a Period of One Second per AWWA D100-11 13.2.7.2
SMS = Compute Maximum Considered Earthquake Spectral Response Acceleration at Short Period per AWWA D100-11 13.2.7.2
SUG = Seismic Use Group
Sac = Compute Convective Design Response Spectrum Acceleration Coefficient For Convective Components per AWWA D100-11 13.2.7.3.2
Sai =
Seismic_Site_Class = Seismic Site Class
Ss = Spectral Response Acceleration Short Period
TL = Regional Dependent Transistion Period for Longer Period Ground Motion (sec)
Tc = Compute Convective Natural Period per AWWA D100-11 13.5.1 (sec)
Ti = Structure Natural Period (sec)
U = Scaling Factor
d_ratio = Dampening Ratio
g = Acceleration Due To Gravity (ft/sec^2)
structure_type = Structure Type

Anchorage_System = SELF-ANCHORED
D = 180.0825 ft
Fa = 1.0
Fv = 1.3
I = 1.5
K = 1.5
Lmax = 40.5 ft
Rwc = 1.5
Rwi = 2.5
S1 = 0.593
SUG = SEISMIC-USE-GROUP-III
Seismic_Site_Class = SEISMIC-SITE-CLASS-C
Ss = 1.794
TL = 12 sec

Ti = 0 sec
U = 0.6667
d_ratio = 0.05
g = 32.17 ft/sec^2
structure_type = GROUND-SUPPORTED-FLAT-BOTTOM-TANK

Tc = 2 * pi * SQRT((D / (3.68 * g * TANH(((3.68 * Lmax) / D)))))
Tc = 2 * pi * SQRT((180.0825 / (3.68 * 32.17 * TANH(((3.68 * 40.5) / 180.0825)))))
Tc = 9.403 sec

SMS = Fa * Ss
SMS = 1.0 * 1.794
SMS = 1.794

SM1 = Fv * S1
SM1 = 1.3 * 0.593
SM1 = 0.7709

SDS = U * SMS
SDS = 0.6667 * 1.794
SDS = 1.196

SD1 = U * SM1
SD1 = 0.6667 * 0.7709
SD1 = 0.5139

Sai = SDS
Sai = 1.196
Sai = 1.196

Sac = MIN(((K * SD1) / Tc) , SDS)
Sac = MIN(((1.5 * 0.5139) / 9.403) , 1.196)
Sac = 0.082

Ai = MAX(((Sai * I) / (1.4 * Rwi)) , ((0.36 * S1 * I) / Rwi))
Ai = MAX(((1.196 * 1.5) / (1.4 * 2.5)) , ((0.36 * 0.593 * 1.5) / 2.5))
Ai = 0.5126

Ac = (Sac * I) / (1.4 * Rwc)
Ac = (0.082 * 1.5) / (1.4 * 1.5)
Ac = 0.0586

Av = 0.14 * SDS
Av = 0.14 * 1.196
Av = 0.1674

Af = (K * SD1) / Tc
Af = (1.5 * 0.5139) / 9.403
Af = 0.082

Seismic Design

A = Roof Surface Area (ft^2)
Ac = Convective Design Response Spectrum Acceleration Coefficient
Af = Acceleration Coefficient for Sloshing Wave Height
Ah-rs = Roof Horizontal Projected Area Supported by The Shell (ft^2)

Ai = Impulsive Design Response Spectrum Acceleration Coefficient
Anchorage_System = Anchorage System
Arss = Roof Area Supported by The Shell (ft^2)
Av = Vertical Ground Acceleration Coefficient
CA = Bottom Corrosion Allowance (in)
D = Nominal Tank Diameter (ft)
DELTA_Cc = Compute Pressure Stabilizing Buckling Coefficient per AWWA D100-11 13.5.4.2.4
DELTA_SIGMAcr = Compute Self Anchored Tank Critical Buckling Stress Increase Caused By Pressure Equation per AWWA D100-11 13.5.4.2.4 (lb/in^2)
Fa = Site Acceleration Coefficient
Freeboard = Actual Freeboard (ft)
Fv = Site Velocity Coefficient
Hs = Shell Total Height (ft)
Hs = Shell height (ft)
I = Importance Factor
J = Compute Anchorage Ratio per AWWA D100-11 13.5.4.1
K = Spectral Acceleration Adjustment Coefficient
L_max = Compute Annular Ring Required Minimum Width Max Limit per AWWA D100-11 13.5.4.1.2 (ft)
Lmax = Maximum Design Product Level (ft)
Ls = Actual Annular Ring Width (ft)
Ma = Material Name
Mmf = Compute Overturning Moment per AWWA D100-11 13.5.2.1 (ft.lb)
Ms = Compute Overturning Moment per AWWA D100-11 13.5.2.1 (ft.lb)
P = Design Pressure (lbf/in^2)
R = (ft)
S1 = Spectral Response Acceleration at a Period of One Second
SD1 = Design Spectral Response Acceleration at a Period of 1 Second
SDS = Design Spectral Response Acceleration at Short Period
SG = Specific Gravity
SIGMAc_self_anchored = Compute Self Anchored Maximum Longitudinal Shell Compression Stress per AWWA D100-11 13.5.4.2.1 (lbf/in^2)
SIGMAe_self_anchored = Compute Seismic Allowable Longitudinal Compressive Stress per AWWA D100-11 13.5.4.2.4 (lb/in^2)
SUG = Seismic Use Group
Seismic_Site_Class = Seismic Site Class
Ss = Spectral Response Acceleration Short Period
TL = Regional Dependent Transistion Period for Longer Period Ground Motion (sec)
Tc = Convective Natural Period (sec)
U = Scaling Factor
V_allow = Compute Self Anchored Sliding Resistance Base Shear per AWWA D100-11 13.5.4.6 (lbf)
Vf = Compute Total Design Base Shear per AWWA D100-11 13.5.3.1 (lbf)
Wc = Compute Convective Effective Weight per AWWA D100-11 13.5.2.2.1 (lbf)
Wf = Tank Bottom Total Weight (lbf)
Wi = Compute Impulsive Effective Weight per AWWA D100-11 13.5.2.2.1 (lbf)
Wp = Tank Contents Total Weight (lbf)
Wr = Total Weight of Fixed Tank Roof including Framing, Knuckles, any Permanent Attachments and 10 % of the Roof Balanced Design Snow Load (lbf)
Wrs = Roof Load Acting on The Tank Shell Including 10 % of the Roof Balanced Design Snow Load (lbf)
Ws = Total Weight of Tank Shell and Appurtenances (lbf)
Wss = Roof Structure Weight Supported by The Tank Shell (lb)
Xc = Height from tank shell bottom to the center of action of convective lateral force for computing ringwall overturning moment per AWWA D100-11 13.5.2.2.2 (ft)
Xcmf = Height from tank shell bottom to the center of action of convective lateral force for computing slab overturning moment per AWWA D100-11 13.5.3.2.2 (ft)
Xi = Height from tank shell bottom to the center of action of impulsive lateral force for computing ringwall overturning moment per AWWA D100-11 13.5.2.2.2 (ft)

Ximf = Height from tank shell bottom to the center of action of impulsive lateral force for computing slab overturning moment per AWWA D100-11 13.5.3.2.2 (ft)
Xs = Height from tank shell bottom to shell's center of gravity (ft)
ca1 = Bottom Shell Course Corrosion Allowance (in)
ca_annulus = Bottom Annular Ring Design Corrosion Allowance (in)
d = Sloshing Wave Height Above Product Design Height per AWWA D100-11 Section 13.5.4.4 (ft)
g = Acceleration Due To Gravity (ft/sec^2)
lw = Lap of the Bottom Plates Over the Annular Plate (in)
outside_projection = Bottom Outside Projection (in)
site_ground_motion_input_mode = Site Ground Motion Input Mode
t_bottom = Bottom Plate Thickness (in)
tb = Bottom Annular Ring Design Thickness (in)
tb_less_ca = Bottom Annular Ring Design Thickness Without Corrosion Allowance (in)
tb_limited_less_ca = (in)
ts1 = Bottom Shell Course Thickness (in)
ts_less_ca = Bottom Shell Course Thickness Without Corrosion Allowance (in)
using_annular_ring = Using Annular Ring
wL = Compute Self Anchored Force Resisting Uplift per AWWA D100-11 13.5.4.1.1 (lbf/ft)
wrs = Specified Tank Roof Load Acting on Tank Shell (lbf/ft)
wt = Compute Tank and Roof Weight Acting at base of Shell per AWWA D100-11 13.5.4.2.1 (lbf/ft)

A = 25,554.4252 ft^2
Ac = 0.0586
Af = 0.082
Ah-rs = 8,638.5493 ft^2
Ai = 0.5126
Anchorage_System = SELF-ANCHORED
Arss = 8,655.405 ft^2
Av = 0.1674
CA = 0 in
D = 180.0825 ft
Fa = 1.0
Fv = 1.3
Hs = 40.5 ft
Hs = 40.5 ft
I = 1.5
K = 1.5
Lmax = 40.5 ft
Ls = 2.1258 ft
Ma = A36
P = 0.0 lbf/in^2
S1 = 0.593
SD1 = 0.5139
SDS = 1.196
SG = 1
SUG = SEISMIC-USE-GROUP-III
Seismic_Site_Class = SEISMIC-SITE-CLASS-C
Ss = 1.794
TL = 12 sec
Tc = 9.403 sec
U = 0.6667
Wp = 64,338,160.6538 lbf
Wss = 24,091.3622 lb
Xs = 15.8876 ft
ca1 = 0 in
ca_annulus = 0 in

g = 32.17 ft/sec^2
lw = 1.5 in
outside_projection = 2 in
site_ground_motion_input_mode = ASCE7-MAPPED-SS-AND-S1
t_bottom = 0.25 in
tb = 0.25 in
ts1 = 0.99 in
using_annular_ring = t

Wf = Wb-pl
Wf = 259,765.8038
Wf = 259,765.8038 lbf

Wr = (Wr-pl + Wr-attachments + W-struct + Wr-DL-add) + (0.1 * Sb * Ah)
Wr = (195,468.3541 + 0.0 + 152,898.1204 + 0.0) + (0.1 * 0.0 * 25,504.66)
Wr = 348,366.4745 lbf

Wrs = ((Wr-pl + Wr-attachments + Wr-DL-add) * (Arss / A)) + Wss + (0.1 * Sb * Ah-rs)
Wrs = ((195,468.3541 + 0.0 + 0.0) * (8,655.405 / 25,554.4252)) + 24,091.3622 + (0.1 * 0.0 * 8,638.5493)
Wrs = 90,297.4209 lbf

Ws = Ws-pl + Ws-framing + Ws-attachments
Ws = 580,034.4853 + 4,057.6387 + 4.0
Ws = 584,096.124 lbf

R = D / 2
R = 180.0825 / 2
R = 90.0412 ft

tb_less_ca = tb - ca_annulus
tb_less_ca = 0.25 - 0
tb_less_ca = 0.25 in

ts_less_ca = ts1 - ca1
ts_less_ca = 0.99 - 0
ts_less_ca = 0.99 in

tb_limited_less_ca = MIN(tb_less_ca , ts_less_ca)
tb_limited_less_ca = MIN(0.25 , 0.99)
tb_limited_less_ca = 0.25 in

Effective weight of product

Wi = (TANH((0.866 * (D / Lmax))) / (0.866 * (D / Lmax))) * Wp
Wi = (TANH((0.866 * (180.0825 / 40.5))) / (0.866 * (180.0825 / 40.5))) * 64,338,160.6538
Wi = 16,693,271.3711 lbf

Wc = 0.23 * (D / Lmax) * TANH(((3.67 * Lmax) / D)) * Wp
Wc = 0.23 * (180.0825 / 40.5) * TANH(((3.67 * 40.5) / 180.0825)) * 64,338,160.6538
Wc = 44,609,953.2195 lbf

Center of action for effective lateral forces

Xi = 0.375 * Lmax
Xi = 0.375 * 40.5
Xi = 15.1875 ft

Xc = (1.0 - ((COSH(((3.67 * Lmax) / D)) - 1) / (((3.67 * Lmax) / D) * SINH(((3.67 * Lmax) / D))))) * Lmax
Xc = (1.0 - ((COSH(((3.67 * 40.5) / 180.0825)) - 1) / (((3.67 * 40.5) / 180.0825) * SINH(((3.67 * 40.5) / 180.0825))))) * 40.5
Xc = 21.3263 ft

Ximf = 0.375 * (1.0 + ((4 / 3) * (((0.866 * (D / Lmax)) / TANH((0.866 * (D / Lmax)))) - 1.0))) * Lmax
Ximf = 0.375 * (1.0 + ((4 / 3) * (((0.866 * (180.0825 / 40.5)) / TANH((0.866 * (180.0825 / 40.5)))) - 1.0))) * 40.5
Ximf = 72.9838 ft

Xcmf = (1.0 - ((COSH(((3.67 * Lmax) / D)) - 1.937) / (((3.67 * Lmax) / D) * SINH(((3.67 * Lmax) / D))))) * Lmax
Xcmf = (1.0 - ((COSH(((3.67 * 40.5) / 180.0825)) - 1.937) / (((3.67 * 40.5) / 180.0825) * SINH(((3.67 * 40.5) / 180.0825))))) * 40.5
Xcmf = 71.1757 ft

Overturning moment

Ms = SQRT((((Ai * ((Ws * Xs) + (Wr * Hs) + (Wi * Xi)))^2) + ((Ac * (Wc * Xc))^2)))
Ms = SQRT((((0.5126 * ((584,096.124 * 15.8876) + (348,366.4745 * 40.5) + (16,693,271.3711 * 15.1875)))^2) + ((0.0586 * (44,609,953.2195 * 21.3263))^2)))
Ms = 152,482,250.1501 ft.lb

Mmf = SQRT((((Ai * ((Ws * Xs) + (Wr * Hs) + (Wi * Ximf)))^2) + ((Ac * (Wc * Xcmf))^2)))
Mmf = SQRT((((0.5126 * ((584,096.124 * 15.8876) + (348,366.4745 * 40.5) + (16,693,271.3711 * 72.9838)))^2) + ((0.0586 * (44,609,953.2195 * 71.1757))^2)))
Mmf = 663,077,019.526 ft.lb

Resistance to design loads

wL = MIN((7.9 * tb_limited_less_ca * SQRT((Fy * Lmax * SG))) , (1.28 * Lmax * D * SG))
wL = MIN((7.9 * 0.25 * SQRT((36,000 * 40.5 * 1))) , (1.28 * 40.5 * 180.0825 * 1))
wL = 2,384.7665 lbf/ft

wrs = Wrs / (pi * D)
wrs = 90,297.4209 / (pi * 180.0825)
wrs = 159.6077 lbf/ft

wt = (Ws / (pi * D)) + wrs
wt = (584,096.124 / (pi * 180.0825)) + 159.6077
wt = 1,192.0433 lbf/ft

Tank Stability

J = Ms / ((D^2) * ((wt * (1 - (0.4 * Av))) + wL))
J = 152,482,250.1501 / ((180.0825^2) * ((1,192.0433 * (1 - (0.4 * 0.1674))) + 2,384.7665))
J = 1.3446

Bottom Annular Plates requirements

As per AWWA 3.10.8
Ls >= 18 ==> PASS

L_max = 0.035 * D
L_max = 0.035 * 180.0825
L_max = 6.3029 ft

As per AWWA 13.5.4.1
Ls <= L_max ==> PASS

Shell Stresses

SIGMAc_self_anchored = ((((wt * (1 + (0.4 * Av))) + wL) / (0.607 - (0.18667 * (J^2.3)))) - wL) * (1 / (12 * ts_less_ca))
SIGMAc_self_anchored = ((((1,192.0433 * (1 + (0.4 * 0.1674))) + 2,384.7665) / (0.607 - (0.18667 * (1.3446^2.3)))) - 2,384.7665) * (1 / (12 * 0.99))
SIGMAc_self_anchored = 1,091.5415 lbf/in^2

DELTA_Cc = 0.72 * (((P / E) * ((R / ts_less_ca)^2))^0.84)
DELTA_Cc = 0.72 * (((0.0 / 28,800,000) * ((1,080.495 / 0.99)^2))^0.84)
DELTA_Cc = 0.0

DELTA_SIGMAcr = (DELTA_Cc * E * ts_less_ca) / R
DELTA_SIGMAcr = (0.0 * 28,800,000 * 0.99) / 1,080.495
DELTA_SIGMAcr = 0.0 lb/in^2

FL = Compute Allowable Local Buckling Compressive Stress per AWWA D100-11 Section 3.4.3.1.2 (lb/in^2)
Material_Class = Compute Material Class From Minimum Yield Strength per AWWA D100-11 Section 3.2 and Table 4
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = Thickness Radius Ratio Boundary Elastic Inelastic Buckling per AWWA D100-11 Sections 3.4.3.1.1 and 3.4.3.1.2

Material_Class = :material-class-2
Material_Class = :material-class-2
Material_Class = :material-class-2

Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035372
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035372
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035

FL = 17.5 * (10^5) * (ts_less_ca / R) * (1 + (50000 * ((ts_less_ca / R)^2)))
FL = 17.5 * (10^5) * (0.99 / 1,080.495) * (1 + (50000 * ((0.99 / 1,080.495)^2)))
FL = 1,670.7365 lb/in^2

Allowable Local Buckling Compressive Stress (FL) = 1,670.7365 lb/in^2

SIGMAe_self_anchored = 1.333 * (FL + (DELTA_SIGMAcr / 2))
SIGMAe_self_anchored = 1.333 * (1,670.7365 + (0.0 / 2))
SIGMAe_self_anchored = 2,227.0917 lb/in^2

Freeboard

d = 0.5 * D * Af
d = 0.5 * 180.0825 * 0.082
d = 7.3834 ft [88.6006 in]

Freeboard = Hs - Lmax-operating
Freeboard = 40.5 - 40.5
Freeboard = 0.0 ft [0.0 in]

(SDS >= One_Third_g) AND (SUG = :seismic-use-group-iii)

[Required]
Sloshing Wave Height Above Product Design Height (d) = 7.3834 ft

Freeboard < d ==> FAIL

***** WARNING *** :** Freeboard, 0.0 ft [0.0 in], is less than the required value of 7.3834 ft [88.6006 in]

Sliding Resistance

Vf = SQRT((((Ai * (Ws + Wr + Wf + Wi))^2) + ((Ac * Wc)^2)))
Vf = SQRT((((0.5126 * (584,096.124 + 348,366.4745 + 259,765.8038 + 16,693,271.3711))^2) + ((0.0586 * 44,609,953.2195)^2)))
Vf = 9,532,536.4861 lbf

V_allow = TAN(30) * (Ws + Wr + Wi + Wc) * (1 - (0.4 * Av))
V_allow = TAN(30) * (584,096.124 + 348,366.4745 + 16,693,271.3711 + 44,609,953.2195) * (1 - (0.4 * 0.1674))
V_allow = 33,525,798.0431 lbf

Vf <= V_allow

Shell Design Calculations

Ac = Convective Design Response Spectrum Acceleration Coefficient
Ai = Impulsive Design Response Spectrum Acceleration Coefficient
Av = Vertical ground acceleration coefficient description
CG-shell = Shell center of gravity (ft)
D = Tank Nominal Diameter (ft)
Hs = Shell height (ft)
Lmax = Max Liquid Level (ft)
P = Design Internal Pressure (psi)
Pv = Design External Pressure (psf)
SG = Product Design Specific Gravity
SGt = Hydrotest Specific Gravity
V = Wind velocity (mile/hr)
W-ins = Shell Insulation Weight (lbf)
W-shell = Shell Nominal Weight (lb)
W-shell-corr = Shell Corroded Weight (lb)
ds-ins = Insulation Density (lbf/ft^3)
h-min = Minimum Shell Course Height per API-650 5.6.1.2 (in)
ts-ins = Insulation Thickness (in)

Ac = 0.0586
Ai = 0.5126
Av = 0.1674
D = 180.0825 ft
Hs = 40.5 ft
Lmax = 40.5 ft
P = 0.0 psi
Pv = 0.0 psf
SG = 1
SGt = 1
V = 100.0 mile/hr
ds-ins = 8 lbf/ft^3
h-min = 96 in
ts-ins = 0 in

Course # 1 (bottom course) Design

CA = Corrosion allowance (in)
D1 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-1 = Shell Course Nominal Weight (lb)
W-1-corr = Shell Course Nominal Weight (lb)
h1 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 40.5 ft

JE = 1
Ma = A36
h1 = 8.0 ft
loc = 0 ft
t = 0.99 in

Shell Course Center of Gravity (CG-1) = 4.0 ft

D1 = ID + t
D1 = 2,160.0 + 0.99
D1 = 2,160.99 in

W-1 = pi * D1 * t * h1 * d
W-1 = pi * 2,160.99 * 0.99 * 96.0 * 0.2833
W-1 = 182,791.3465 lb

W-1-corr = pi * D1 * (t - CA) * h1 * d
W-1-corr = pi * 2,160.99 * (0.99 - 0) * 96.0 * 0.2833
W-1-corr = 182,791.3465 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi
Maximum Thickness (t-max) = 0.75 in

t > t-max ==> FAIL

***** WARNING *** :** Course-1, installed thickness , 0.99 in, is greater than the maximum allowable thickness of 0.75 in for A36 material

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 40.5
hp = 40.5 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0825 * 40.5 * 1) / (1 * 15,000)) + 0
td = 1.2642 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 40.5 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0825 * 40.5 * ((40.5 / 40.5) - (0.5 * ((40.5 / 40.5)^2))) * TANH((0.866 * (180.0825 / 40.5)))

Ni = 8,403.7019 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0586 * 1 * (180.0825^2) * COSH(((3.68 * (40.5 - 40.5)) / 180.0825))) / COSH(((3.68 * 40.5) / 180.0825))
Nc = 1,365.9694 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (40.5 - 0) * 180.0825 * 1
Nh = 18,962.6872 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (18,962.6872 + SQRT(((8,403.7019^2) + (1,365.9694^2) + (((0.1674 * 18,962.6872) / 2.5)^2)))) / MAX((0.99 - 0) , 0.0001)
S_T+ = 27,849.335 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (18,962.6872 - SQRT(((8,403.7019^2) + (1,365.9694^2) + (((0.1674 * 18,962.6872) / 2.5)^2)))) / MAX((0.99 - 0) , 0.0001)
S_T- = 10,459.1241 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((27,849.335 * (0.99 - 0)) / 19,950.0) + 0
ts = 1.382 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 1.2642 , 1.382)
t-min = 1.382 in

t < t-min ==> FAIL

***** WARNING *** :** Course 1 thickness, 0.99 in, is less than the required value of 1.382 in

Course # 2 Design
CA = Corrosion allowance (in)
D2 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-2 = Shell Course Nominal Weight (lb)
W-2-corr = Shell Course Nominal Weight (lb)
h2 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 32.5 ft
JE = 1
Ma = A36
h2 = 8.0 ft
loc = 8.0 ft
t = 0.79 in

Shell Course Center of Gravity (CG-2) = 12.0 ft

D2 = ID + t
D2 = 2,160.0 + 0.79
D2 = 2,160.79 in

W-2 = pi * D2 * t * h2 * d
W-2 = pi * 2,160.79 * 0.79 * 96.0 * 0.2833
W-2 = 145,850.302 lb

W-2-corr = pi * D2 * (t - CA) * h2 * d
W-2-corr = pi * 2,160.79 * (0.79 - 0) * 96.0 * 0.2833
W-2-corr = 145,850.302 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi
Maximum Thickness (t-max) = 0.75 in

t > t-max ==> FAIL

***** WARNING *** :** Course-2, installed thickness , 0.79 in, is greater than the maximum allowable thickness of 0.75 in for A36 material

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 32.5
hp = 32.5 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0825 * 32.5 * 1) / (1 * 15,000)) + 0
td = 1.0145 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 32.5 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))

Ni = 4.5 * 0.5126 * 1 * 180.0825 * 40.5 * ((32.5 / 40.5) - (0.5 * ((32.5 / 40.5)^2))) * TANH((0.866 * (180.0825 / 40.5)))
Ni = 8,075.8026 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0586 * 1 * (180.0825^2) * COSH(((3.68 * (40.5 - 32.5)) / 180.0825))) / COSH(((3.68 * 40.5) / 180.0825))
Nc = 1,384.2635 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (32.5 - 0) * 180.0825 * 1
Nh = 15,216.9712 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (15,216.9712 + SQRT(((8,075.8026^2) + (1,384.2635^2) + (((0.1674 * 15,216.9712) / 2.5)^2)))) / MAX((0.79 - 0) , 0.0001)
S_T+ = 29,713.4997 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (15,216.9712 - SQRT(((8,075.8026^2) + (1,384.2635^2) + (((0.1674 * 15,216.9712) / 2.5)^2)))) / MAX((0.79 - 0) , 0.0001)
S_T- = 8,810.4782 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((29,713.4997 * (0.79 - 0)) / 19,950.0) + 0
ts = 1.1766 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 1.0145 , 1.1766)
t-min = 1.1766 in

t < t-min ==> FAIL

***** WARNING *** :** Course 2 thickness, 0.79 in, is less than the required value of 1.1766 in

Course # 3 Design
CA = Corrosion allowance (in)
D3 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-3 = Shell Course Nominal Weight (lb)
W-3-corr = Shell Course Nominal Weight (lb)
h3 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)

td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 24.5 ft
JE = 1
Ma = A36
h3 = 8.0 ft
loc = 16.0 ft
t = 0.59 in

Shell Course Center of Gravity (CG-3) = 20.0 ft

D3 = ID + t
D3 = 2,160.0 + 0.59
D3 = 2,160.59 in

W-3 = pi * D3 * t * h3 * d
W-3 = pi * 2,160.59 * 0.59 * 96.0 * 0.2833
W-3 = 108,916.0929 lb

W-3-corr = pi * D3 * (t - CA) * h3 * d
W-3-corr = pi * 2,160.59 * (0.59 - 0) * 96.0 * 0.2833
W-3-corr = 108,916.0929 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 24.5
hp = 24.5 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0825 * 24.5 * 1) / (1 * 15,000)) + 0
td = 0.7648 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 24.5 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0825 * 40.5 * ((24.5 / 40.5) - (0.5 * ((24.5 / 40.5)^2))) * TANH((0.866 * (180.0825 / 40.5)))
Ni = 7,092.1045 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0586 * 1 * (180.0825^2) * COSH(((3.68 * (40.5 - 24.5)) / 180.0825))) / COSH(((3.68 * 40.5) / 180.0825))
Nc = 1,439.6358 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (24.5 - 0) * 180.0825 * 1
Nh = 11,471.2553 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (11,471.2553 + SQRT(((7,092.1045^2) + (1,439.6358^2) + (((0.1674 * 11,471.2553) / 2.5)^2)))) / MAX((0.59 - 0) , 0.0001)
S_T+ = 31,777.3757 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (11,471.2553 - SQRT(((7,092.1045^2) + (1,439.6358^2) + (((0.1674 * 11,471.2553) / 2.5)^2)))) / MAX((0.59 - 0) , 0.0001)
S_T- = 7,108.2354 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((31,777.3757 * (0.59 - 0)) / 19,950.0) + 0
ts = 0.9398 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.7648 , 0.9398)
t-min = 0.9398 in

t < t-min ==> FAIL

***** WARNING *** :** Course 3 thickness, 0.59 in, is less than the required value of 0.9398 in

Course # 4 Design
CA = Corrosion allowance (in)
D4 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-4 = Shell Course Nominal Weight (lb)
W-4-corr = Shell Course Nominal Weight (lb)
h4 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 16.5 ft

JE = 1
Ma = A36
h4 = 8.0 ft
loc = 24.0 ft
t = 0.4 in

Shell Course Center of Gravity (CG-4) = 28.0 ft

D4 = ID + t
D4 = 2,160.0 + 0.4
D4 = 2,160.4 in

W-4 = pi * D4 * t * h4 * d
W-4 = pi * 2,160.4 * 0.4 * 96.0 * 0.2833
W-4 = 73,834.9254 lb

W-4-corr = pi * D4 * (t - CA) * h4 * d
W-4-corr = pi * 2,160.4 * (0.4 - 0) * 96.0 * 0.2833
W-4-corr = 73,834.9254 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 16.5
hp = 16.5 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0825 * 16.5 * 1) / (1 * 15,000)) + 0
td = 0.515 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 16.5 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0825 * 40.5 * ((16.5 / 40.5) - (0.5 * ((16.5 / 40.5)^2))) * TANH((0.866 * (180.0825 / 40.5)))
Ni = 5,452.6077 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0586 * 1 * (180.0825^2) * COSH(((3.68 * (40.5 - 16.5)) / 180.0825))) / COSH(((3.68 * 40.5) / 180.0825))
Nc = 1,533.5694 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (16.5 - 0) * 180.0825 * 1
Nh = 7,725.5393 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (7,725.5393 + SQRT(((5,452.6077^2) + (1,533.5694^2) + (((0.1674 * 7,725.5393) / 2.5)^2)))) / MAX((0.4 - 0) , 0.0001)
S_T+ = 33,533.1939 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (7,725.5393 - SQRT(((5,452.6077^2) + (1,533.5694^2) + (((0.1674 * 7,725.5393) / 2.5)^2)))) / MAX((0.4 - 0) , 0.0001)
S_T- = 5,094.5023 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((33,533.1939 * (0.4 - 0)) / 19,950.0) + 0
ts = 0.6723 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.515 , 0.6723)
t-min = 0.6723 in

t < t-min ==> FAIL

***** WARNING *** :** Course 4 thickness, 0.4 in, is less than the required value of 0.6723 in

Course # 5 Design
CA = Corrosion allowance (in)
D5 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-5 = Shell Course Nominal Weight (lb)
W-5-corr = Shell Course Nominal Weight (lb)
h5 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 8.5 ft
JE = 1
Ma = A36
h5 = 8.5 ft
loc = 32.0 ft

t = 0.35 in

Shell Course Center of Gravity (CG-5) = 36.25 ft

D5 = ID + t
D5 = 2,160.0 + 0.35
D5 = 2,160.35 in

W-5 = pi * D5 * t * h5 * d
W-5 = pi * 2,160.35 * 0.35 * 102.0 * 0.2833
W-5 = 68,641.8185 lb

W-5-corr = pi * D5 * (t - CA) * h5 * d
W-5-corr = pi * 2,160.35 * (0.35 - 0) * 102.0 * 0.2833
W-5-corr = 68,641.8185 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 8.5
hp = 8.5 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0825 * 8.5 * 1) / (1 * 15,000)) + 0
td = 0.2653 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 8.5 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0825 * 40.5 * ((8.5 / 40.5) - (0.5 * ((8.5 / 40.5)^2))) * TANH((0.866 * (180.0825 / 40.5)))
Ni = 3,157.3122 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0586 * 1 * (180.0825^2) * COSH(((3.68 * (40.5 - 8.5)) / 180.0825))) / COSH(((3.68 * 40.5) / 180.0825))
Nc = 1,668.5804 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (8.5 - 0) * 180.0825 * 1
Nh = 3,979.8233 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (3,979.8233 + SQRT(((3,157.3122^2) + (1,668.5804^2) + (((0.1674 * 3,979.8233) / 2.5)^2)))) / MAX((0.35 - 0) , 0.0001)
S_T+ = 21,602.4464 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (3,979.8233 - SQRT(((3,157.3122^2) + (1,668.5804^2) + (((0.1674 * 3,979.8233) / 2.5)^2)))) / MAX((0.35 - 0) , 0.0001)
S_T- = 1,139.4008 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((21,602.4464 * (0.35 - 0)) / 19,950.0) + 0
ts = 0.379 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.2653 , 0.379)
t-min = 0.379 in

t < t-min ==> FAIL

***** WARNING *** :** Course 5 thickness, 0.35 in, is less than the required value of 0.379 in

W-ins = ts-ins * ds-ins * pi * (OD + ts-ins) * Hs
W-ins = 0.0 * 8 * pi * (180.165 + 0.0) * 40.5
W-ins = 0.0 lbf

W-shell-corr = W-1-corr + W-2-corr + W-3-corr + W-4-corr + W-5-corr
W-shell-corr = 182,791.3465 + 145,850.302 + 108,916.0929 + 73,834.9254 + 68,641.8185
W-shell-corr = 580,034.4853 lb

W-shell = W-1 + W-2 + W-3 + W-4 + W-5
W-shell = 182,791.3465 + 145,850.302 + 108,916.0929 + 73,834.9254 + 68,641.8185
W-shell = 580,034.4853 lb

CG-shell = ((CG-1 * W-1) + (CG-2 * W-2) + (CG-3 * W-3) + (CG-4 * W-4) + (CG-5 * W-5)) / W-shell
CG-shell = ((4.0 * 182,791.3465) + (12.0 * 145,850.302) + (20.0 * 108,916.0929) + (28.0 * 73,834.9254) + (36.25 * 68,641.8185)) / 580,034.4853
CG-shell = 15.8876 ft

Shell Design Summary

Course	Height (ft)	Material	CA (in)	JE	Sy (psi)	Sut (psi)	Sd (psi)	St (psi)	t-erec (in)
5	8.5	A36	0	1	36,000	58,000	15,000	15,000	0.3125
4	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
3	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
2	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125

1	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125

Shell Design Summary (continued)

Course	t-design (in)	t-test (in)	t-seismic (in)	t-ext (in)	t-min (in)	t-installed (in)	Status	H-max-@-Pi (ft)	Pi-max-@-H (psi)
5	0.2653	N/A	0.379	N/A	0.379	0.35	FAIL	44.2128	1.6096
4	0.515	N/A	0.6723	N/A	0.6723	0.4	FAIL	37.8146	0.0
3	0.7648	N/A	0.9398	N/A	0.9398	0.59	FAIL	35.9016	0.0
2	1.0145	N/A	1.1766	N/A	1.1766	0.79	FAIL	34.3089	0.0
1	1.2642	N/A	1.382	N/A	1.382	0.99	FAIL	32.7162	0.0

Intermediate Stiffeners Design

Stiffeners Design For Wind Loading

D = Nominal Tank Diameter (ft)
N = Actual Wind Girders Quantity
Ns = Required Number of Girders per API 650 5.9.6.3 and 5.9.6.4
V = Wind velocity (mile/hr)
h = Maximum Unstiffened Transformed Shell Height per AWWA-D100-11 3.5.2 (ft)
ts_min = Thickness of the Thinnest Shell Course

D = 180.0825 ft
N = 0
V = 100.0 mile/hr

Shell Courses Heights (W) = [8.0 8.0 8.0 8.0 8.5] ft

ts_min = MIN(ts_corr_1 , ts_corr_2 , ts_corr_3 , ts_corr_4 , ts_corr_5)
ts_min = MIN(0.99 , 0.79 , 0.59 , 0.4 , 0.35)
ts_min = 0.35

Stiffeners Required Quantity

HTS = Height of Transformed Shell per API 650 5.9.6.2 (ft)

Transformed shell courses heights

Variable	Equation	Value	Unit
Wtr_1	W_1 * SQRT(((ts_min / ts_corr_1)^5))	0.5945	ft
Wtr_2	W_2 * SQRT(((ts_min / ts_corr_2)^5))	1.0452	ft
Wtr_3	W_3 * SQRT(((ts_min / ts_corr_3)^5))	2.1684	ft
Wtr_4	W_4 * SQRT(((ts_min / ts_corr_4)^5))	5.7294	ft
Wtr_5	W_5 * SQRT(((ts_min / ts_corr_5)^5))	8.5000	ft

HTS = Wtr_1 + Wtr_2 + Wtr_3 + Wtr_4 + Wtr_5
HTS = 0.5945 + 1.0452 + 2.1684 + 5.7294 + 8.5
HTS = 18.0375 ft

h = (10.625 * (10^6) * ts_min) / (PWS * ((D / ts_min)^1.5))

h = (10.625 * (10^6) * 0.35) / (18.0 * ((180.0825 / 0.35)^1.5))
h = 17.7019 ft

Ns = CEILING(((HTS / h) - 1))
Ns = CEILING(((18.0375 / 17.7019) - 1))
Ns = 1

N < Ns ==> FAIL

***** WARNING *** :** Number of intermediate stiffeners, 0, is less than the required number of 1

Option 1
Seismic and Shell Analysis

Seismic Design Calculations

Site Ground Motion Design

Ac = Compute Impulsive Design Response Spectrum Acceleration Coefficient per AWWA D100-11 13.2.9.2
Af = Compute Acceleration Coefficient for Sloshing Wave Height per AWWA D100-11 13.5.4.4
Ai = Compute Impulsive Design Response Spectrum Acceleration Coefficient per AWWA D100-11 13.2.9.2
Anchorage_System = Anchorage System
Av = Vertical Ground Acceleration Coefficient per AWWA D100-11 13.5.4.1 and 13.5.4.3
D = Nominal Tank Diameter (ft)
Fa = Site Acceleration Coefficient
Fv = Site Velocity Coefficient
I = Importance Factor
K = Spectral Acceleration Adjustment Coefficient
Lmax = Maximum Design Product Level (ft)
Rwc = Convective Force Reduction Factor
Rwi = Impulsive Force Reduction Factor
S1 = Spectral Response Acceleration at a Period of One Second
SD1 = Compute Design Spectral Response Acceleration at a Period of One Second per AWWA D100-11 13.2.7.3
SDS = Compute Design Spectral Response Acceleration at Short Period per AWWA D100-11 13.2.7.3
SM1 = Compute Maximum Considered Earthquake Spectral Response Acceleration at a Period of One Second per AWWA D100-11 13.2.7.2
SMS = Compute Maximum Considered Earthquake Spectral Response Acceleration at Short Period per AWWA D100-11 13.2.7.2
SUG = Seismic Use Group
Sac = Compute Convective Design Response Spectrum Acceleration Coefficient For Convective Components per AWWA D100-11 13.2.7.3.2
Sai =
Seismic_Site_Class = Seismic Site Class
Ss = Spectral Response Acceleration Short Period
TL = Regional Dependent Transistion Period for Longer Period Ground Motion (sec)
Tc = Compute Convective Natural Period per AWWA D100-11 13.5.1 (sec)
Ti = Structure Natural Period (sec)
U = Scaling Factor
d_ratio = Dampening Ratio
g = Acceleration Due To Gravity (ft/sec^2)
structure_type = Structure Type

Anchorage_System = SELF-ANCHORED
D = 180.0828 ft
Fa = 1.0
Fv = 1.5
I = 1.5
K = 1.5
Lmax = 29 ft
Rwc = 1.5
Rwi = 2.5
S1 = 0.593
SUG = SEISMIC-USE-GROUP-III
Seismic_Site_Class = SEISMIC-SITE-CLASS-D
Ss = 1.794
TL = 12 sec

Ti = 0 sec
U = 0.6667
d_ratio = 0.05
g = 32.17 ft/sec^2
structure_type = GROUND-SUPPORTED-FLAT-BOTTOM-TANK

Tc = 2 * pi * SQRT((D / (3.68 * g * TANH(((3.68 * Lmax) / D)))))
Tc = 2 * pi * SQRT((180.0828 / (3.68 * 32.17 * TANH(((3.68 * 29) / 180.0828)))))
Tc = 10.6268 sec

SMS = Fa * Ss
SMS = 1.0 * 1.794
SMS = 1.794

SM1 = Fv * S1
SM1 = 1.5 * 0.593
SM1 = 0.8895

SDS = U * SMS
SDS = 0.6667 * 1.794
SDS = 1.196

SD1 = U * SM1
SD1 = 0.6667 * 0.8895
SD1 = 0.593

Sai = SDS
Sai = 1.196
Sai = 1.196

Sac = MIN(((K * SD1) / Tc) , SDS)
Sac = MIN(((1.5 * 0.593) / 10.6268) , 1.196)
Sac = 0.0837

Ai = MAX(((Sai * I) / (1.4 * Rwi)) , ((0.36 * S1 * I) / Rwi))
Ai = MAX(((1.196 * 1.5) / (1.4 * 2.5)) , ((0.36 * 0.593 * 1.5) / 2.5))
Ai = 0.5126

Ac = (Sac * I) / (1.4 * Rwc)
Ac = (0.0837 * 1.5) / (1.4 * 1.5)
Ac = 0.0598

Av = 0.14 * SDS
Av = 0.14 * 1.196
Av = 0.1674

Af = (K * SD1) / Tc
Af = (1.5 * 0.593) / 10.6268
Af = 0.0837

Seismic Design

A = Roof Surface Area (ft^2)
Ac = Convective Design Response Spectrum Acceleration Coefficient
Af = Acceleration Coefficient for Sloshing Wave Height
Ah-rs = Roof Horizontal Projected Area Supported by The Shell (ft^2)

Ai = Impulsive Design Response Spectrum Acceleration Coefficient
Anchorage_System = Anchorage System
Arss = Roof Area Supported by The Shell (ft^2)
Av = Vertical Ground Acceleration Coefficient
CA = Bottom Corrosion Allowance (in)
D = Nominal Tank Diameter (ft)
DELTA_Cc = Compute Pressure Stabilizing Buckling Coefficient per AWWA D100-11 13.5.4.2.4
DELTA_SIGMAcr = Compute Self Anchored Tank Critical Buckling Stress Increase Caused By Pressure Equation per AWWA D100-11 13.5.4.2.4 (lb/in^2)
Fa = Site Acceleration Coefficient
Freeboard = Actual Freeboard (ft)
Fv = Site Velocity Coefficient
Hs = Shell height (ft)
Hs = Shell Total Height (ft)
I = Importance Factor
J = Compute Anchorage Ratio per AWWA D100-11 13.5.4.1
K = Spectral Acceleration Adjustment Coefficient
Lmax = Maximum Design Product Level (ft)
Ls = Actual Annular Ring Width (ft)
Ma = Material Name
Mmf = Compute Overturning Moment per AWWA D100-11 13.5.2.1 (ft.lb)
Ms = Compute Overturning Moment per AWWA D100-11 13.5.2.1 (ft.lb)
P = Design Pressure (lbf/in^2)
R = (ft)
S1 = Spectral Response Acceleration at a Period of One Second
SD1 = Design Spectral Response Acceleration at a Period of 1 Second
SDS = Design Spectral Response Acceleration at Short Period
SG = Specific Gravity
SIGMAc_self_anchored = Compute Self Anchored Maximum Longitudinal Shell Compression Stress per AWWA D100-11 13.5.4.2.1 (lbf/in^2)
SIGMAe_self_anchored = Compute Seismic Allowable Longitudinal Compressive Stress per AWWA D100-11 13.5.4.2.4 (lb/in^2)
SUG = Seismic Use Group
Seismic_Site_Class = Seismic Site Class
Ss = Spectral Response Acceleration Short Period
TL = Regional Dependent Transistion Period for Longer Period Ground Motion (sec)
Tc = Convective Natural Period (sec)
U = Scaling Factor
V_allow = Compute Self Anchored Sliding Resistance Base Shear per AWWA D100-11 13.5.4.6 (lbf)
Vf = Compute Total Design Base Shear per AWWA D100-11 13.5.3.1 (lbf)
Wc = Compute Convective Effective Weight per AWWA D100-11 13.5.2.2.1 (lbf)
Wf = Tank Bottom Total Weight (lbf)
Wi = Compute Impulsive Effective Weight per AWWA D100-11 13.5.2.2.1 (lbf)
Wp = Tank Contents Total Weight (lbf)
Wr = Total Weight of Fixed Tank Roof including Framing, Knuckles, any Permanent Attachments and 10 % of the Roof Balanced Design Snow Load (lbf)
Wrs = Roof Load Acting on The Tank Shell Including 10 % of the Roof Balanced Design Snow Load (lbf)
Ws = Total Weight of Tank Shell and Appurtenances (lbf)
Wss = Roof Structure Weight Supported by The Tank Shell (lb)
Xc = Height from tank shell bottom to the center of action of convective lateral force for computing ringwall overturning moment per AWWA D100-11 13.5.2.2.2 (ft)
Xcmf = Height from tank shell bottom to the center of action of convective lateral force for computing slab overturning moment per AWWA D100-11 13.5.3.2.2 (ft)
Xi = Height from tank shell bottom to the center of action of impulsive lateral force for computing ringwall overturning moment per AWWA D100-11 13.5.2.2.2 (ft)
Ximf = Height from tank shell bottom to the center of action of impulsive lateral force for computing slab

overturning moment per AWWA D100-11 13.5.3.2.2 (ft)
Xs = Height from tank shell bottom to shell's center of gravity (ft)
ca1 = Bottom Shell Course Corrosion Allowance (in)
ca_annulus = Bottom Annular Ring Design Corrosion Allowance (in)
d = Sloshing Wave Height Above Product Design Height per AWWA D100-11 Section 13.5.4.4 (ft)
g = Acceleration Due To Gravity (ft/sec^2)
lw = Lap of the Bottom Plates Over the Annular Plate (in)
outside_projection = Bottom Outside Projection (in)
site_ground_motion_input_mode = Site Ground Motion Input Mode
t_bottom = Bottom Plate Thickness (in)
tb = Bottom Annular Ring Design Thickness (in)
tb_less_ca = Bottom Annular Ring Design Thickness Without Corrosion Allowance (in)
tb_limited_less_ca = (in)
ts1 = Bottom Shell Course Thickness (in)
ts_less_ca = Bottom Shell Course Thickness Without Corrosion Allowance (in)
using_annular_ring = Using Annular Ring
wL = Compute Self Anchored Force Resisting Uplift per AWWA D100-11 13.5.4.1.1 (lbf/ft)
wrs = Specified Tank Roof Load Acting on Tank Shell (lbf/ft)
wt = Compute Tank and Roof Weight Acting at base of Shell per AWWA D100-11 13.5.4.2.1 (lbf/ft)

A = 25,591.0721 ft^2
Ac = 0.0598
Af = 0.0837
Ah-rs = 8,675.0865 ft^2
Ai = 0.5126
Anchorage_System = SELF-ANCHORED
Arss = 8,692.0135 ft^2
Av = 0.1674
CA = 0 in
D = 180.0828 ft
Fa = 1.0
Fv = 1.5
Hs = 40.5 ft
Hs = 40.5 ft
I = 1.5
K = 1.5
Lmax = 29 ft
Ls = 2.1255 ft
Ma = A36
P = 0.0 lbf/in^2
S1 = 0.593
SD1 = 0.593
SDS = 1.196
SG = 1
SUG = SEISMIC-USE-GROUP-III
Seismic_Site_Class = SEISMIC-SITE-CLASS-D
Ss = 1.794
TL = 12 sec
Tc = 10.6268 sec
U = 0.6667
Wp = 46,069,300.2213 lbf
Wss = 23,642.8267 lb
Xs = 15.8724 ft
ca1 = 0 in
ca_annulus = 0 in
g = 32.17 ft/sec^2

lw = 1.5 in
outside_projection = 2 in
site_ground_motion_input_mode = ASCE7-MAPPED-SS-AND-S1
t_bottom = 0.25 in
tb = 0.25 in
ts1 = 0.994 in
using_annular_ring = t

Wf = Wb-pl
Wf = 259,766.7655
Wf = 259,766.7655 lbf

Wr = (Wr-pl + Wr-attachments + W-struct + Wr-DL-add) + (0.1 * Sb * Ah)
Wr = (260,998.2266 + 0.0 + 152,429.9155 + 0.0) + (0.1 * 0.0 * 25,541.2355)
Wr = 413,428.1421 lbf

Wrs = ((Wr-pl + Wr-attachments + Wr-DL-add) * (Arss / A)) + Wss + (0.1 * Sb * Ah-rs)
Wrs = ((260,998.2266 + 0.0 + 0.0) * (8,692.0135 / 25,591.0721)) + 23,642.8267 + (0.1 * 0.0 * 8,675.0865)
Wrs = 112,290.9341 lbf

Ws = Ws-pl + Ws-framing + Ws-attachments
Ws = 580,773.3759 + 9,920.082 + 4.0
Ws = 590,697.4579 lbf

R = D / 2
R = 180.0828 / 2
R = 90.0414 ft

tb_less_ca = tb - ca_annulus
tb_less_ca = 0.25 - 0
tb_less_ca = 0.25 in

ts_less_ca = ts1 - ca1
ts_less_ca = 0.994 - 0
ts_less_ca = 0.994 in

tb_limited_less_ca = MIN(tb_less_ca , ts_less_ca)
tb_limited_less_ca = MIN(0.25 , 0.994)
tb_limited_less_ca = 0.25 in

Effective weight of product
Wi = (TANH((0.866 * (D / Lmax))) / (0.866 * (D / Lmax))) * Wp
Wi = (TANH((0.866 * (180.0828 / 29))) / (0.866 * (180.0828 / 29))) * 46,069,300.2213
Wi = 8,566,449.8632 lbf

Wc = 0.23 * (D / Lmax) * TANH(((3.67 * Lmax) / D)) * Wp
Wc = 0.23 * (180.0828 / 29) * TANH(((3.67 * 29) / 180.0828)) * 46,069,300.2213
Wc = 34,913,729.6493 lbf

Center of action for effective lateral forces
Xi = 0.375 * Lmax
Xi = 0.375 * 29
Xi = 10.875 ft

Xc = (1.0 - ((COSH(((3.67 * Lmax) / D)) - 1) / (((3.67 * Lmax) / D) * SINH(((3.67 * Lmax) / D))))) * Lmax

Xc = (1.0 - ((COSH(((3.67 * 29) / 180.0828)) - 1) / (((3.67 * 29) / 180.0828) * SINH(((3.67 * 29) / 180.0828))))) * 29
Xc = 14.9078 ft

Ximf = 0.375 * (1.0 + ((4 / 3) * (((0.866 * (D / Lmax)) / TANH((0.866 * (D / Lmax)))) - 1.0))) * Lmax
Ximf = 0.375 * (1.0 + ((4 / 3) * (((0.866 * (180.0828 / 29)) / TANH((0.866 * (180.0828 / 29)))) - 1.0))) * 29
Ximf = 74.3542 ft

Xcmf = (1.0 - ((COSH(((3.67 * Lmax) / D)) - 1.937) / (((3.67 * Lmax) / D) * SINH(((3.67 * Lmax) / D))))) * Lmax
Xcmf = (1.0 - ((COSH(((3.67 * 29) / 180.0828)) - 1.937) / (((3.67 * 29) / 180.0828) * SINH(((3.67 * 29) / 180.0828))))) * 29
Xcmf = 88.3524 ft

Overturning moment

Ms = SQRT((((Ai * ((Ws * Xs) + (Wr * Hs) + (Wi * Xi)))^2) + ((Ac * (Wc * Xc))^2)))
Ms = SQRT((((0.5126 * ((590,697.4579 * 15.8724) + (413,428.1421 * 40.5) + (8,566,449.8632 * 10.875)))^2) + ((0.0598 * (34,913,729.6493 * 14.9078))^2)))
Ms = 68,603,346.1485 ft.lb

Mmf = SQRT((((Ai * ((Ws * Xs) + (Wr * Hs) + (Wi * Ximf)))^2) + ((Ac * (Wc * Xcmf))^2)))
Mmf = SQRT((((0.5126 * ((590,697.4579 * 15.8724) + (413,428.1421 * 40.5) + (8,566,449.8632 * 74.3542)))^2) + ((0.0598 * (34,913,729.6493 * 88.3524))^2)))
Mmf = 386,686,755.762 ft.lb

Resistance to design loads

wL = MIN((7.9 * tb_limited_less_ca * SQRT((Fy * Lmax * SG))) , (1.28 * Lmax * D * SG))
wL = MIN((7.9 * 0.25 * SQRT((36,000 * 29 * 1))) , (1.28 * 29 * 180.0828 * 1))
wL = 2,017.9823 lbf/ft

wrs = Wrs / (pi * D)
wrs = 112,290.9341 / (pi * 180.0828)
wrs = 198.4826 lbf/ft

wt = (Ws / (pi * D)) + wrs
wt = (590,697.4579 / (pi * 180.0828)) + 198.4826
wt = 1,242.5846 lbf/ft

Tank Stability

J = Ms / ((D^2) * ((wt * (1 - (0.4 * Av))) + wL))
J = 68,603,346.1485 / ((180.0828^2) * ((1,242.5846 * (1 - (0.4 * 0.1674))) + 2,017.9823))
J = 0.6658

Bottom Annular Plates requirements

As per AWWA 3.10.8
Ls >= 18 ==> PASS

Shell Stresses

SIGMAc_self_anchored = ((wt * (1 + (0.4 * Av))) + ((1.273 * Ms) / (D^2))) * (1 / (12 * ts_less_ca))
SIGMAc_self_anchored = ((1,242.5846 * (1 + (0.4 * 0.1674))) + ((1.273 * 68,603,346.1485) / (180.0828^2))) * (1 / (12 * 0.994))
SIGMAc_self_anchored = 336.9167 lbf/in^2

DELTA_Cc = 0.72 * (((P / E) * ((R / ts_less_ca)^2))^0.84)
DELTA_Cc = 0.72 * (((0.0 / 28,800,000) * ((1,080.497 / 0.994)^2))^0.84)

DELTA_Cc = 0.0

DELTA_SIGMAcr = (DELTA_Cc * E * ts_less_ca) / R
DELTA_SIGMAcr = (0.0 * 28,800,000 * 0.994) / 1,080.497
DELTA_SIGMAcr = 0.0 lb/in^2

FL = Compute Allowable Local Buckling Compressive Stress per AWWA D100-11 Section 3.4.3.1.2 (lb/in^2)
Material_Class = Compute Material Class From Minimum Yield Strength per AWWA D100-11 Section 3.2 and Table 4
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = Thickness Radius Ratio Boundary Elastic Inelastic Buckling per AWWA D100-11 Sections 3.4.3.1.1 and 3.4.3.1.2

Material_Class = :material-class-2
Material_Class = :material-class-2
Material_Class = :material-class-2

Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035372
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035372
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035

FL = 17.5 * (10^5) * (ts_less_ca / R) * (1 + (50000 * ((ts_less_ca / R)^2)))
FL = 17.5 * (10^5) * (0.994 / 1,080.497) * (1 + (50000 * ((0.994 / 1,080.497)^2)))
FL = 1,678.0307 lb/in^2

Allowable Local Buckling Compressive Stress (FL) = 1,678.0307 lb/in^2

SIGMAe_self_anchored = 1.333 * (FL + (DELTA_SIGMAcr / 2))
SIGMAe_self_anchored = 1.333 * (1,678.0307 + (0.0 / 2))
SIGMAe_self_anchored = 2,236.815 lb/in^2

Freeboard

d = 0.5 * D * Af
d = 0.5 * 180.0828 * 0.0837
d = 7.5365 ft [90.4376 in]

Freeboard = Hs - Lmax-operating
Freeboard = 40.5 - 29
Freeboard = 11.5 ft [138.0 in]

(SDS >= One_Third_g) AND (SUG = :seismic-use-group-iii)

[Required]
Sloshing Wave Height Above Product Design Height (d) = 7.5365 ft

Freeboard >= d ==> PASS

Sliding Resistance

Vf = SQRT((((Ai * (Ws + Wr + Wf + Wi))^2) + ((Ac * Wc)^2)))
Vf = SQRT((((0.5126 * (590,697.4579 + 413,428.1421 + 259,766.7655 + 8,566,449.8632))^2) + ((0.0598 * 34,913,729.6493)^2)))
Vf = 5,454,024.2158 lbf

V_allow = TAN(30) * (Ws + Wr + Wi + Wc) * (1 - (0.4 * Av))

V_allow = TAN(30) * (590,697.4579 + 413,428.1421 + 8,566,449.8632 + 34,913,729.6493) * (1 - (0.4 * 0.1674))
V_allow = 23,963,290.1418 lbf

Vf <= V_allow

Shell Design Calculations

Ac = Convective Design Response Spectrum Acceleration Coefficient
Ai = Impulsive Design Response Spectrum Acceleration Coefficient
Av = Vertical ground acceleration coefficient description
CG-shell = Shell center of gravity (ft)
D = Tank Nominal Diameter (ft)
Hs = Shell height (ft)
Lmax = Max Liquid Level (ft)
P = Design Internal Pressure (psi)
Pv = Design External Pressure (psf)
SG = Product Design Specific Gravity
SGt = Hydrotest Specific Gravity
V = Wind velocity (mile/hr)
W-ins = Shell Insulation Weight (lbf)
W-shell = Shell Nominal Weight (lb)
W-shell-corr = Shell Corroded Weight (lb)
ds-ins = Insulation Density (lbf/ft^3)
h-min = Minimum Shell Course Height per API-650 5.6.1.2 (in)
ts-ins = Insulation Thickness (in)

Ac = 0.0598
Ai = 0.5126
Av = 0.1674
D = 180.0828 ft
Hs = 40.5 ft
Lmax = 29 ft
P = 0.0 psi
Pv = 0.0 psf
SG = 1
SGt = 1
V = 5.0 mile/hr
ds-ins = 8 lbf/ft^3
h-min = 96 in
ts-ins = 0 in

Course # 1 (bottom course) Design

CA = Corrosion allowance (in)
D1 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-1 = Shell Course Nominal Weight (lb)
W-1-corr = Shell Course Nominal Weight (lb)
h1 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 29 ft

JE = 1
Ma = A36
h1 = 8.0 ft
loc = 0 ft
t = 0.994 in

Shell Course Center of Gravity (CG-1) = 4.0 ft

D1 = ID + t
D1 = 2,160.0 + 0.994
D1 = 2,160.994 in

W-1 = pi * D1 * t * h1 * d
W-1 = pi * 2,160.994 * 0.994 * 96.0 * 0.2833
W-1 = 183,530.2371 lb

W-1-corr = pi * D1 * (t - CA) * h1 * d
W-1-corr = pi * 2,160.994 * (0.994 - 0) * 96.0 * 0.2833
W-1-corr = 183,530.2371 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi
Maximum Thickness (t-max) = 0.75 in

t > t-max ==> FAIL

***** WARNING *** :** Course-1, installed thickness , 0.994 in, is greater than the maximum allowable thickness of 0.75 in for A36 material

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 29
hp = 29 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0828 * 29 * 1) / (1 * 15,000)) + 0
td = 0.9052 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 29 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0828 * 29 * ((29 / 29) - (0.5 * ((29 / 29)^2))) * TANH((0.866 * (180.0828 / 29)))
Ni = 6,022.6649 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0598 * 1 * (180.0828^2) * COSH(((3.68 * (29 - 29)) / 180.0828))) / COSH(((3.68 * 29) / 180.0828))
Nc = 1,609.2027 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (29 - 0) * 180.0828 * 1
Nh = 13,578.2456 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (13,578.2456 + SQRT(((6,022.6649^2) + (1,609.2027^2) + (((0.1674 * 13,578.2456) / 2.5)^2)))) / MAX((0.994 - 0) , 0.0001)
S_T+ = 19,998.1287 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (13,578.2456 - SQRT(((6,022.6649^2) + (1,609.2027^2) + (((0.1674 * 13,578.2456) / 2.5)^2)))) / MAX((0.994 - 0) , 0.0001)
S_T- = 7,322.285 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((19,998.1287 * (0.994 - 0)) / 19,950.0) + 0
ts = 0.9964 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.9052 , 0.9964)
t-min = 0.9964 in

t < t-min ==> FAIL

***** WARNING *** :** Course 1 thickness, 0.994 in, is less than the required value of 0.9964 in

Course # 2 Design
CA = Corrosion allowance (in)
D2 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-2 = Shell Course Nominal Weight (lb)
W-2-corr = Shell Course Nominal Weight (lb)
h2 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in

H = 21.0 ft
JE = 1
Ma = A36
h2 = 8.0 ft
loc = 8.0 ft
t = 0.79 in

Shell Course Center of Gravity (CG-2) = 12.0 ft

D2 = ID + t
D2 = 2,160.0 + 0.79
D2 = 2,160.79 in

W-2 = pi * D2 * t * h2 * d
W-2 = pi * 2,160.79 * 0.79 * 96.0 * 0.2833
W-2 = 145,850.302 lb

W-2-corr = pi * D2 * (t - CA) * h2 * d
W-2-corr = pi * 2,160.79 * (0.79 - 0) * 96.0 * 0.2833
W-2-corr = 145,850.302 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi
Maximum Thickness (t-max) = 0.75 in

t > t-max ==> FAIL

***** WARNING *** :** Course-2, installed thickness , 0.79 in, is greater than the maximum allowable thickness of 0.75 in for A36 material

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 21.0
hp = 21.0 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0828 * 21.0 * 1) / (1 * 15,000)) + 0
td = 0.6555 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 21.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0828 * 29 * ((21.0 / 29) - (0.5 * ((21.0 / 29)^2))) * TANH((0.866 * (180.0828 /

29)))
Ni = 5,564.3408 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0598 * 1 * (180.0828^2) * COSH(((3.68 * (29 - 21.0)) / 180.0828))) / COSH(((3.68 * 29) / 180.0828))
Nc = 1,630.7542 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (21.0 - 0) * 180.0828 * 1
Nh = 9,832.5227 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (9,832.5227 + SQRT(((5,564.3408^2) + (1,630.7542^2) + (((0.1674 * 9,832.5227) / 2.5)^2)))) / MAX((0.79 - 0) , 0.0001)
S_T+ = 19,833.1201 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (9,832.5227 - SQRT(((5,564.3408^2) + (1,630.7542^2) + (((0.1674 * 9,832.5227) / 2.5)^2)))) / MAX((0.79 - 0) , 0.0001)
S_T- = 5,059.3425 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((19,833.1201 * (0.79 - 0)) / 19,950.0) + 0
ts = 0.7854 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.6555 , 0.7854)
t-min = 0.7854 in

Course # 3 Design
CA = Corrosion allowance (in)
D3 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-3 = Shell Course Nominal Weight (lb)
W-3-corr = Shell Course Nominal Weight (lb)
h3 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 13.0 ft
JE = 1

Ma = A36
h3 = 8.0 ft
loc = 16.0 ft
t = 0.59 in

Shell Course Center of Gravity (CG-3) = 20.0 ft

D3 = ID + t
D3 = 2,160.0 + 0.59
D3 = 2,160.59 in

W-3 = pi * D3 * t * h3 * d
W-3 = pi * 2,160.59 * 0.59 * 96.0 * 0.2833
W-3 = 108,916.0929 lb

W-3-corr = pi * D3 * (t - CA) * h3 * d
W-3-corr = pi * 2,160.59 * (0.59 - 0) * 96.0 * 0.2833
W-3-corr = 108,916.0929 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 13.0
hp = 13.0 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0828 * 13.0 * 1) / (1 * 15,000)) + 0
td = 0.4058 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 13.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0828 * 29 * ((13.0 / 29) - (0.5 * ((13.0 / 29)^2))) * TANH((0.866 * (180.0828 / 29)))
Ni = 4,189.3685 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0598 * 1 * (180.0828^2) * COSH(((3.68 * (29 - 13.0)) / 180.0828))) / COSH(((3.68 * 29) / 180.0828))
Nc = 1,695.9862 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (13.0 - 0) * 180.0828 * 1
Nh = 6,086.7998 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (6,086.7998 + SQRT(((4,189.3685^2) + (1,695.9862^2) + (((0.1674 * 6,086.7998) / 2.5)^2)))) / MAX((0.59 - 0) , 0.0001)
S_T+ = 18,008.107 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (6,086.7998 - SQRT(((4,189.3685^2) + (1,695.9862^2) + (((0.1674 * 6,086.7998) / 2.5)^2)))) / MAX((0.59 - 0) , 0.0001)
S_T- = 2,625.1126 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((18,008.107 * (0.59 - 0)) / 19,950.0) + 0
ts = 0.5326 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.4058 , 0.5326)
t-min = 0.5326 in

Course # 4 Design
CA = Corrosion allowance (in)
D4 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-4 = Shell Course Nominal Weight (lb)
W-4-corr = Shell Course Nominal Weight (lb)
h4 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 5.0 ft
JE = 1
Ma = A36
h4 = 8.0 ft
loc = 24.0 ft
t = 0.4 in

Shell Course Center of Gravity (CG-4) = 28.0 ft

D4 = ID + t

D4 = 2,160.0 + 0.4
D4 = 2,160.4 in

W-4 = pi * D4 * t * h4 * d
W-4 = pi * 2,160.4 * 0.4 * 96.0 * 0.2833
W-4 = 73,834.9254 lb

W-4-corr = pi * D4 * (t - CA) * h4 * d
W-4-corr = pi * 2,160.4 * (0.4 - 0) * 96.0 * 0.2833
W-4-corr = 73,834.9254 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 5.0
hp = 5.0 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0828 * 5.0 * 1) / (1 * 15,000)) + 0
td = 0.1561 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 5.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0828 * 29 * ((5.0 / 29) - (0.5 * ((5.0 / 29)^2))) * TANH((0.866 * (180.0828 / 29)))
Ni = 1,897.7481 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0598 * 1 * (180.0828^2) * COSH(((3.68 * (29 - 5.0)) / 180.0828))) / COSH(((3.68 * 29) / 180.0828))
Nc = 1,806.6458 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (5.0 - 0) * 180.0828 * 1
Nh = 2,341.0768 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (2,341.0768 + SQRT(((1,897.7481^2) + (1,806.6458^2) + (((0.1674 * 2,341.0768) / 2.5)^2)))) /

MAX((0.4 - 0) , 0.0001)
S_T+ = 12,414.8898 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (2,341.0768 - SQRT(((1,897.7481^2) + (1,806.6458^2) + (((0.1674 * 2,341.0768) / 2.5)^2)))) /
MAX((0.4 - 0) , 0.0001)
S_T- = -709.5057 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((12,414.8898 * (0.4 - 0)) / 19,950.0) + 0
ts = 0.2489 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.1561 , 0.2489)
t-min = 0.3125 in

Course # 5 Design
CA = Corrosion allowance (in)
D5 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-5 = Shell Course Nominal Weight (lb)
W-5-corr = Shell Course Nominal Weight (lb)
h5 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = -3.0 ft
JE = 1
Ma = A36
h5 = 8.5 ft
loc = 32.0 ft
t = 0.35 in

Shell Course Center of Gravity (CG-5) = 36.25 ft

D5 = ID + t
D5 = 2,160.0 + 0.35
D5 = 2,160.35 in

W-5 = pi * D5 * t * h5 * d
W-5 = pi * 2,160.35 * 0.35 * 102.0 * 0.2833
W-5 = 68,641.8185 lb

W-5-corr = pi * D5 * (t - CA) * h5 * d
W-5-corr = pi * 2,160.35 * (0.35 - 0) * 102.0 * 0.2833

W-5-corr = 68,641.8185 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = -3.0
hp = -3.0 ft

Design liquid level is below the design point under consideration

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.0828 * -3.0 * 1) / (1 * 15,000)) + 0
td = -0.0936 (Set to 0 in since it cannot be less than 0)

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = -3.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.0828 * 29 * ((-3.0 / 29) - (0.5 * ((-3.0 / 29)^2))) * TANH((0.866 * (180.0828 / 29)))
Ni = -1,310.5204 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0598 * 1 * (180.0828^2) * COSH(((3.68 * (29 - -3.0)) / 180.0828))) / COSH(((3.68 * 29) / 180.0828))
Nc = 1,965.6971 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (-3.0 - 0) * 180.0828 * 1
Nh = -1,404.6461 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (-1,404.6461 + SQRT(((-1,310.5204^2) + (1,965.6971^2) + (((0.1674 * -1,404.6461) / 2.5)^2)))) / MAX((0.35 - 0) , 0.0001)
S_T+ = 2,742.0863 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (-1,404.6461 - SQRT(((-1,310.5204^2) + (1,965.6971^2) + (((0.1674 * -1,404.6461) / 2.5)^2)))) / MAX((0.35 - 0) , 0.0001)

S_T- = -10,768.6354 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((2,742.0863 * (0.35 - 0)) / 19,950.0) + 0
ts = 0.0481 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0 , 0.0481)
t-min = 0.3125 in

W-ins = ts-ins * ds-ins * pi * (OD + ts-ins) * Hs
W-ins = 0.0 * 8 * pi * (180.1657 + 0.0) * 40.5
W-ins = 0.0 lbf

W-shell-corr = W-1-corr + W-2-corr + W-3-corr + W-4-corr + W-5-corr
W-shell-corr = 183,530.2371 + 145,850.302 + 108,916.0929 + 73,834.9254 + 68,641.8185
W-shell-corr = 580,773.3759 lb

W-shell = W-1 + W-2 + W-3 + W-4 + W-5
W-shell = 183,530.2371 + 145,850.302 + 108,916.0929 + 73,834.9254 + 68,641.8185
W-shell = 580,773.3759 lb

CG-shell = ((CG-1 * W-1) + (CG-2 * W-2) + (CG-3 * W-3) + (CG-4 * W-4) + (CG-5 * W-5)) / W-shell
CG-shell = ((4.0 * 183,530.2371) + (12.0 * 145,850.302) + (20.0 * 108,916.0929) + (28.0 * 73,834.9254) + (36.25 * 68,641.8185)) / 580,773.3759
CG-shell = 15.8724 ft

Shell Design Summary

Course	Height (ft)	Material	CA (in)	JE	Sy (psi)	Sut (psi)	Sd (psi)	St (psi)	t-erec (in)
5	8.5	A36	0	1	36,000	58,000	15,000	15,000	0.3125
4	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
3	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
2	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
1	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125

Shell Design Summary (continued)

Course	t-design (in)	t-test (in)	t-seismic (in)	t-ext (in)	t-min (in)	t-installed (in)	Status	H-max-@-Pi (ft)	Pi-max-@-H (psi)
5	0	N/A	0.0481	N/A	0.3125	0.35	PASS	44.2128	6.595
4	0.1561	N/A	0.2489	N/A	0.3125	0.4	PASS	37.8146	3.8213
3	0.4058	N/A	0.5326	N/A	0.5326	0.59	PASS	35.9016	2.9919
2	0.6555	N/A	0.7854	N/A	0.7854	0.79	PASS	34.3089	2.3015
1	0.9052	N/A	0.9964	N/A	0.9964	0.994	FAIL	32.8443	1.6666

Intermediate Stiffeners Design

Stiffeners Design For Wind Loading

D = Nominal Tank Diameter (ft)
N = Actual Wind Girders Quantity
Ns = Required Number of Girders per API 650 5.9.6.3 and 5.9.6.4
V = Wind velocity (mile/hr)
h = Maximum Unstiffened Transformed Shell Height per AWWA-D100-11 3.5.2 (ft)
ts_min = Thickness of the Thinnest Shell Course

D = 180.0828 ft
N = 0
V = 5.0 mile/hr

Shell Courses Heights (W) = [8.0 8.0 8.0 8.0 8.5] ft

ts_min = MIN(ts_1 , ts_2 , ts_3 , ts_4 , ts_5)
ts_min = MIN(0.994 , 0.79 , 0.59 , 0.4 , 0.35)
ts_min = 0.35

Stiffeners Required Quantity

HTS = Height of Transformed Shell per API 650 5.9.6.2 (ft)

Transformed shell courses heights

Variable	Equation	Value	Unit
Wtr_1	W_1 * SQRT(((ts_min / ts_1)^5))	0.5886	ft
Wtr_2	W_2 * SQRT(((ts_min / ts_2)^5))	1.0452	ft
Wtr_3	W_3 * SQRT(((ts_min / ts_3)^5))	2.1684	ft
Wtr_4	W_4 * SQRT(((ts_min / ts_4)^5))	5.7294	ft
Wtr_5	W_5 * SQRT(((ts_min / ts_5)^5))	8.5000	ft

HTS = Wtr_1 + Wtr_2 + Wtr_3 + Wtr_4 + Wtr_5
HTS = 0.5886 + 1.0452 + 2.1684 + 5.7294 + 8.5
HTS = 18.0315 ft

h = (10.625 * (10^6) * ts_min) / (PWS * ((D / ts_min)^1.5))
h = (10.625 * (10^6) * 0.35) / (18.0 * ((180.0828 / 0.35)^1.5))
h = 17.7018 ft

Ns = CEILING(((HTS / h) - 1))
Ns = CEILING(((18.0315 / 17.7018) - 1))
Ns = 1

N < Ns ==> FAIL

***** WARNING *** :** Number of intermediate stiffeners, 0, is less than the required number of 1

Option 2
Seismic and Shell Analysis

Seismic Design Calculations

Site Ground Motion Design

Ac = Compute Impulsive Design Response Spectrum Acceleration Coefficient per AWWA D100-11 13.2.9.2
Af = Compute Acceleration Coefficient for Sloshing Wave Height per AWWA D100-11 13.5.4.4
Ai = Compute Impulsive Design Response Spectrum Acceleration Coefficient per AWWA D100-11 13.2.9.2
Anchorage_System = Anchorage System
Av = Vertical Ground Acceleration Coefficient per AWWA D100-11 13.5.4.1 and 13.5.4.3
D = Nominal Tank Diameter (ft)
Fa = Site Acceleration Coefficient
Fv = Site Velocity Coefficient
I = Importance Factor
K = Spectral Acceleration Adjustment Coefficient
Lmax = Maximum Design Product Level (ft)
Rwc = Convective Force Reduction Factor
Rwi = Impulsive Force Reduction Factor
S1 = Spectral Response Acceleration at a Period of One Second
SD1 = Compute Design Spectral Response Acceleration at a Period of One Second per AWWA D100-11 13.2.7.3
SDS = Compute Design Spectral Response Acceleration at Short Period per AWWA D100-11 13.2.7.3
SM1 = Compute Maximum Considered Earthquake Spectral Response Acceleration at a Period of One Second per AWWA D100-11 13.2.7.2
SMS = Compute Maximum Considered Earthquake Spectral Response Acceleration at Short Period per AWWA D100-11 13.2.7.2
SUG = Seismic Use Group
Sac = Compute Convective Design Response Spectrum Acceleration Coefficient For Convective Components per AWWA D100-11 13.2.7.3.2
Sai =
Seismic_Site_Class = Seismic Site Class
Ss = Spectral Response Acceleration Short Period
TL = Regional Dependent Transistion Period for Longer Period Ground Motion (sec)
Tc = Compute Convective Natural Period per AWWA D100-11 13.5.1 (sec)
Ti = Structure Natural Period (sec)
U = Scaling Factor
d_ratio = Dampening Ratio
g = Acceleration Due To Gravity (ft/sec^2)
structure_type = Structure Type

Anchorage_System = SELF-ANCHORED
D = 180.1142 ft
Fa = 1.0
Fv = 1.5
I = 1.5
K = 1.5
Lmax = 35 ft
Rwc = 1.5
Rwi = 2.5
S1 = 0.593
SUG = SEISMIC-USE-GROUP-III
Seismic_Site_Class = SEISMIC-SITE-CLASS-D
Ss = 1.794
TL = 12 sec

Ti = 0 sec
U = 0.6667
d_ratio = 0.05
g = 32.17 ft/sec^2
structure_type = GROUND-SUPPORTED-FLAT-BOTTOM-TANK

Tc = 2 * pi * SQRT((D / (3.68 * g * TANH(((3.68 * Lmax) / D)))))
Tc = 2 * pi * SQRT((180.1142 / (3.68 * 32.17 * TANH(((3.68 * 35) / 180.1142)))))
Tc = 9.8916 sec

SMS = Fa * Ss
SMS = 1.0 * 1.794
SMS = 1.794

SM1 = Fv * S1
SM1 = 1.5 * 0.593
SM1 = 0.8895

SDS = U * SMS
SDS = 0.6667 * 1.794
SDS = 1.196

SD1 = U * SM1
SD1 = 0.6667 * 0.8895
SD1 = 0.593

Sai = SDS
Sai = 1.196
Sai = 1.196

Sac = MIN(((K * SD1) / Tc) , SDS)
Sac = MIN(((1.5 * 0.593) / 9.8916) , 1.196)
Sac = 0.0899

Ai = MAX(((Sai * I) / (1.4 * Rwi)) , ((0.36 * S1 * I) / Rwi))
Ai = MAX(((1.196 * 1.5) / (1.4 * 2.5)) , ((0.36 * 0.593 * 1.5) / 2.5))
Ai = 0.5126

Ac = (Sac * I) / (1.4 * Rwc)
Ac = (0.0899 * 1.5) / (1.4 * 1.5)
Ac = 0.0642

Av = 0.14 * SDS
Av = 0.14 * 1.196
Av = 0.1674

Af = (K * SD1) / Tc
Af = (1.5 * 0.593) / 9.8916
Af = 0.0899

Seismic Design

A = Roof Surface Area (ft^2)
Ac = Convective Design Response Spectrum Acceleration Coefficient
Af = Acceleration Coefficient for Sloshing Wave Height
Ah-rs = Roof Horizontal Projected Area Supported by The Shell (ft^2)

Ai = Impulsive Design Response Spectrum Acceleration Coefficient
Anchorage_System = Anchorage System
Arss = Roof Area Supported by The Shell (ft^2)
Av = Vertical Ground Acceleration Coefficient
CA = Bottom Corrosion Allowance (in)
D = Nominal Tank Diameter (ft)
DELTA_Cc = Compute Pressure Stabilizing Buckling Coefficient per AWWA D100-11 13.5.4.2.4
DELTA_SIGMAcr = Compute Self Anchored Tank Critical Buckling Stress Increase Caused By Pressure Equation per AWWA D100-11 13.5.4.2.4 (lb/in^2)
Fa = Site Acceleration Coefficient
Freeboard = Actual Freeboard (ft)
Fv = Site Velocity Coefficient
Hs = Shell height (ft)
Hs = Shell Total Height (ft)
I = Importance Factor
J = Compute Anchorage Ratio per AWWA D100-11 13.5.4.1
K = Spectral Acceleration Adjustment Coefficient
Lmax = Maximum Design Product Level (ft)
Ls = Actual Annular Ring Width (ft)
Ma = Material Name
Mmf = Compute Overturning Moment per AWWA D100-11 13.5.2.1 (ft.lb)
Ms = Compute Overturning Moment per AWWA D100-11 13.5.2.1 (ft.lb)
P = Design Pressure (lbf/in^2)
R = (ft)
S1 = Spectral Response Acceleration at a Period of One Second
SD1 = Design Spectral Response Acceleration at a Period of 1 Second
SDS = Design Spectral Response Acceleration at Short Period
SG = Specific Gravity
SIGMAc_self_anchored = Compute Self Anchored Maximum Longitudinal Shell Compression Stress per AWWA D100-11 13.5.4.2.1 (lbf/in^2)
SIGMAe_self_anchored = Compute Seismic Allowable Longitudinal Compressive Stress per AWWA D100-11 13.5.4.2.4 (lb/in^2)
SUG = Seismic Use Group
Seismic_Site_Class = Seismic Site Class
Ss = Spectral Response Acceleration Short Period
TL = Regional Dependent Transistion Period for Longer Period Ground Motion (sec)
Tc = Convective Natural Period (sec)
U = Scaling Factor
V_allow = Compute Self Anchored Sliding Resistance Base Shear per AWWA D100-11 13.5.4.6 (lbf)
Vf = Compute Total Design Base Shear per AWWA D100-11 13.5.3.1 (lbf)
Wc = Compute Convective Effective Weight per AWWA D100-11 13.5.2.2.1 (lbf)
Wf = Tank Bottom Total Weight (lbf)
Wi = Compute Impulsive Effective Weight per AWWA D100-11 13.5.2.2.1 (lbf)
Wp = Tank Contents Total Weight (lbf)
Wr = Total Weight of Fixed Tank Roof including Framing, Knuckles, any Permanent Attachments and 10 % of the Roof Balanced Design Snow Load (lbf)
Wrs = Roof Load Acting on The Tank Shell Including 10 % of the Roof Balanced Design Snow Load (lbf)
Ws = Total Weight of Tank Shell and Appurtenances (lbf)
Wss = Roof Structure Weight Supported by The Tank Shell (lb)
Xc = Height from tank shell bottom to the center of action of convective lateral force for computing ringwall overturning moment per AWWA D100-11 13.5.2.2.2 (ft)
Xcmf = Height from tank shell bottom to the center of action of convective lateral force for computing slab overturning moment per AWWA D100-11 13.5.3.2.2 (ft)
Xi = Height from tank shell bottom to the center of action of impulsive lateral force for computing ringwall overturning moment per AWWA D100-11 13.5.2.2.2 (ft)
Ximf = Height from tank shell bottom to the center of action of impulsive lateral force for computing slab

overturning moment per AWWA D100-11 13.5.3.2.2 (ft)
Xs = Height from tank shell bottom to shell's center of gravity (ft)
ca1 = Bottom Shell Course Corrosion Allowance (in)
ca_annulus = Bottom Annular Ring Design Corrosion Allowance (in)
d = Sloshing Wave Height Above Product Design Height per AWWA D100-11 Section 13.5.4.4 (ft)
g = Acceleration Due To Gravity (ft/sec^2)
lw = Lap of the Bottom Plates Over the Annular Plate (in)
outside_projection = Bottom Outside Projection (in)
site_ground_motion_input_mode = Site Ground Motion Input Mode
t_bottom = Bottom Plate Thickness (in)
tb = Bottom Annular Ring Design Thickness (in)
tb_less_ca = Bottom Annular Ring Design Thickness Without Corrosion Allowance (in)
tb_limited_less_ca = (in)
ts1 = Bottom Shell Course Thickness (in)
ts_less_ca = Bottom Shell Course Thickness Without Corrosion Allowance (in)
using_annular_ring = Using Annular Ring
wL = Compute Self Anchored Force Resisting Uplift per AWWA D100-11 13.5.4.1.1 (lbf/ft)
wrs = Specified Tank Roof Load Acting on Tank Shell (lbf/ft)
wt = Compute Tank and Roof Weight Acting at base of Shell per AWWA D100-11 13.5.4.2.1 (lbf/ft)

A = 25,554.4252 ft^2
Ac = 0.0642
Af = 0.0899
Ah-rs = 8,634.9045 ft^2
Ai = 0.5126
Anchorage_System = SELF-ANCHORED
Arss = 8,651.7531 ft^2
Av = 0.1674
CA = 0 in
D = 180.1142 ft
Fa = 1.0
Fv = 1.5
Hs = 48 ft
Hs = 48 ft
I = 1.5
K = 1.5
Lmax = 35 ft
Ls = 2.0942 ft
Ma = A537-2
P = 0.0 lbf/in^2
S1 = 0.593
SD1 = 0.593
SDS = 1.196
SG = 1
SUG = SEISMIC-USE-GROUP-III
Seismic_Site_Class = SEISMIC-SITE-CLASS-D
Ss = 1.794
TL = 12 sec
Tc = 9.8916 sec
U = 0.6667
Wp = 55,600,879.5774 lbf
Wss = 24,091.3622 lb
Xs = 17.6995 ft
ca1 = 0 in
ca_annulus = 0 in
g = 32.17 ft/sec^2

lw = 1.5 in
outside_projection = 2 in
site_ground_motion_input_mode = ASCE7-MAPPED-SS-AND-S1
t_bottom = 0.25 in
tb = 0.25 in
ts1 = 1.37 in
using_annular_ring = t

Wf = Wb-pl
Wf = 259,857.169
Wf = 259,857.169 lbf

Wr = (Wr-pl + Wr-attachments + W-struct + Wr-DL-add) + (0.1 * Sb * Ah)
Wr = (195,468.3541 + 0.0 + 157,760.6059 + 0.0) + (0.1 * 0.0 * 25,504.66)
Wr = 353,228.9599 lbf

Wrs = ((Wr-pl + Wr-attachments + Wr-DL-add) * (Arss / A)) + Wss + (0.1 * Sb * Ah-rs)
Wrs = ((195,468.3541 + 0.0 + 0.0) * (8,651.7531 / 25,554.4252)) + 24,091.3622 + (0.1 * 0.0 * 8,634.9045)
Wrs = 90,269.4867 lbf

Ws = Ws-pl + Ws-framing + Ws-attachments
Ws = 828,994.8935 + 4,057.6387 + 4.0
Ws = 833,056.5322 lbf

R = D / 2
R = 180.1142 / 2
R = 90.0571 ft

tb_less_ca = tb - ca_annulus
tb_less_ca = 0.25 - 0
tb_less_ca = 0.25 in

ts_less_ca = ts1 - ca1
ts_less_ca = 1.37 - 0
ts_less_ca = 1.37 in

tb_limited_less_ca = MIN(tb_less_ca , ts_less_ca)
tb_limited_less_ca = MIN(0.25 , 1.37)
tb_limited_less_ca = 0.25 in

Effective weight of product

Wi = (TANH((0.866 * (D / Lmax))) / (0.866 * (D / Lmax))) * Wp
Wi = (TANH((0.866 * (180.1142 / 35))) / (0.866 * (180.1142 / 35))) * 55,600,879.5774
Wi = 12,472,887.7672 lbf

Wc = 0.23 * (D / Lmax) * TANH(((3.67 * Lmax) / D)) * Wp
Wc = 0.23 * (180.1142 / 35) * TANH(((3.67 * 35) / 180.1142)) * 55,600,879.5774
Wc = 40,318,508.7383 lbf

Center of action for effective lateral forces

Xi = 0.375 * Lmax
Xi = 0.375 * 35
Xi = 13.125 ft

Xc = (1.0 - ((COSH(((3.67 * Lmax) / D)) - 1) / (((3.67 * Lmax) / D) * SINH(((3.67 * Lmax) / D))))) * Lmax

Xc = (1.0 - ((COSH(((3.67 * 35) / 180.1142)) - 1) / (((3.67 * 35) / 180.1142) * SINH(((3.67 * 35) / 180.1142))))) * 35
Xc = 18.2058 ft

Ximf = 0.375 * (1.0 + ((4 / 3) * (((0.866 * (D / Lmax)) / TANH((0.866 * (D / Lmax)))) - 1.0))) * Lmax
Ximf = 0.375 * (1.0 + ((4 / 3) * (((0.866 * (180.1142 / 35)) / TANH((0.866 * (180.1142 / 35)))) - 1.0))) * 35
Ximf = 73.6354 ft

Xcmf = (1.0 - ((COSH(((3.67 * Lmax) / D)) - 1.937) / (((3.67 * Lmax) / D) * SINH(((3.67 * Lmax) / D))))) * Lmax
Xcmf = (1.0 - ((COSH(((3.67 * 35) / 180.1142)) - 1.937) / (((3.67 * 35) / 180.1142) * SINH(((3.67 * 35) / 180.1142))))) * 35
Xcmf = 77.5293 ft

Overturning moment

Ms = SQRT((((Ai * ((Ws * Xs) + (Wr * Hs) + (Wi * Xi)))^2) + ((Ac * (Wc * Xc))^2)))
Ms = SQRT((((0.5126 * ((833,056.5322 * 17.6995) + (353,228.9599 * 48) + (12,472,887.7672 * 13.125)))^2) + ((0.0642 * (40,318,508.7383 * 18.2058))^2)))
Ms = 110,701,933.6481 ft.lb

Mmf = SQRT((((Ai * ((Ws * Xs) + (Wr * Hs) + (Wi * Ximf)))^2) + ((Ac * (Wc * Xcmf))^2)))
Mmf = SQRT((((0.5126 * ((833,056.5322 * 17.6995) + (353,228.9599 * 48) + (12,472,887.7672 * 73.6354)))^2) + ((0.0642 * (40,318,508.7383 * 77.5293))^2)))
Mmf = 526,781,705.484 ft.lb

Resistance to design loads

wL = MIN((7.9 * tb_limited_less_ca * SQRT((Fy * Lmax * SG))) , (1.28 * Lmax * D * SG))
wL = MIN((7.9 * 0.25 * SQRT((60,000.0 * 35 * 1))) , (1.28 * 35 * 180.1142 * 1))
wL = 2,862.0469 lbf/ft

wrs = Wrs / (pi * D)
wrs = 90,269.4867 / (pi * 180.1142)
wrs = 159.5303 lbf/ft

wt = (Ws / (pi * D)) + wrs
wt = (833,056.5322 / (pi * 180.1142)) + 159.5303
wt = 1,631.7639 lbf/ft

Tank Stability

J = Ms / ((D^2) * ((wt * (1 - (0.4 * Av))) + wL))
J = 110,701,933.6481 / ((180.1142^2) * ((1,631.7639 * (1 - (0.4 * 0.1674))) + 2,862.0469))
J = 0.7783

Bottom Annular Plates requirements

As per AWWA 3.10.8
Ls >= 18 ==> PASS

Shell Stresses

SIGMAc_self_anchored = ((wt * (1 + (0.4 * Av))) + ((1.273 * Ms) / (D^2))) * (1 / (12 * ts_less_ca))
SIGMAc_self_anchored = ((1,631.7639 * (1 + (0.4 * 0.1674))) + ((1.273 * 110,701,933.6481) / (180.1142^2))) * (1 / (12 * 1.37))
SIGMAc_self_anchored = 370.1343 lbf/in^2

DELTA_Cc = 0.72 * (((P / E) * ((R / ts_less_ca)^2))^0.84)
DELTA_Cc = 0.72 * (((0.0 / 28,800,000) * ((1,080.685 / 1.37)^2))^0.84)

DELTA_Cc = 0.0

DELTA_SIGMAcr = (DELTA_Cc * E * ts_less_ca) / R
DELTA_SIGMAcr = (0.0 * 28,800,000 * 1.37) / 1,080.685
DELTA_SIGMAcr = 0.0 lb/in^2

FL = Compute Allowable Local Buckling Compressive Stress per AWWA D100-11 Section 3.4.3.1.2 (lb/in^2)
Material_Class = Compute Material Class From Minimum Yield Strength per AWWA D100-11 Section 3.2 and Table 4
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = Thickness Radius Ratio Boundary Elastic Inelastic Buckling per AWWA D100-11 Sections 3.4.3.1.1 and 3.4.3.1.2

Material_Class = :material-class-2
Material_Class = :material-class-2
Material_Class = :material-class-2

Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035372
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035372
Thickness_Radius_Ratio_Boundary_Elastic_Inelastic_Buckling = 0.0035

FL = 17.5 * (10^5) * (ts_less_ca / R) * (1 + (50000 * ((ts_less_ca / R)^2)))
FL = 17.5 * (10^5) * (1.37 / 1,080.685) * (1 + (50000 * ((1.37 / 1,080.685)^2)))
FL = 2,396.7679 lb/in^2

Allowable Local Buckling Compressive Stress (FL) = 2,396.7679 lb/in^2

SIGMAe_self_anchored = 1.333 * (FL + (DELTA_SIGMAcr / 2))
SIGMAe_self_anchored = 1.333 * (2,396.7679 + (0.0 / 2))
SIGMAe_self_anchored = 3,194.8916 lb/in^2

Freeboard

d = 0.5 * D * Af
d = 0.5 * 180.1142 * 0.0899
d = 8.0961 ft [97.1536 in]

Freeboard = Hs - Lmax-operating
Freeboard = 48 - 35
Freeboard = 13 ft [156.0 in]

(SDS >= One_Third_g) AND (SUG = :seismic-use-group-iii)

[Required]
Sloshing Wave Height Above Product Design Height (d) = 8.0961 ft

Freeboard >= d ==> PASS

Sliding Resistance

Vf = SQRT((((Ai * (Ws + Wr + Wf + Wi))^2) + ((Ac * Wc)^2)))
Vf = SQRT((((0.5126 * (833,056.5322 + 353,228.9599 + 259,857.169 + 12,472,887.7672))^2) + ((0.0642 * 40,318,508.7383)^2)))
Vf = 7,589,977.9447 lbf

V_allow = TAN(30) * (Ws + Wr + Wi + Wc) * (1 - (0.4 * Av))

V_allow = TAN(30) * (833,056.5322 + 353,228.9599 + 12,472,887.7672 + 40,318,508.7383) * (1 - (0.4 * 0.1674))
V_allow = 29,077,285.8343 lbf

Vf <= V_allow

Shell Design Calculations

Ac = Convective Design Response Spectrum Acceleration Coefficient
Ai = Impulsive Design Response Spectrum Acceleration Coefficient
Av = Vertical ground acceleration coefficient description
CG-shell = Shell center of gravity (ft)
D = Tank Nominal Diameter (ft)
Hs = Shell height (ft)
Lmax = Max Liquid Level (ft)
P = Design Internal Pressure (psi)
Pv = Design External Pressure (psf)
SG = Product Design Specific Gravity
SGt = Hydrotest Specific Gravity
V = Wind velocity (mile/hr)
W-ins = Shell Insulation Weight (lbf)
W-shell = Shell Nominal Weight (lb)
W-shell-corr = Shell Corroded Weight (lb)
ds-ins = Insulation Density (lbf/ft^3)
h-min = Minimum Shell Course Height per API-650 5.6.1.2 (in)
ts-ins = Insulation Thickness (in)

Ac = 0.0642
Ai = 0.5126
Av = 0.1674
D = 180.1142 ft
Hs = 48 ft
Lmax = 35 ft
P = 0.0 psi
Pv = 0.0 psf
SG = 1
SGt = 1
V = 100.0 mile/hr
ds-ins = 8 lbf/ft^3
h-min = 96 in
ts-ins = 0 in

Course # 1 (bottom course) Design

CA = Corrosion allowance (in)
D1 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-1 = Shell Course Nominal Weight (lb)
W-1-corr = Shell Course Nominal Weight (lb)
h1 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 35 ft

JE = 1
Ma = A537-2
h1 = 8.0 ft
loc = 0 ft
t = 1.37 in

Shell Course Center of Gravity (CG-1) = 4.0 ft

D1 = ID + t
D1 = 2,160.0 + 1.37
D1 = 2,161.37 in

W-1 = pi * D1 * t * h1 * d
W-1 = pi * 2,161.37 * 1.37 * 96.0 * 0.2833
W-1 = 252,998.1623 lb

W-1-corr = pi * D1 * (t - CA) * h1 * d
W-1-corr = pi * 2,161.37 * (1.37 - 0) * 96.0 * 0.2833
W-1-corr = 252,998.1623 lb

Material Properties
Material = A537-2
Minimum Tensile Strength (Sut) = 80,000 psi
Minimum Yield Strength (Sy) = 60,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 35
hp = 35 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.1142 * 35 * 1) / (1 * 15,000)) + 0
td = 1.0927 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 35 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.1142 * 35 * ((35 / 35) - (0.5 * ((35 / 35)^2))) * TANH((0.866 * (180.1142 / 35)))
Ni = 7,268.3512 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0642 * 1 * (180.1142^2) * COSH(((3.68 * (35 - 35)) / 180.1142))) / COSH(((3.68 * 35) / 180.1142))
Nc = 1,612.0366 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (35 - 0) * 180.1142 * 1
Nh = 16,390.3892 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (16,390.3892 + SQRT(((7,268.3512^2) + (1,612.0366^2) + (((0.1674 * 16,390.3892) / 2.5)^2)))) / MAX((1.37 - 0) , 0.0001)
S_T+ = 17,456.8024 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (16,390.3892 - SQRT(((7,268.3512^2) + (1,612.0366^2) + (((0.1674 * 16,390.3892) / 2.5)^2)))) / MAX((1.37 - 0) , 0.0001)
S_T- = 6,470.773 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 60,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((17,456.8024 * (1.37 - 0)) / 19,950.0) + 0
ts = 1.1988 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 1.0927 , 1.1988)
t-min = 1.1988 in

Course # 2 Design
CA = Corrosion allowance (in)
D2 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-2 = Shell Course Nominal Weight (lb)
W-2-corr = Shell Course Nominal Weight (lb)
h2 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 27.0 ft
JE = 1
Ma = A573-58
h2 = 8.0 ft
loc = 8.0 ft
t = 0.99 in

Shell Course Center of Gravity (CG-2) = 12.0 ft

D2 = ID + t

D2 = 2,160.0 + 0.99
D2 = 2,160.99 in

W-2 = pi * D2 * t * h2 * d
W-2 = pi * 2,160.99 * 0.99 * 96.0 * 0.2833
W-2 = 182,791.3465 lb

W-2-corr = pi * D2 * (t - CA) * h2 * d
W-2-corr = pi * 2,160.99 * (0.99 - 0) * 96.0 * 0.2833
W-2-corr = 182,791.3465 lb

Material Properties
Material = A573-58
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 32,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 27.0
hp = 27.0 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.1142 * 27.0 * 1) / (1 * 15,000)) + 0
td = 0.8429 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 27.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.1142 * 35 * ((27.0 / 35) - (0.5 * ((27.0 / 35)^2))) * TANH((0.866 * (180.1142 / 35)))
Ni = 6,888.6169 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0642 * 1 * (180.1142^2) * COSH(((3.68 * (35 - 27.0)) / 180.1142))) / COSH(((3.68 * 35) / 180.1142))
Nc = 1,633.6186 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (27.0 - 0) * 180.1142 * 1
Nh = 12,644.0145 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)

S_T+ = (12,644.0145 + SQRT(((6,888.6169^2) + (1,633.6186^2) + (((0.1674 * 12,644.0145) / 2.5)^2)))) / MAX((0.99 - 0) , 0.0001)
S_T+ = 19,973.8694 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (12,644.0145 - SQRT(((6,888.6169^2) + (1,633.6186^2) + (((0.1674 * 12,644.0145) / 2.5)^2)))) / MAX((0.99 - 0) , 0.0001)
S_T- = 5,569.5942 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 32,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((19,973.8694 * (0.99 - 0)) / 19,950.0) + 0
ts = 0.9912 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.8429 , 0.9912)
t-min = 0.9912 in

t < t-min ==> FAIL

***** WARNING *** :** Course 2 thickness, 0.99 in, is less than the required value of 0.9912 in

Course # 3 Design
CA = Corrosion allowance (in)
D3 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-3 = Shell Course Nominal Weight (lb)
W-3-corr = Shell Course Nominal Weight (lb)
h3 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 19.0 ft
JE = 1
Ma = A36
h3 = 8.0 ft
loc = 16.0 ft
t = 0.79 in

Shell Course Center of Gravity (CG-3) = 20.0 ft

D3 = ID + t
D3 = 2,160.0 + 0.79
D3 = 2,160.79 in

W-3 = pi * D3 * t * h3 * d

W-3 = pi * 2,160.79 * 0.79 * 96.0 * 0.2833
W-3 = 145,850.302 lb

W-3-corr = pi * D3 * (t - CA) * h3 * d
W-3-corr = pi * 2,160.79 * (0.79 - 0) * 96.0 * 0.2833
W-3-corr = 145,850.302 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi
Maximum Thickness (t-max) = 0.75 in

t > t-max ==> FAIL

***** WARNING *** :** Course-3, installed thickness , 0.79 in, is greater than the maximum allowable thickness of 0.75 in for A36 material

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 19.0
hp = 19.0 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.1142 * 19.0 * 1) / (1 * 15,000)) + 0
td = 0.5932 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 19.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.1142 * 35 * ((19.0 / 35) - (0.5 * ((19.0 / 35)^2))) * TANH((0.866 * (180.1142 / 35)))
Ni = 5,749.4141 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0642 * 1 * (180.1142^2) * COSH(((3.68 * (35 - 19.0)) / 180.1142))) / COSH(((3.68 * 35) / 180.1142))
Nc = 1,698.9425 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (19.0 - 0) * 180.1142 * 1
Nh = 8,897.6398 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (8,897.6398 + SQRT(((5,749.4141^2) + (1,698.9425^2) + (((0.1674 * 8,897.6398) / 2.5)^2)))) / MAX((0.79 - 0) , 0.0001)
S_T+ = 18,889.0503 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (8,897.6398 - SQRT(((5,749.4141^2) + (1,698.9425^2) + (((0.1674 * 8,897.6398) / 2.5)^2)))) / MAX((0.79 - 0) , 0.0001)
S_T- = 3,636.6202 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((18,889.0503 * (0.79 - 0)) / 19,950.0) + 0
ts = 0.748 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.5932 , 0.748)
t-min = 0.748 in

Course # 4 Design

CA = Corrosion allowance (in)
D4 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-4 = Shell Course Nominal Weight (lb)
W-4-corr = Shell Course Nominal Weight (lb)
h4 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 11.0 ft
JE = 1
Ma = A36
h4 = 8.0 ft
loc = 24.0 ft
t = 0.59 in

Shell Course Center of Gravity (CG-4) = 28.0 ft

D4 = ID + t
D4 = 2,160.0 + 0.59
D4 = 2,160.59 in

W-4 = pi * D4 * t * h4 * d
W-4 = pi * 2,160.59 * 0.59 * 96.0 * 0.2833
W-4 = 108,916.0929 lb

W-4-corr = pi * D4 * (t - CA) * h4 * d
W-4-corr = pi * 2,160.59 * (0.59 - 0) * 96.0 * 0.2833
W-4-corr = 108,916.0929 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 11.0
hp = 11.0 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.1142 * 11.0 * 1) / (1 * 15,000)) + 0
td = 0.3434 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 11.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.1142 * 35 * ((11.0 / 35) - (0.5 * ((11.0 / 35)^2))) * TANH((0.866 * (180.1142 / 35)))
Ni = 3,850.7428 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0642 * 1 * (180.1142^2) * COSH(((3.68 * (35 - 11.0)) / 180.1142))) / COSH(((3.68 * 35) / 180.1142))
Nc = 1,809.7573 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (11.0 - 0) * 180.1142 * 1
Nh = 5,151.2652 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (5,151.2652 + SQRT(((3,850.7428^2) + (1,809.7573^2) + (((0.1674 * 5,151.2652) / 2.5)^2)))) / MAX((0.59 - 0) , 0.0001)
S_T+ = 15,966.1653 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (5,151.2652 - SQRT(((3,850.7428^2) + (1,809.7573^2) + (((0.1674 * 5,151.2652) / 2.5)^2)))) /

MAX((0.59 - 0) , 0.0001)
S_T- = 1,495.7505 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((15,966.1653 * (0.59 - 0)) / 19,950.0) + 0
ts = 0.4722 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.3434 , 0.4722)
t-min = 0.4722 in

Course # 5 Design
CA = Corrosion allowance (in)
D5 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-5 = Shell Course Nominal Weight (lb)
W-5-corr = Shell Course Nominal Weight (lb)
h5 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = 3.0 ft
JE = 1
Ma = A36
h5 = 8.0 ft
loc = 32.0 ft
t = 0.4 in

Shell Course Center of Gravity (CG-5) = 36.0 ft

D5 = ID + t
D5 = 2,160.0 + 0.4
D5 = 2,160.4 in

W-5 = pi * D5 * t * h5 * d
W-5 = pi * 2,160.4 * 0.4 * 96.0 * 0.2833
W-5 = 73,834.9254 lb

W-5-corr = pi * D5 * (t - CA) * h5 * d
W-5-corr = pi * 2,160.4 * (0.4 - 0) * 96.0 * 0.2833
W-5-corr = 73,834.9254 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi

Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = 3.0
hp = 3.0 ft

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.1142 * 3.0 * 1) / (1 * 15,000)) + 0
td = 0.0937 in

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = 3.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.1142 * 35 * ((3.0 / 35) - (0.5 * ((3.0 / 35)^2))) * TANH((0.866 * (180.1142 / 35)))
Ni = 1,192.6029 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0642 * 1 * (180.1142^2) * COSH(((3.68 * (35 - 3.0)) / 180.1142))) / COSH(((3.68 * 35) / 180.1142))
Nc = 1,969.0303 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (3.0 - 0) * 180.1142 * 1
Nh = 1,404.8905 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (1,404.8905 + SQRT(((1,192.6029^2) + (1,969.0303^2) + (((0.1674 * 1,404.8905) / 2.5)^2)))) / MAX((0.4 - 0) , 0.0001)
S_T+ = 9,272.1261 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (1,404.8905 - SQRT(((1,192.6029^2) + (1,969.0303^2) + (((0.1674 * 1,404.8905) / 2.5)^2)))) / MAX((0.4 - 0) , 0.0001)
S_T- = -2,247.6736 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((9,272.1261 * (0.4 - 0)) / 19,950.0) + 0

ts = 0.1859 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0.0937 , 0.1859)
t-min = 0.3125 in

Course # 6 Design
CA = Corrosion allowance (in)
D6 = Shell Course Centerline Diameter (in)
H = Design Liquid Level (ft)
JE = Joint efficiency
Ma = Course Material
W-6 = Shell Course Nominal Weight (lb)
W-6-corr = Shell Course Nominal Weight (lb)
h6 = Course Height (ft)
hp = Effective Design Liquid Level per AWWA-D100-11 3.7 (ft)
loc = Course Location (ft)
t = Installed Thickness (in)
t-min = Minimum Required Thickness (in)
td = Course Design Thickness per AWWA-D100-11 3-40 (in)

CA = 0 in
H = -5.0 ft
JE = 1
Ma = A36
h6 = 8.0 ft
loc = 40.0 ft
t = 0.35 in

Shell Course Center of Gravity (CG-6) = 44.0 ft

D6 = ID + t
D6 = 2,160.0 + 0.35
D6 = 2,160.35 in

W-6 = pi * D6 * t * h6 * d
W-6 = pi * 2,160.35 * 0.35 * 96.0 * 0.2833
W-6 = 64,604.0645 lb

W-6-corr = pi * D6 * (t - CA) * h6 * d
W-6-corr = pi * 2,160.35 * (0.35 - 0) * 96.0 * 0.2833
W-6-corr = 64,604.0645 lb

Material Properties
Material = A36
Minimum Tensile Strength (Sut) = 58,000 psi
Minimum Yield Strength (Sy) = 36,000 psi
Allowable Design Stress (Sd) = 15,000 psi

Thickness Required by Erection
As per AWWA-D100-11 3.10.3 and Table 16, Thickness Required by Erection (t-erec) = 0.3125 in

Thickness Required by Design
hp = H
hp = -5.0

hp = -5.0 ft

Design liquid level is below the design point under consideration

td = ((2.6 * D * hp * SG) / (JE * Sd)) + CA
td = ((2.6 * 180.1142 * -5.0 * 1) / (1 * 15,000)) + 0
td = -0.1561 (Set to 0 in since it cannot be less than 0)

Seismic Design Required Thickness
Nc = Convective Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Nh = Product Hydrostatic Membrane Force per API 650 Section E.6.1.4 and Section 5.6.3.2 (lbf/in)
Ni = Impulsive Hoop Membrane Unit Force per API 650 Section E.6.1.4 (lbf/in)
Sd-seismic = Maximum Allowable Hoop Tension Membrane Stress per API-650 E.6.2.4 (psi)
ts = Seismic Minimum Thickness per API 650 Section E.6.2.4 (in)

As per API 650 Section E.6.1.4, Shell Course Liquid Surface to Analysis Point Distance (Y) = -5.0 ft

Ni = 4.5 * Ai * SG * D * Lmax * ((Y / Lmax) - (0.5 * ((Y / Lmax)^2))) * TANH((0.866 * (D / Lmax)))
Ni = 4.5 * 0.5126 * 1 * 180.1142 * 35 * ((-5.0 / 35) - (0.5 * ((-5.0 / 35)^2))) * TANH((0.866 * (180.1142 / 35)))
Ni = -2,225.0055 lbf/in

Nc = (0.98 * Ac * SG * (D^2) * COSH(((3.68 * (Lmax - Y)) / D))) / COSH(((3.68 * Lmax) / D))
Nc = (0.98 * 0.0642 * 1 * (180.1142^2) * COSH(((3.68 * (35 - -5.0)) / 180.1142))) / COSH(((3.68 * 35) / 180.1142))
Nc = 2,181.0261 lbf/in

Nh = 2.6 * (Y - H_offset) * D * SG
Nh = 2.6 * (-5.0 - 0) * 180.1142 * 1
Nh = -2,341.4842 lbf/in

S_T+ = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)
S_T- = Total Combined Hoop Stress per API 650 Section E.6.1.4 (psi)

S_T+ = (Nh + SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T+ = (-2,341.4842 + SQRT(((-2,225.0055^2) + (2,181.0261^2) + (((0.1674 * -2,341.4842) / 2.5)^2)))) / MAX((0.35 - 0) , 0.0001)
S_T+ = 2,223.2805 psi

S_T- = (Nh - SQRT(((Ni^2) + (Nc^2) + (((Av * Nh) / 2.5)^2)))) / MAX((t - CA) , 0.0001)
S_T- = (-2,341.4842 - SQRT(((-2,225.0055^2) + (2,181.0261^2) + (((0.1674 * -2,341.4842) / 2.5)^2)))) / MAX((0.35 - 0) , 0.0001)
S_T- = -15,603.19 psi

Sd-seismic = MIN((1.33 * Sd) , (0.9 * Sy * JE))
Sd-seismic = MIN((1.33 * 15,000) , (0.9 * 36,000 * 1))
Sd-seismic = 19,950 psi

ts = ((S_T+ * (t - CA)) / Sd-seismic) + CA
ts = ((2,223.2805 * (0.35 - 0)) / 19,950.0) + 0
ts = 0.039 in

Minimum Required Thickness
t-min = MAX(t-erec , td , ts)
t-min = MAX(0.3125 , 0 , 0.039)
t-min = 0.3125 in

W-ins = ts-ins * ds-ins * pi * (OD + ts-ins) * Hs
W-ins = 0.0 * 8 * pi * (180.2283 + 0.0) * 48
W-ins = 0.0 lbf

W-shell-corr = W-1-corr + W-2-corr + W-3-corr + W-4-corr + W-5-corr + W-6-corr
W-shell-corr = 252,998.1623 + 182,791.3465 + 145,850.302 + 108,916.0929 + 73,834.9254 + 64,604.0645
W-shell-corr = 828,994.8935 lb

W-shell = W-1 + W-2 + W-3 + W-4 + W-5 + W-6
W-shell = 252,998.1623 + 182,791.3465 + 145,850.302 + 108,916.0929 + 73,834.9254 + 64,604.0645
W-shell = 828,994.8935 lb

CG-shell = ((CG-1 * W-1) + (CG-2 * W-2) + (CG-3 * W-3) + (CG-4 * W-4) + (CG-5 * W-5) + (CG-6 * W-6)) / W-shell
CG-shell = ((4.0 * 252,998.1623) + (12.0 * 182,791.3465) + (20.0 * 145,850.302) + (28.0 * 108,916.0929) + (36.0 * 73,834.9254) + (44.0 * 64,604.0645)) / 828,994.8935
CG-shell = 17.6995 ft

Shell Design Summary

Course	Height (ft)	Material	CA (in)	JE	Sy (psi)	Sut (psi)	Sd (psi)	St (psi)	t-erec (in)
6	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
5	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
4	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
3	8.0	A36	0	1	36,000	58,000	15,000	15,000	0.3125
2	8.0	A573-58	0	1	32,000	58,000	15,000	15,000	0.3125
1	8.0	A537-2	0	1	60,000	80,000	15,000	15,000	0.3125

Shell Design Summary (continued)

Course	t-design (in)	t-test (in)	t-seismic (in)	t-ext (in)	t-min (in)	t-installed (in)	Status	H-max-@-Pi (ft)	Pi-max-@-H (psi)
6	0	N/A	0.039	N/A	0.3125	0.35	PASS	52.2108	7.4612
5	0.0937	N/A	0.1859	N/A	0.3125	0.4	PASS	45.8124	4.6873
4	0.3434	N/A	0.4722	N/A	0.4722	0.59	PASS	43.8983	3.8575
3	0.5932	N/A	0.748	N/A	0.748	0.79	PASS	42.3045	3.1666
2	0.8429	N/A	0.9912	N/A	0.9912	0.99	FAIL	40.7107	2.4757
1	1.0927	N/A	1.1988	N/A	1.1988	1.37	PASS	44.8824	4.2842

Intermediate Stiffeners Design

Stiffeners Design For Wind Loading

D = Nominal Tank Diameter (ft)
N = Actual Wind Girders Quantity
Ns = Required Number of Girders per API 650 5.9.6.3 and 5.9.6.4
V = Wind velocity (mile/hr)
h = Maximum Unstiffened Transformed Shell Height per AWWA-D100-11 3.5.2 (ft)
ts_min = Thickness of the Thinnest Shell Course

D = 180.1142 ft
N = 0
V = 100.0 mile/hr

Shell Courses Heights (W) = [8.0 8.0 8.0 8.0 8.0 8.0] ft

ts_min = MIN(ts_corr_1 , ts_corr_2 , ts_corr_3 , ts_corr_4 , ts_corr_5 , ts_corr_6)
ts_min = MIN(1.37 , 0.99 , 0.79 , 0.59 , 0.4 , 0.35)
ts_min = 0.35

Stiffeners Required Quantity

HTS = Height of Transformed Shell per API 650 5.9.6.2 (ft)

Transformed shell courses heights

Variable	Equation	Value	Unit
Wtr_1	W_1 * SQRT(((ts_min / ts_corr_1)^5))	0.2639	ft
Wtr_2	W_2 * SQRT(((ts_min / ts_corr_2)^5))	0.5945	ft
Wtr_3	W_3 * SQRT(((ts_min / ts_corr_3)^5))	1.0452	ft
Wtr_4	W_4 * SQRT(((ts_min / ts_corr_4)^5))	2.1684	ft
Wtr_5	W_5 * SQRT(((ts_min / ts_corr_5)^5))	5.7294	ft
Wtr_6	W_6 * SQRT(((ts_min / ts_corr_6)^5))	8.0000	ft

HTS = Wtr_1 + Wtr_2 + Wtr_3 + Wtr_4 + Wtr_5 + Wtr_6
HTS = 0.2639 + 0.5945 + 1.0452 + 2.1684 + 5.7294 + 8.0
HTS = 17.8014 ft

h = (10.625 * (10^6) * ts_min) / (PWS * ((D / ts_min)^1.5))
h = (10.625 * (10^6) * 0.35) / (18.0 * ((180.1142 / 0.35)^1.5))
h = 17.6972 ft

Ns = CEILING(((HTS / h) - 1))
Ns = CEILING(((17.8014 / 17.6972) - 1))
Ns = 1

N < Ns ==> FAIL

***** WARNING *** :** Number of intermediate stiffeners, 0, is less than the required number of 1