FINAL REPORT

Crude Oil Storage Tank 8 Floor and Cathodic Protection System Design Review

Report Prepared for:

PRINCE WILLIAM SOUND
RCAC
REGIONAL CITIZENS' ADVISORY COUNCIL

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Table of Contents

ACRONYMS & ABBREVIATIONS

API – American Petroleum Institute

APSC – Alyeska Pipeline Service Company

CP – Cathodic Protection

ETF – East Tank Farm

MMO - Mixed Metal Oxide

NACE – National Association of Corrosion Engineers

PWSRCAC - Prince William Sound Regional Citizens' Advisory Council

VMT – Valdez Marine Terminal

WTF – West Tank Farm

1.0 EXECUTIVE SUMMARY

1.1 GENERAL

In October of 2021, Prince William Sound Regional Citizen's Advisory Council (PWSRCAC) tasked Taku Engineering (Taku) with reviewing documents associated with the replacement of the Tank 8 cathodic protection system and floor at the Alyeska Pipeline Service Company (APSC) Valdez Marine Terminal (VMT). The intent was to identify opportunities for reducing the risks of a leak associated with the VMT tanks.

Constructed in 1976, Tank 8 is a 250-foot diameter, 500,000-barrel, welded steel, crude oil storage tank located in the VMT's East Tank Farm (ETF). In 1995, the tank was removed from service and a new floor with a sub-floor cathodic protection (CP) system was installed. The tank was again removed from service for internal inspections in 2007 and 2019. After the 2019 out-of-service inspection, minor repairs were completed, and the tank was prepared to be coated and returned to service. An individual within APSC noted concerns with the inspection and initiated a follow-up inspection that identified more significant soil-side corrosion damage than had been discovered during the first inspection. At that point, APSC made the decision to replace the tank floor and CP system.

Problems associated with the COVID-19 pandemic prompted the decision to complete minor floor repairs in 2020, and return the tank to service until 2023, at which time Tank 8 will be removed from service and the floor and CP system will be replaced.

This study reviewed preliminary design documents for the floor and CP system replacement as well as historical operating data for the VMT tank CP systems. It has resulted in the development of a number of findings and recommendations. Detailed discussions are provided in Section 3 of this document. General findings and recommendations are discussed below:

1.2 FINDINGS

Based on our review of the Tank 8 CP system preliminary design documents provided by APSC, we have derived to following conclusions:

- The conclusions, assumptions, calculations, and designs for the bulk area of the tank floorplates are reasonable and aligned with standard industry practices.
- The new CP system design includes the use of monitoring tubes that are slotted in the region beneath the annular plate. That will allow APSC to monitor the level of cathodic protection afforded the annular plate. This is an improvement over the existing CP system.
- The CP system design intended to protect the annular plate will not effectively provide CP current to most of the annular plate. That plate will remain unprotected.
- The lack of an annular plate to ringwall seal will exacerbate the inadequacy of cathodic protection afforded the annular plate.

- The CP design calculations for the annular plate CP system do not address anode crowding. As configured, the rectifier proposed in the design does not have sufficient voltage range to overcome the increase in circuit resistance that will result from anode crowding.
- The bottom side of the sump will not be protected from soil-side corrosion with cathodic protection.
- The plate immediately beneath the columns may not receive adequate cathodic protection. Based on the design, the level of CP beneath the columns cannot be monitored.

1.3 RECOMMENDATIONS

Based on the study findings, we offer the following recommendations:

- The CP system designed for the annular plate should be modified as recommended in section 3.5 of this report, including but not limited to relocating the two outermost Anodeflex loops so that they are beneath the annular plate. This will alleviate distribution issues as well as issues caused by anode crowding.
- The annular plate to ringwall seal should be replaced and maintained.
- Anodes should be designed and installed to be mounted on the internal surfaces of the sump floor.
- The new sump should be fabricated outside of the tank and the soil-side surfaces of the assembly should be coated prior to installation.
- The designer should consider the impacts of anode crowding at the sump. Based on those calculations, they may want to modify the design proposed for the CP system around the sump to alleviate anode crowding issues.
- APSC should consider an additional corrosion allowance for the sump by fabricating the sump from thicker steel than the remainder of the floor.
- The Anodeflex rings should be run directly beneath the roof columns to ensure CP current distribution to the plate beneath the columns.
- APSC should ensure that the floorplates beneath the columns and the column pads are both fully seal welded so that the column base pads are true “doubler” plates (that may already be the case, but it is not obvious in the design drawings).

2.0 INTRODUCTION

Tank 8 at the VMT is one of the 14 crude oil storage tanks that make up the VMT's ETF. Four additional tanks are located in the West Tank Farm (WTF). However, the WTF was removed from service in the early 2000s. The general VMT layout is shown below in Figure 1.

Figure 1 - VMT Aerial Photo (photo courtesy of NOAA)

All 14 ETF tanks are 250 feet in diameter, 62 feet high, welded steel, crude storage tanks built to American Petroleum Institute (API) Standard 650. They were designed and erected by Chicago Bridge and Iron in 1976. The ETF tanks were constructed on concrete ringwalls with subsurface secondary containment liners and oiled sand bedding. The sketch in Figure 2 shows the general layout and typical components of a VMT crude storage tank.

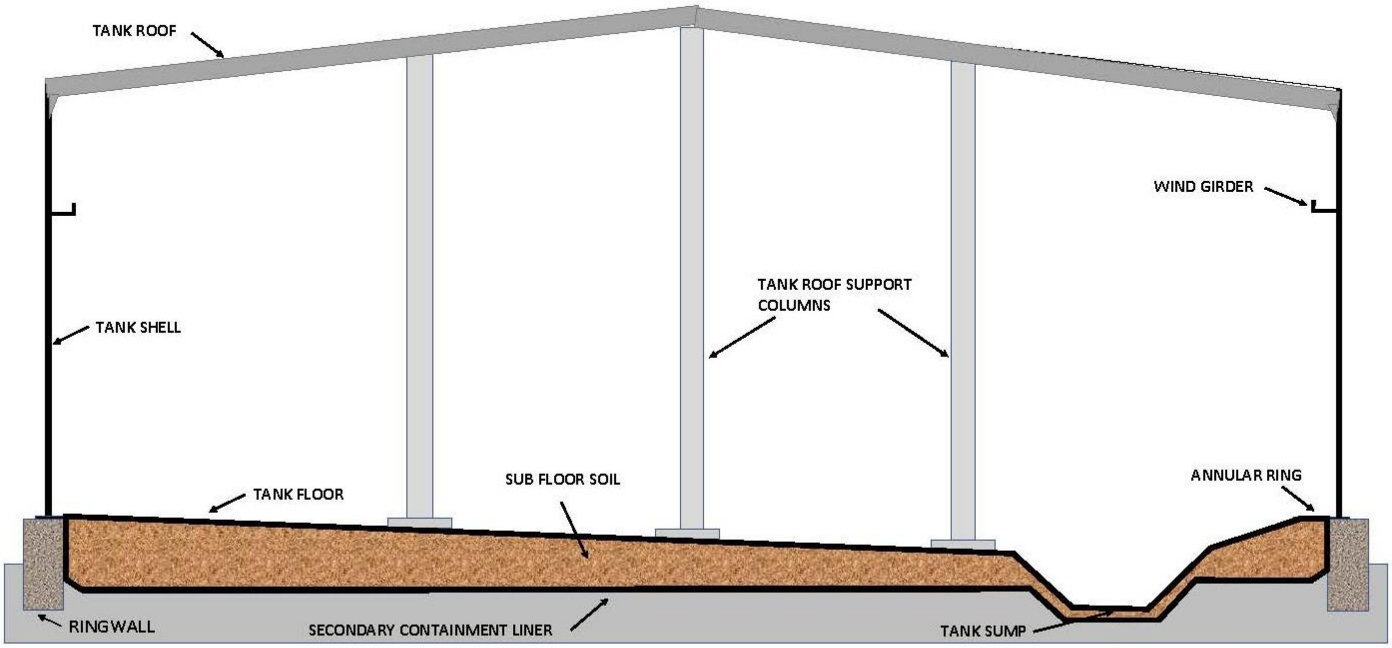

Figure 2 - Typical VMT Tank Configuration

The 1991 discovery of soil-side corrosion in the tank floors prompted APSC to systematically replace the tank floors and install sub-floor CP systems on all ETF tanks between the years 1991 and 1998. The initial CP system installed on Tank 5 in 1991 consisted of mixed metal oxide rod anodes. After the Tank 5 floor replacement, all other tanks were fitted with mixed metal oxide (MMO) grid cathodic protection systems which included monitoring tubes and/or permanent reference cells for collection of tank-to-soil potential measurements. The Tank 5 CP system was later replaced with a grid CP system in 2002.

The floorplates on Tank 8 were removed and replaced in 1995. The original oiled sand bedding was excavated and clean bedding, an MMO grid CP system, and new floorplates were installed in the tank. The existing annular (perimeter) plates remained in place.

Tank 8 was removed from service for internal inspection in 2007 and 2019. After the 2019 out-of-service inspection, minor repairs were completed on the tank floor and the tank was prepared to be coated and returned to service (Figure 3). A follow-up inspection, prompted by one of APSC's engineers, resulted in the discovery of more than 160 additional locations of corrosion that had been missed during the first inspection. At that point, the decision was made to replace the tank floor and CP system. Due to issues arising from the COVID-19 pandemic in 2020, the decision was made to complete minor repairs on Tank 8 and return it to short-term service until 2023. At that time, APSC plans to remove the tank from service and replace the tank floor and CP system.

Figure 3 - Tank 8 During 2019 Out-of-Service Inspection (photo courtesy of Austin Love/PWSRCAC)

3.0 FINDINGS, DISCUSSION, AND RECOMMENDATIONS

3.1 GENERAL

This assessment was based upon a review of the new Tank 8 CP system and floor design drawings and calculations provided by APSC. The new floor and CP system are scheduled to be installed in 2023. The design drawings were marked as “Draft.” However, the drawings were engineer stamped and signed. It is not normal for drawings that are other than issued-for-construction or final design (such as conceptual, preliminary, or draft) to be sealed and signed. Other than the “Draft” watermark, the drawings provided appear to be final design (issued-for-construction) documents.

3.2 ANNULAR PLATE CP ANODE PLACEMENT

The ground bed design for the new Tank 8 floor CP system, consists of Anodeflex rings distributed throughout the area beneath the tank floorplate. The CP design includes two separate anode flex loops intended to protect the tank’s annular plates. However, in that design, the annular ring Anodeflex loops are located beneath the floorplate, not beneath the annular plate. They are located roughly 1-foot from the inside diameter of the annular plate (see Figure 4, excerpted from drawing D-54-Z768-CP101).

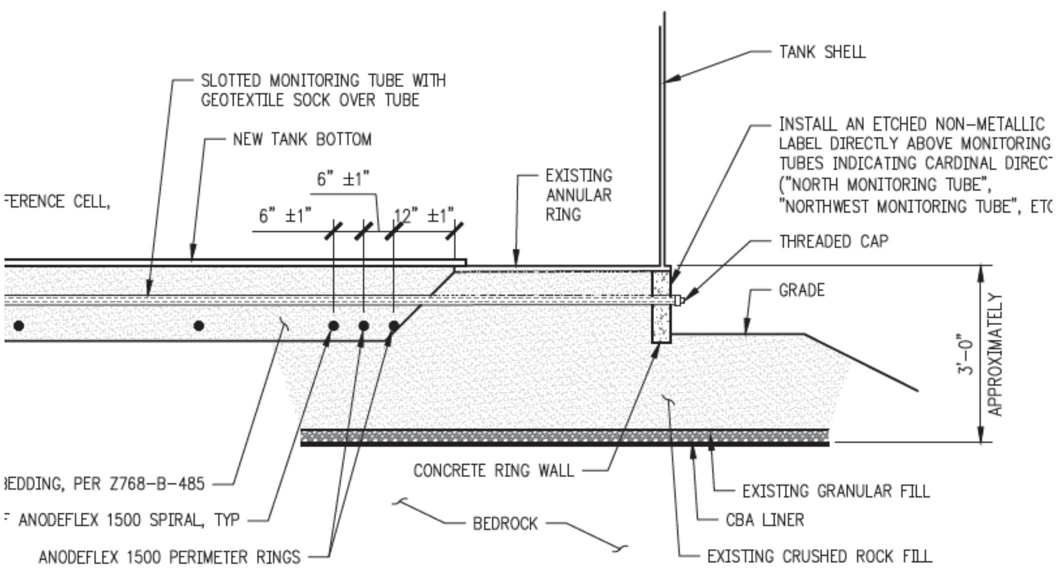

Figure 4 – Annular Ring CP Groundbed

This configuration is unlikely to protect the annular plates for the following reasons:

First, the annular plate and floorplate are welded together and therefore electrically continuous. The Anodeflex loops intended to protect the annular plates will distribute current primarily via the lowest resistance pathways. In this case, assuming similar backfill resistivity, the current will go to the closest steel, which is the regular floorplate steel, not the annular plate.

A general rule of thumb, used for designing uniform distribution of CP current for close coupled anodes, is to assume that the anode will distribute current to the steel surface in a (roughly) 120-degree arc of influence.[1] This is depicted below in Figure 5. As shown in the figure, the Anodeflex loops intended to protect the annular plate, will only impact a small section of the annular plate that is located closest to the Anodeflex (also depicted in Figure 5).

Based on this geometry, over 85% of the soil-side surface area of the annular plate is likely to remain unprotected from corrosion with the proposed cathodic protection design.

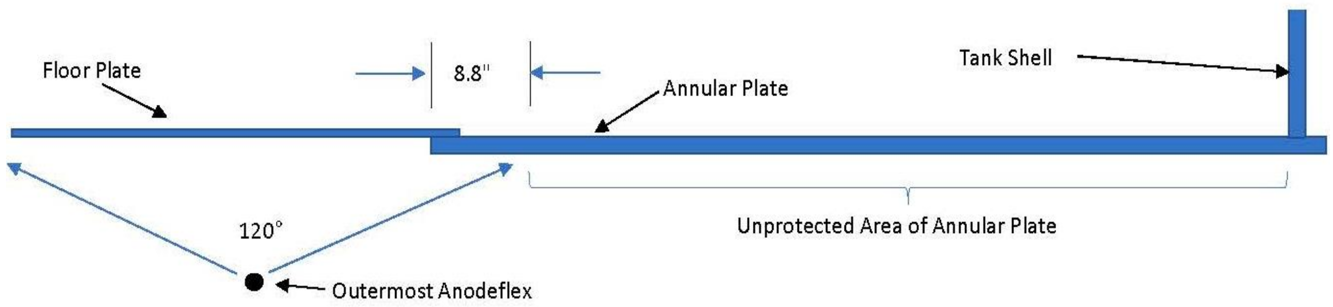

Figure 5 – Annular Plate CP Groundbed Current Distribution in Proposed Design

The two Anodeflex loops that are dedicated for the annular plate are tied to a separate circuit that can be adjusted independently of the floorplate system. It appears that APSC will attempt to protect the annular plate by using a higher driving voltage on the dedicated Anodeflex loops. This approach is very unlikely to be effective. As discussed above, the Anodeflex loops dedicated to protecting the annular plate are much closer to the floorplate than they are to the annular plate. Even with the ability to independently power the annular plate Anodeflex loops, the resulting CP current will go predominantly to the perimeter floorplate and will not measurably increase the annular plate area impacted by cathodic protection.

The CP designer appears to recognize this shortcoming in the design. Within the document "Cathodic Protection Calculations Annular Ring Circuit," Section 3.0, "Assumptions," the designer included the following statement: "Anodeflex will not be installed directly under the annular ring due to construction restraints; therefore, reduced CP current density is expected near the shell."

The lack of a ringwall to annular plate seal on Tank 8 will exacerbate the situation by allowing rainwater flowing off the tank to seep beneath the annular plate. The constant influx of oxygenated water will increase the cathodic protection current necessary to protect the annular plate, further enforcing the need to add cathodic protection to that region of the tank bottom.

[1] NACE Cathodic Protection Technologist Manual, Section 4.1.1.4, "Effects of Anode-to-Structure Spacing on Current Distribution," January 2010

3.3 ANNULAR PLATE CP CALCULATIONS AND ANODE SPACING

We conducted a review of the calculations for the preliminary design of the annular plate cathodic protection system. The area, current requirement, and assumptions seem to be reasonable and in order.

However, the preliminary annular plate CP system design includes placing the outermost three anode loops very closely spaced together (6 inches apart) as shown in Figure 6 (excerpted from drawing D-54-Z768-CP101). The two outermost rings are dedicated to protecting the annular plate. The innermost of the three rings is intended to protect the floorplate.

The CP system designer appears to have correctly calculated the annular plate anode resistance for a single isolated Anodeflex ring. However, at that point the designer divided the resistance by the number of anodes (Figure 7). The calculation note in Figure 7 suggests that that calculation negates the effect of close-coupling or crowding the anodes. That is not the case. The calculation in Figure 7 is intended for anodes that are widely spaced and not subjected to the impacts of crowding.[2] It does not account for the increase in circuit resistance that will accompany installing those anodes as closely as designed.

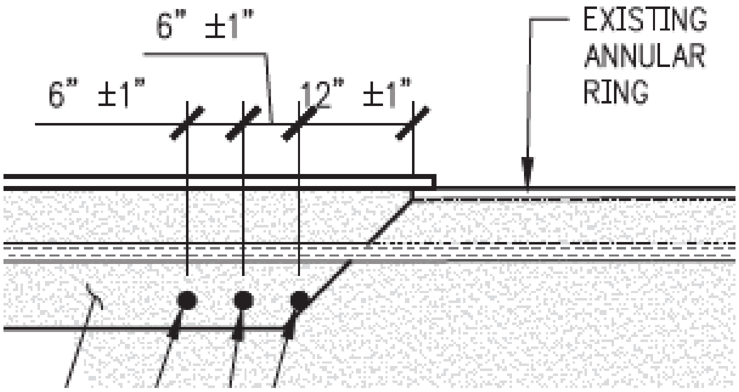

Figure 6 – Annular Ring CP Groundbed Spacing

$$R_A := \left(\frac{R_{aflx}}{N_{aflx}}\right) = 2.57$$

Total anode-to-soil resistance using parallel circuit formula, negating crowding and close-coupled effects (ohms)

Figure 7 – Annular Plate Cathodic Protection Calculations

The designer should have utilized a modified Sunde Equation to calculate the added resistance that will occur due to mutual interference between closely spaced anodes.
We have run these calculations using soil resistivities that are typical of what would be expected for clean graded fill. Based on the results of those calculations, the rectifier included in the design will not have sufficient voltage to overcome the resistance caused by the anode crowding.

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[2] NACE CP Technologist Manual, "CP Design Fundamentals" (July 2007 Revision), Section 4.4.2 p. 4-25.

3.4 REQUIREMENTS FOR CATHODIC PROTECTION ON THE ANNULAR PLATE

In prior meetings, APSC personnel have suggested that since no annular plate repairs were necessary during the inspection of Tank 8, then additional CP on the annular plate is not necessary. However, the corrosion rates reported on the annular plates were similar in magnitude to the corrosion rates on the general floorplates. CP is intended to be a proactive effort to ameliorate corrosion before significant damage occurs, not a reactive action based on damage that has already occurred. The annular plates are significantly thicker than the floorplates, which negated the need for immediate repairs. However, that does not negate the need for CP in that area. Without correcting the deficiency in CP for the annular plate, repairs in that area will eventually be necessary.

In some cases, code allows for a facility operator to forgo the application of CP to an aboveground storage tank if the owner can demonstrate that the environment beneath the floor is non-corrosive. However, in the case of Tank 8, APSC's inspections have already determined that the sub-annular plate environment is corrosive. Based on these findings, the effective application of cathodic protection to the annular plates is required in order to halt active corrosion on the structure.

3.5 RECOMMENDED ANNULAR PLATE CP SYSTEM DESIGN CHANGES

To ensure protection of the annular plate using an anode depth of 12-inches, it would be necessary to modify the design to relocate the two outermost Anodeflex loops so that they are beneath the annular plate. The outermost loop would need to be located within about 20 inches of the concrete ringwall and the second loop would need to be located within roughly 60 inches of the ringwall. See Figure 8.

This configuration would provide sufficient current and current distribution to the annular plate. It would also correct for the deficiencies associated with anode crowding. As with the proposed design, these anode rings should be designed such that the voltage and current driving them can be adjusted independently of the remainder of the soil-side CP system.

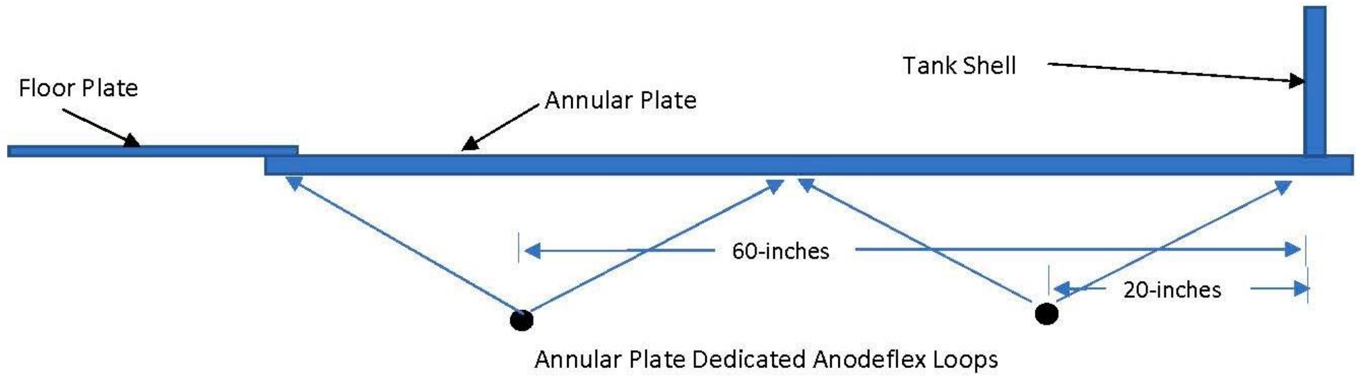

Figure 8 – Recommended Annular Plate Cathodic Protection Distribution

The challenge with this approach is that it will require that APSC excavate beneath the annular plate to install the anodes. Backfilling that area is challenging as it is not possible to compact the backfilled soils. APSC typically uses a lean slurry to backfill these types of areas to gain complete backfill of the area without having to compact the soils.

3.6 ANNULAR PLATE CP MONITORING

The existing CP system design utilized CP monitoring tubes that are slotted to allow the collection of CP readings beneath the floor. However, for some reason, the old monitoring tube design did not extend the slots to beneath the annular plate. That basically left APSC blind to the level of CP being afforded the annular plates on their crude tanks.

The new CP system design appears to correct this shortcoming. Figure 9 is an excerpt of preliminary design drawing D-54-768-CP101, showing the proposed monitoring tube. It appears that APSC intends to install slotted tubes beneath the annular plate as well as the floorplate. That will enable APSC to monitor the levels of cathodic protection on the annular plate as well as the floorplate. This represents a design improvement over the existing systems.

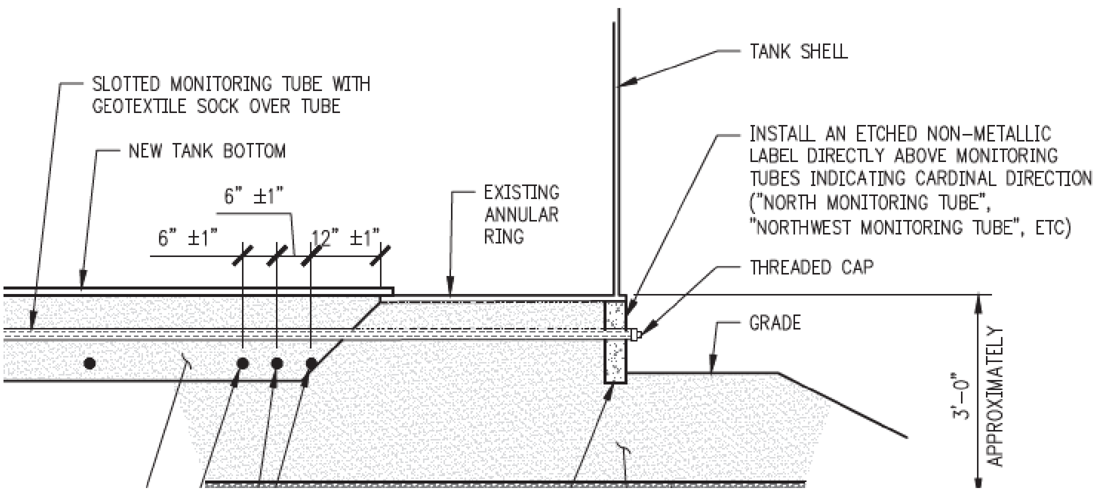

Figure 9 – CP Monitoring Tube Detail

3.7 SUMP – CP DESIGN ISSUES

Both the existing and new CP systems are not configured to protect the steel associated with the bottom of the tank sump. The sump rests within a few inches of the secondary containment liner. That close proximity precludes the installation of anodes beneath the sump. Figure 10 is an excerpt from APSC design drawing D-54-C285 Sheet 20, showing the sump location relative to the secondary containment liner (shown as “XR5 Liner” on the drawing excerpt).

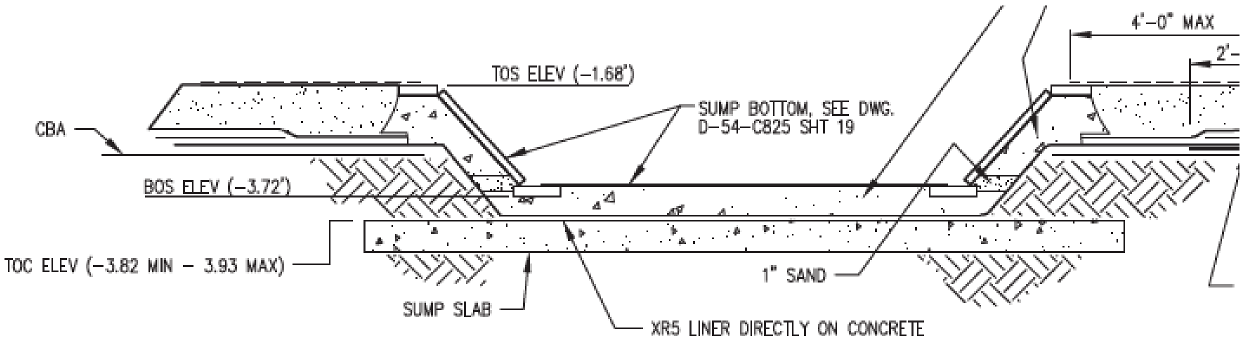

Figure 10 – Sump/Secondary Containment Liner Details

The design details provided by Alyeska and depicted in Figure 10, confirm that there is not sufficient clearance to accommodate anodes between the sump bottom and secondary containment liner. Figure 11 (an excerpt from design drawing D-54-Z768-CP102 Sheet 1) shows the routing of anode material around the sump to accommodate the lack of clearance. No anodes will be installed directly beneath the sump. Based on this configuration, the soil-side surfaces of the sump bottom will not see any benefit from the new cathodic protection system.

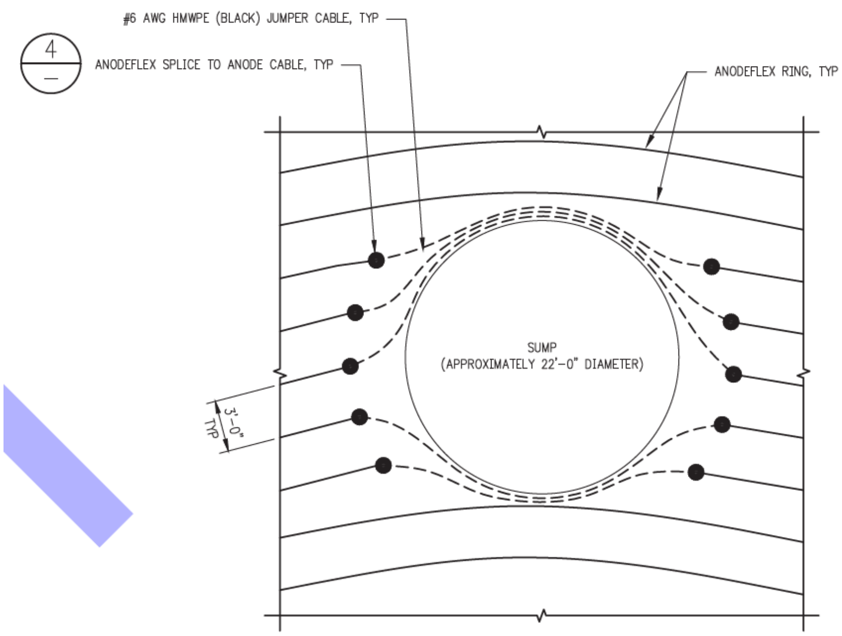

Figure 11 – Anode Distribution Around the Tank 8 Sump

Further, the secondary containment liner elevation follows the contour of the slope forming a low point beneath the sump. This means that the sump bottom will spend more time in contact with water than any other soil-side surface.

The output of the anode placed as shown in Figure 11 will also be impacted by the crowding effect of placing three or four Anodeflex rings in such close proximity (similar to the situation discussed in Section 3.3 of this report). The result will be that significantly less current will be distributed to this area.

The CP designer appears to recognize this shortcoming in the design. Within the document "Cathodic Protection Calculations Tank Bottom Circuit," Section 3.0, "Assumptions," the designer included the following statement: "Anodeflex will not be installed under the columns, sump or annular ring due to construction restraints; therefore, reduced CP current density is expected at these locations."

The sump design includes 3/8-inch plate for the sump bottom. This is the same thickness as the rest of the tank floor surfaces.

3.8 SUMP DESIGN RECOMMENDATIONS

The sump will be the component of the tank floor that sees the highest time of contact with water on both the internal and external surfaces. Internally, any water accumulation within the tank will naturally settle into the sump. It has been conveyed that APSC no longer executes water draws on the crude tanks. So, water settling out in the tanks that is not entrained in the crude stream outflow during tanker loading will remain in the sump until the tank is removed from service for the next inspection.

The soil-side surfaces of the sump are likewise located in the lowest point of the secondary containment. The sump bottom is roughly 1.2 feet below the sub-floor drainpipe. Assuming that the secondary containment is intact, soils beneath the drainpipe, including the area of the sump, will be saturated with water 100% of the time.

Based on these findings, we recommend that APSC's design be modified in the following manner:

- Anodes should be designed and installed to be mounted on the internal surfaces of the sump floor.
- The new sump should be fabricated outside of the tank and the soil-side surfaces of the assembly should be coated prior to installation.
- The designer should consider the impacts of anode crowding at the sump. Based on those calculations, they may want to modify the design proposed in Figure 11 to alleviate anode crowding issues.
- Alyeska should consider an additional corrosion allowance for the sump by fabricating the sump from thicker steel than the remainder of the floor.

3.9 COLUMNS – CP DESIGN ISSUES

Neither the existing nor new CP system designs are configured to afford full protection of the steel beneath the tank columns. The new CP system design includes routing the Anodeflex material around the soil pads beneath the columns (see Figure 12).

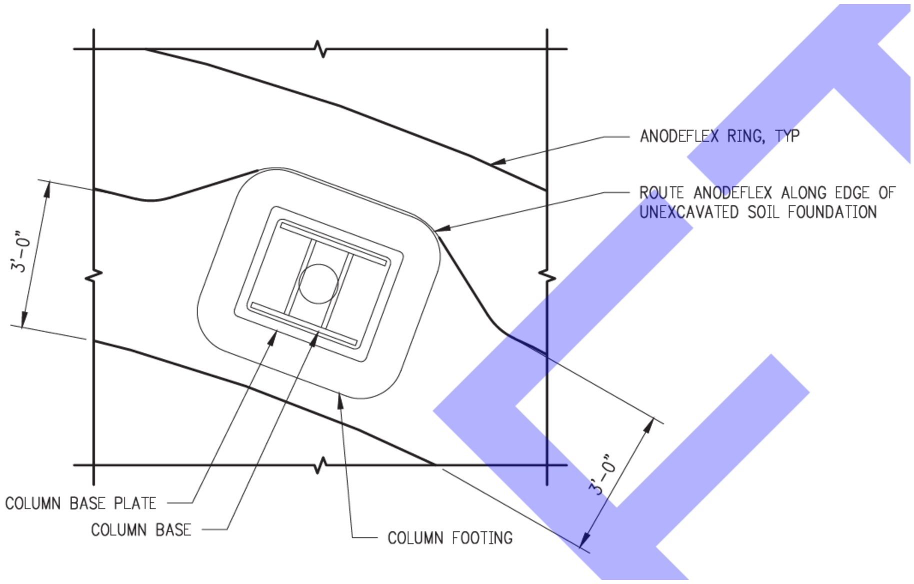

Figure 12 - Column Base Anode Routing

Figure 12, excerpted from drawing D-54-Z768-CP104, presents the best-case scenario for how far the Anodeflex rings will need to deviate to avoid column base pads. In Figure 12, the column base is aligned in parallel to the Anodeflex rings. However, as shown in Figure 13, the column bases are not all oriented the same. In some cases, the column bases may be oriented perpendicular or diagonal to the Anodeflex rings as depicted in Figure 14.

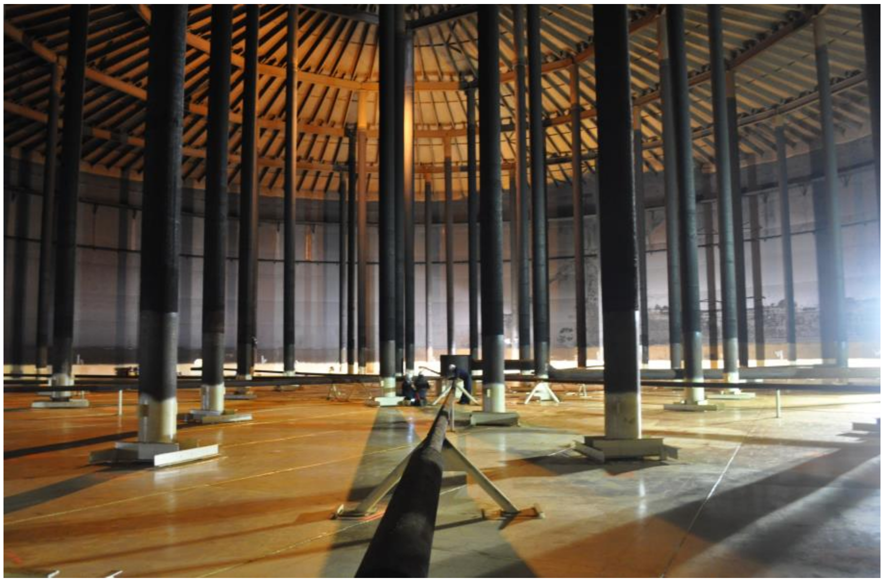

Figure 13 – Actual Column Orientation

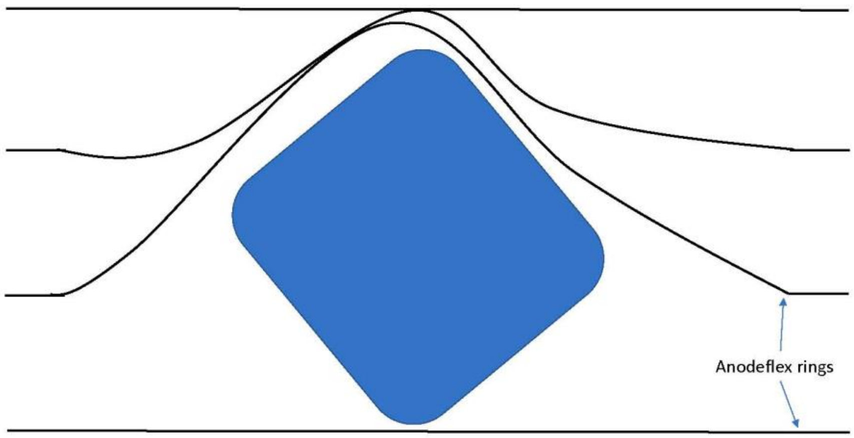

Figure 14 – Diagonal Column Base

The soil pad beneath the column base will slope down and the Anodeflex will be placed at the toe of that slope as shown in Figure 15.

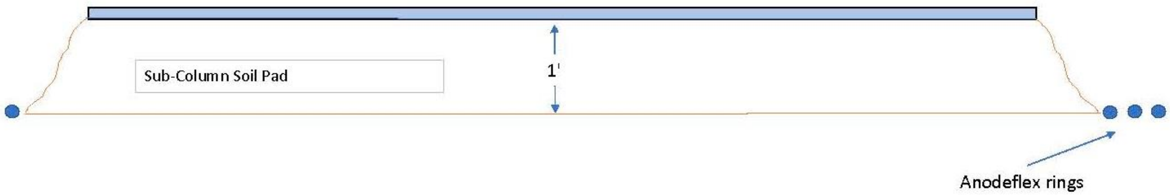

Figure 15 – Cutaway View of Column Pad

The design doesn't include dimensions of the existing column pad remnants that will be left in place or the dimensions of the column feet. Without those dimensions, we can't define the exact impact to anode spacing. However, the presence of a column base that is diagonal to the Anodeflex rings could shift the location of two or more anode rings.

This design detail could impact the CP system in two ways:

- Current from the Anodeflex rings located at the toe of the column pads will go to the area immediately above the anodes and not reach the floorplate directly beneath the columns (similar to the situation described in Section 3.2 of this report).
- Placing two or more anode rings in close proximity at the toe of the pad will create a "crowding" issue. The sections of Anodeflex rings that are too closely co-located will not provide current to that area (similar to the situation described in Section 3.3 of this report).

The CP designer appears to recognize this shortcoming in the design. Within the document "Cathodic Protection Calculations Tank Bottom Circuit," Section 3.0, "Assumptions," the designer included the following statement: "Anodeflex will not be installed under the columns, sump or annular ring due to construction restraints; therefore, reduced CP current density is expected at these locations". This crowding effect will create localized high resistance areas of the groundbed that will further reduce the CP current afforded to the soil-side surfaces of the floorplate beneath the columns.

The design also calls for the CP monitoring tubes to be routed around the columns. APSC operators will not be able to monitor the levels of CP afforded the floorplate beneath the columns.

3.10 COLUMN/CP SYSTEM DESIGN RECOMMENDATIONS

Due to tight clearance between the column bases and the floorplate, it may be difficult to complete competent welds on the floorplate seams directly beneath the columns. That area is also difficult to uniformly coat and difficult to inspect. It is important that CP currents be well distributed to that area and that effective doubler-plates (column pads) be installed.

- The design should be modified to allow installation of the Anodeflex rings beneath the columns. That would alleviate issues with anode crowding and ensure uniform current distribution.
- The design should ensure that the floorplates beneath the columns are fully seal welded prior to setting the column pads to ensure that the pads are truly doubler-plates. That may already be the intent of the design, but it was not entirely obvious in the design documents.

4.0 REFERENCES

The following documents were reviewed in the course of this study:

- APSC. 2019-2021. TK-8 CP Survey Data.
- APSC. 2019. Valdez Marine Terminal VMT TK-8 Cathodic Protection Contingency Plan Z768 Drawing Index.
- Coffman Engineers. 2019. Corrosion Calculations for Z768 VMT TK-8 CP Contingency Design: Cathodic Protection Calculations Tank Bottom Circuit.
- Coffman Engineers. 2019. Corrosion Calculations for Z768 VMT TK-8 CP Contingency Design: Cathodic Protection Calculations Annual Ring Circuit.