U.S. Department
of Transportation
**Pipeline and Hazardous
Materials Safety
Administration**

1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Maria Cantwell
Chair, Committee on Commerce, Science,
and Transportation
United States Senate
Washington, DC 20510

Dear Chair Cantwell:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

I hope this information is helpful. Should you require further information or assistance, please feel free to call me or have your staff contact Patricia Klinger, PHMSA's Deputy Director of Governmental, International, and Public Affairs, by phone at (202) 366-6374 or by email at patricia.klinger@dot.gov.

A similar response was sent to the Ranking Member of the Senate Committee on Commerce, Science, and Transportation; the Chairman and Vice Chairman of the Senate Committee on Appropriations; the Chairwoman and Ranking Member of the House Committee on Appropriations; the Chair and Ranking Member of the House Committee on Transportation and Infrastructure; and the Chairman and Ranking Member of the House Committee on Energy and Commerce.

Sincerely,

Tristan H. Brown

Tristan H. Brown
Deputy Administrator

Enclosure

U.S. Department
of Transportation
**Pipeline and Hazardous
Materials Safety
Administration**

1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Roger Wicker
Ranking Member, Committee on Commerce,
Science, and Transportation
United States Senate
Washington, DC 20510

Dear Ranking Member Wicker:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Frank Pallone, Jr.
Chairman, House Committee on Energy
and Commerce
U.S. House of Representatives
Washington, DC 20515

Dear Chairman Pallone:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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Deputy Administrator

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U.S. Department
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**Pipeline and Hazardous
Materials Safety
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1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Cathy McMorris Rodgers,
Ranking Member, House Committee on
Energy and Commerce
U.S. House of Representatives
Washington, DC 20515

Dear Ranking Member McMorris Rodgers:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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Tristan H. Brown
Deputy Administrator

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U.S. Department
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**Pipeline and Hazardous
Materials Safety
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1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Peter A. DeFazio
Chair, Committee on Transportation
and Infrastructure
U.S. House of Representatives
Washington, DC 20515

Dear Chair DeFazio:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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Deputy Administrator

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U.S. Department
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1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Sam Graves
Ranking Member, Committee on Transportation
and Infrastructure
U.S. House of Representatives
Washington, DC 20515

Dear Ranking Member Graves:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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U.S. Department
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Materials Safety
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1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Rosa DeLauro
Chairwoman, Committee on Appropriations
U.S. House of Representatives
Washington, DC 20515

Dear Chair DeLauro:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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U.S. Department
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**Pipeline and Hazardous
Materials Safety
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1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Kay Granger
Ranking Member, Committee on Appropriations
U.S. House of Representatives
Washington, DC 20515

Dear Ranking Member Granger:

Enclosed please find the report titled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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U.S. Department
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1200 New Jersey Avenue, SE
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January 12, 2022

The Honorable Patrick Leahy
Chairman, Committee on Appropriations
United States Senate
Washington, DC 20510

Dear Chairman Leahy:

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U.S. Department
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**Pipeline and Hazardous
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1200 New Jersey Avenue, SE
Washington, DC 20590

January 12, 2022

The Honorable Richard Shelby
Vice Chairman, Committee on Appropriations
United States Senate
Washington, DC 20510

Dear Vice Chairman Shelby:

Enclosed please find the report entitled, "Aboveground Storage Tanks: Review of Current and New Corrosion Control Techniques," as requested in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021, which requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. Congress also requested PHMSA to submit a report detailing the findings on supplementary or alternative techniques to cathodic protection systems and the application of such techniques to aboveground storage tanks.

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Tristan H. Brown

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Deputy Administrator

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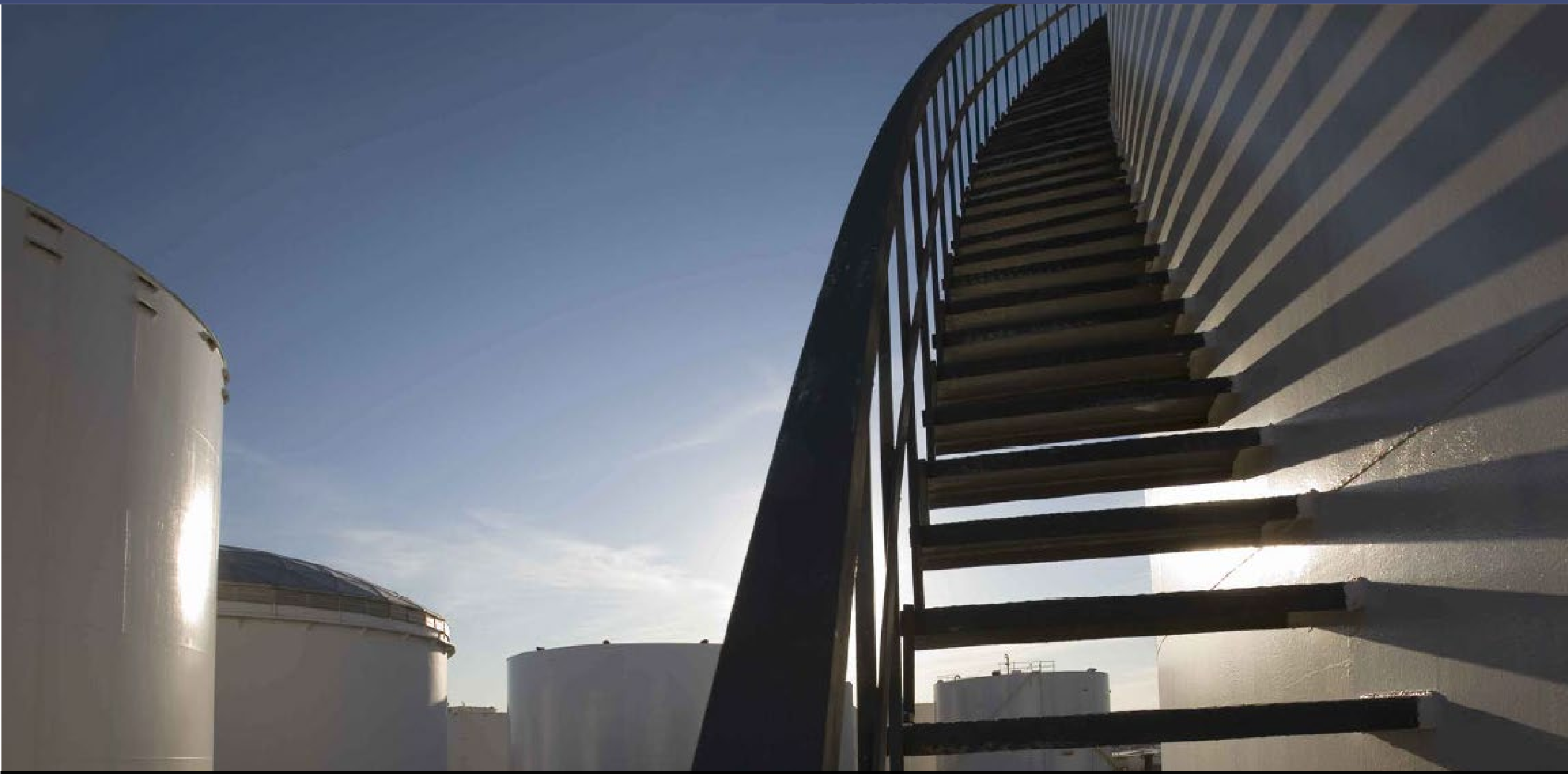
U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration



Report to Congress

Aboveground Storage Tanks Review of Current and New Corrosion Control Techniques

December 2021

Contents

Cover Photo courtesy of an operator

Abbreviation List

AST	Aboveground Storage Tanks
AC	Alternating Current
API	American Petroleum Institute
CAAP	Competitive Academic Agreement Program
CNT	Carbon Nanotubes
CP	Cathodic Protection
CSE	Copper Sulfate Reference Electrode
CUI	Corrosion Under Insulation
DC	Direct Current
ER	Electrical Resistance
FBG	Fiber Bragg Gratings
GNP	Graphene Nanoplatelets
LSP	Laser Shock Peening
LPFG	Long Period Fiber Gratings
MIC	Microbially Induced Corrosion
NS	Nano-Silica
PHMSA	Pipeline and Hazardous Materials Safety Administration
PRCI	Pipeline Research Council International
PSRP	Pipeline Safety Research Program
R&D	Research and Development
SCM	Supplementary Cementitious Materials
VCI	Vapor Corrosion Inhibitors

Executive Summary

In the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021 Congress requested the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA), to conduct a review of existing and new corrosion control technologies being utilized on aboveground storage tanks for leak prevention.

PHMSA's mission is to protect people and the environment by advancing the safe transportation of energy and other hazardous materials that are essential to our daily lives. As part of this mission, PHMSA administers a national regulatory safety program for pipeline facilities which include more than 2.8 million miles of interstate and intrastate pipelines and over 8,400 aboveground storage tanks in the United States. This program requires that pipeline operators design, construct, operate, and maintain pipeline facilities, including aboveground storage tanks (sometimes also referred to as tanks or breakout tanks), in compliance with the Federal Pipeline Safety Regulations (PSR) found in 49 CFR parts 190 through 199.

In preparing this report, PHMSA reviewed available literature, expert presentation materials, and operator documents on corrosion control provided to PHMSA during its regular inspection activities and engaged in discussions with corrosion subject matter experts. PHMSA specifically focused on reviewing existing corrosion control technologies and practices in accordance with Federal regulations, and alternative corrosion control technologies that are being researched and/or utilized by industry and manufacturers on non-regulated aboveground storage tanks.

PHMSA currently requires cathodic protection (CP) on all newly constructed or modified aboveground storage tanks under its jurisdiction. The CP systems installed on aboveground storage tanks are intended to protect the outside tank bottoms from corrosion and prevent leaks that could impact people, property, and the environment. CP is a well-developed technology that is understood by regulators and pipeline operators. However, there are instances in which CP can be ineffective due to local conditions, electrical interference, or other circumstances. In these instances, other forms of corrosion control may help lower the risk and prevent leaks. Some of the new technologies reviewed by PHMSA would either supplement or be an alternative to currently applied CP systems. These newer techniques are similarly intended to mitigate corrosion and to improve leak prevention as well as maintain asset integrity.

Additionally, a review of available literature indicates operators have employed a few other corrosion control methods to replace or supplement failing CP systems for the protection of aboveground storage tanks. Those corrosion control methods are not authorized by the Federal PSR as standalone corrosion control measures. If an operator is voluntarily using another method as an additional layer of corrosion control while still using CP on regulated tanks, the operator must assure that those other methods are not detrimental to the required CP. However, if an operator intends to use other technology in lieu of CP, authorization for use would be required through special permits.

One alternative corrosion control method reviewed by PHMSA is vapor corrosion inhibitors (VCIs). VCIs are a class of chemicals that form a protective barrier on a surface to help reduce the corrosion rate of the protected metal. Research on VCIs has shown that their use may improve bottom plate corrosion control but does not have the level of corrosion control for adequate CP to meet Federal PSR. There is currently no industry standard for the use and monitoring of VCIs for tank bottom corrosion control, which is typically required before PHMSA would adopt a new technology into the Federal PSR.

Another practice seen in the literature for corrosion control is to isolate the tank bottom from a corrosive environment by using either a non-conductive membrane or similar material. This approach will typically employ a leak detection system under the tank due to electrical isolation of the tank bottom that makes it difficult to monitor potential corrosion. There do not appear to be studies on the long-term success of this methodology at this time, and there is currently no industry standard for these types of designs.

PHMSA executes a robust research and development program designed to improve pipeline safety and has funded a number of projects on corrosion management. PHMSA funds research projects by soliciting topics and safety gaps from the regulated community and the public and would welcome potential research projects on the prevention of corrosion on aboveground storage tank.

PHMSA also has a special permit process that allows pipeline operators to apply for the use of alternate technologies and practices that do not meet pipeline safety code requirements but provide an equivalent level of safety. Operators could use the special permit process to propose alternate corrosion control methods for tank bottoms.

While PHMSA is responsible for developing and enforcing regulations for the safe and environmentally sound operation of pipeline transportation systems in the United States, through its review and in this report, PHMSA remains impartial regarding specific technologies used to meet Federal PSR. PHMSA does not endorse or promote any particular aboveground storage technology or product.

1. Introduction

PHMSA has jurisdiction over certain aboveground storage tanks (ASTs), which are subject to the hazardous liquid PSR found in 49 CFR part 195.[1] These tanks are called breakout tanks and are defined as tanks that relieve surges in a hazardous liquid pipeline system or tanks that receive and store hazardous liquids transported by a pipeline for reinjection and continued transportation by pipelines.[2] Other ASTs, such as tanks at a terminal, are under the jurisdiction of the Environmental Protection Agency or other Federal or state agencies. PHMSA currently regulates over 8,400 breakout tanks in the United States. These tanks range in size from smaller than 50 US Barrels (bbl) or 2,100 gallons to over 600,000 bbl or 25,200,000 gallons.

Tanks are generally a safe way for operators to store crude oil and refined products. However, due to the size of ASTs, a release from these tanks may have a catastrophic effect on people, property, and the environment. As a result, PHMSA regulations require jurisdictional ASTs be constructed, operated, and maintained to the Federal PSR and industry standards that are incorporated by reference in the safety regulations.

One major threat to the integrity of ASTs is corrosion of the bottom of the tank that can lead to a leak of the product stored in the tank. To reduce this risk, Federal PSR require CP be applied to each tank. CP is a technique used to control the corrosion of a metal surface (i.e., cathode) by connecting the surface to a more corrosive metal or by using an electric current to impress a protective current onto the metal surface.

While CP is largely effective in protecting pipelines and ASTs, it is difficult to protect some tanks with CP due to soil conditions, tank design, electrical interference, or other issues. As a result of this difficulty, operators would benefit from finding additional corrosion control systems to use in lieu of or in conjunction with CP systems to protect AST bottoms. Congress has directed PHMSA in the Joint Explanatory Statement of the Consolidated Appropriations Act of 2021 to submit a report on leak prevention for ASTs by reviewing existing technologies such as CP and new technologies that industry and manufacturers are researching and proposing to use. The following is the text in the Joint Explanatory Statement:

> "*Aboveground storage tanks - The agreement directs PHMSA to conduct a review of current and new corrosion control techniques that may be used to improve leak prevention of regulated aboveground storage tanks. PHMSA is directed to submit a report within 1 year of enactment of this Act to the House and Senate Committees on Appropriations, the House Committee on*

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1 https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-D/part-195.

2 *See* 49 CFR § 195.2, definition for "breakout tank."

Transportation and Infrastructure, and Senate Committee on Commerce, Science and Transportation detailing the findings on supplementary or alternative techniques to CP systems and the application of such techniques to aboveground storage tanks."

This report will outline the types of storage tanks that PHMSA regulates, how corrosion can degrade the bottom of a tank, and how CP can protect tanks. PHMSA's current regulations and incorporated by reference industry standards set requirements for CP and corrosion control on jurisdictional ASTs. Moreover, this report will discuss new CP techniques that may be used to control corrosion on tanks, as well as the opportunity for PHMSA to undertake future research projects on corrosion control for ASTs.

2. Types of Aboveground Storage Tanks

PHMSA's regulations allow an operator to construct and operate various types of ASTs. These tanks can be used for different purposes and products; therefore, an operator must follow the regulations to ensure it is using the correct and compliant tank. The most common types of tanks allowed by the pipeline safety code include:

- **American Petroleum Institute (API) Standard 650: Welded Tanks for Oil Storage**

  API Standard 650 (API 650) tanks are the most common type of tanks PHMSA regulates and can hold oil and petroleum products at up to 2.5 pounds per square inch gauge (psig). API 650 is a very general specification and can be used for a wide variety of sizes of tanks. **Figures 1, 2, and 3** show typical API 650 tanks.

  API 650 states "This Standard establishes minimum requirements for material, design, fabrication, erection, and testing for vertical, cylindrical, aboveground, closed- and open-top, welded storage tanks in various sizes and capacities for internal pressures approximating atmospheric pressure (internal pressures not exceeding the weight of the roof plates), but a higher internal pressure is permitted when additional requirements are met. This Standard applies only to tanks whose entire bottom is uniformly supported and to tanks in non-refrigerated service that have a maximum design temperature of 93°C (200°F) or less."[3]

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[3] API Standard 650, "Welded Steel Tanks for Oil Storage," 11th edition, June 2007, effective February 1, 2012, (including addendum 1 (November 2008), addendum 2 (November 2009), addendum 3 (August 2011), and errata (October 2011) (incorporated by reference, *see* 49 CFR § 195.3).

Figure 1 *– API 650 Tank (Photo courtesy of PHMSA)*

***Figure 2** – API 650 tanks as part of a tank farm (Photo courtesy of an operator)*

***Figure 3** – API 650 Tank under construction (Photo courtesy of PHMSA)*

- **API Specification 12F: Specification for Shop Welded Tanks for the Storage of Production Liquids**

  API Specification 12F tanks are shop built (not field fabricated) to sizes in the specification between 90 and 750 bbl, which is often smaller than API 650 tanks. This standardized approach can eliminate some of the steps in the engineering process, and these tanks can be manufactured relatively quickly as compared to other tanks. A typical API Specification 12F tank is shown in **Figure 4**.

  API Specification 12F states: "This Specification covers material, design, fabrication, and testing requirements for shop-fabricated vertical, cylindrical, aboveground, closed top, welded steel storage tanks in various standard sizes and capacities for internal pressures approximately atmospheric.

  This specification is designed to provide the oil production industry with tanks of adequate safety and reasonable economy for use in the storage of crude petroleum and other liquids commonly handled and stored by the production segment of the industry. This specification is for the convenience of purchasers and manufacturers in ordering and fabrication."[4]

***Figure 4** – API Specification 12F shop-built tank (Photo courtesy of PHMSA)*

[4] API Specification 12F, "Specification for Shop Welded Tanks for Storage of Production Liquids," 12th edition, October 2008, effective April 1, 2009 (incorporated by reference, *see* 49 CFR § 195.3).

Several other tank standards, such as API Standard 620, Underwater Laboratories Standard 142, Steel Tank Institute F921, and more, are available for various products.[5] The choice of tank standard depends on the product, tank volume, pressure requirements, and regulatory jurisdiction.

3. Types of Corrosion on Aboveground Storage Tanks

Corrosion at the soil side of tank bottoms occurs when the materials, structure, and the environment create conditions for an electrochemical reaction to take place resulting in metal loss from the tank bottom.

The most common types of AST corrosion are general and localized (pitting) corrosion. General corrosion refers to thousands of microscopic corrosion cells occurring on an area of the metal surface resulting in relatively uniform metal loss. Localized corrosion refers to individual corrosion cells that are larger, and metal loss from localized corrosion may be concentrated within relatively small areas with substantial areas of the surface unaffected by corrosion. According to NACE International (formerly known as the National Association of Corrosion Engineers):

"[t]he primary corrosion mechanism contributing to aboveground storage tank bottom corrosion is localized pitting corrosion. In the most aggressive environments, tank bottom leaks are from pitting corrosion and can occur in less than 5 years."[6]

The following sections below describe different types of localized corrosion that can occur depending on varying conditions.

3.1 Galvanic (Differential Metal) Corrosion

Galvanic corrosion takes place when different metals electrically contact with each other. The more electrochemically active the material[7] is, the more likely it is to corrode creating corrosion pits on a metal surface. The uneven distribution of alloying elements or contaminants within the metal structure could also result in localized pitting corrosion. If there are differences on the material compositions between weld metal, heated affected zones, and the base metal, pitting corrosion is likely to occur.

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5 While the Federal PSR allow for API 620 tanks, there are a small number of PHMSA jurisdictional API 620 tanks.

6 *Corrosion Protection of Soil Side Bottoms of Aboveground Storage Tanks.* Efim Lyublinski, etc. San Antonio, TX : NACE International, 2014. Corrosion 2014. Vol. Paper No. 4337.

7 Materials are ranked on the galvanic series for different environments from more non-reactive (noble) to more active.

3.2 Oxygen Concentration Cell Corrosion

Localized corrosion can take place when the oxygen concentration differs between two or more areas on the soil side of the tank bottom. The difference of oxygen concentration could be the result of the uneven distribution of the dissolved oxygen in the soil layer or in the crevices where the oxygen level is different from the bulk level due to the restricted flow. The areas with lower oxygen concentrations are likely to experience corrosion. API states:

> "[t]he oxygen induced localized corrosion of tank bottom could occur on a homogeneous sand pad, and/or when contaminated with clay or other debris or natural soil that does not have a uniform consistency."[8]

Figure 5 shows an example of an oxygen concentration cell developed by large sized particles in the tank bottom substrate, which contacts the steel bottom.[9]

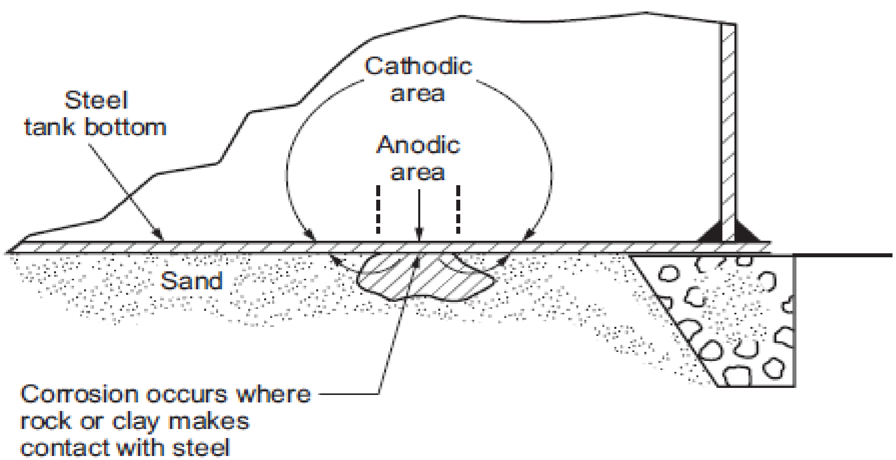

***Figure 5** – Oxygen Concentration Cell Caused by Rocks or Clay in Tank Pad*

Soil characteristics substantially affect the type and rate of corrosion on the tank bottoms. Moisture content, pH, oxygen concentration, soil contaminants (e.g., chlorides, sulfides, sulfate, etc.), the groundwater table, and temperature are also factors that affect the corrosion of soil side tank bottoms.

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8 API Recommended Practice 651, "Cathodic Protection of Aboveground Petroleum Storage Tanks," 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

9 API Recommended Practice 651, "Cathodic Protection of Aboveground Petroleum Storage Tanks," 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

Ordinarily, the oxygen concentration cell occurs in the tank bottom substrate with a mixture of clay and clean sand fill material. “When a clump of clay is positioned against a tank, a lower oxygen level is created at the surface of the steel under the clay relative to the level in the sand.”[10]

3.3 Stray Current Corrosion

Stray current corrosion is also known as interference current corrosion. The currents generated from the grounded direct current (DC) power systems can travel through the soil electrolyte and can be picked up by the unprotected tank bottom. At the locations where the DC current discharges back into the soil, corrosion occurs resulting in localized metal loss. The DC currents that could potentially cause interference corrosion are generated from grounded DC electric power systems, including electric railroads, subways, welding machines, impressed current CP systems, thermoelectric generators, etc.

Figure 6 illustrates an example of the path of stray currents, which travel from an external DC electric power system through the soil electrolyte to the unprotected tank and then discharge back into soil.[11]

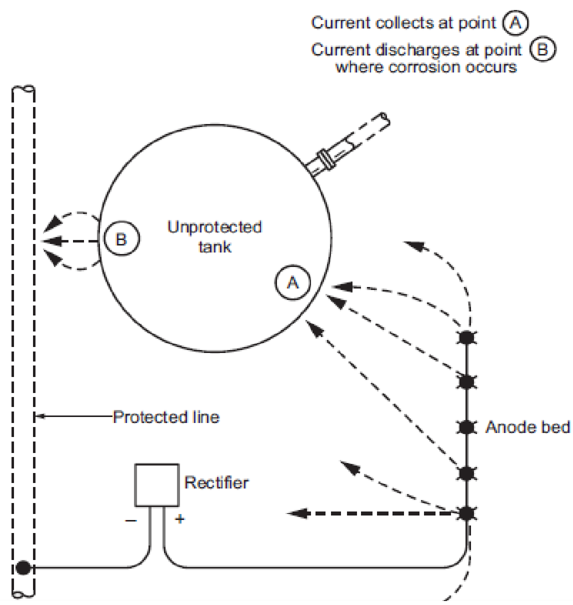

***Figure 6** – Example of Stray Current Corrosion of an Unprotected Tank*

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[10] Corrosion Control for Aboveground Storage Tanks: Part 1-Causes and Controls. Petrolplaza. [Online] Petrol Plaza, 1999. https://www.petrolplaza.com/knowledge/1952.

[11] API Recommended Practice 651, “Cathodic Protection of Aboveground Petroleum Storage Tanks,” 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

The severity of corrosion resulting from interference currents depends on several factors as described in API 651:

- "Separation and routing of the interfering and affected structures and location of the interfering current source
- Magnitude and density of the current
- Quality or absence of a coating on the affected structures
- The presence and location of mechanical joints having high electrical resistance
- Temperature"

3.4 Microbially Induced Corrosion

Microbially induced corrosion (MIC) can be defined as bacteria present in the tank bottom substrate materials or introduced into the substrate during flooding, rain, or from other types of sources. The growth of bacteria colonies could create the corrosive conditions, which will accelerate localized corrosion on the steel surface of the tank bottom. Soil samples are normally taken from the tank bottom substrate for analytical testing to determine the presence and types of bacteria in the tank bottom substrate.

4. Current Regulations

The Federal PSR, 49 CFR part 195, contain requirements for the design and construction of aboveground breakout tanks, CP systems, inspection of in-service breakout tanks, and more.

The applicable regulatory requirements for breakout tanks and the associated CP requirements are as follows:

- **49 CFR §195.2 Definitions**

  Breakout tank means a tank used to (a) relieve surges in a hazardous liquid pipeline system or (b) receive and store hazardous liquid transported by a pipeline for reinjection and continued transportation by pipeline.

  Pipeline or *Pipeline system* means all parts of a pipeline facility through which a hazardous liquid or carbon dioxide moves in transportation, including, but not limited to, line pipe, valves, and other appurtenances connected to line pipe, pumping units, fabricated assemblies associated with pumping units, metering and delivery stations and fabricated assemblies therein, and breakout tanks.

- **49 CFR §195.3 What documents are incorporated by reference partly or wholly in this part?**

  ANSI/API Recommended Practice 651, "Cathodic Protection of Aboveground Petroleum Storage Tanks," 3rd edition, January 2007.

  ANSI/API Recommended Practice 652, "Linings of Aboveground Petroleum Storage Tank Bottoms," 3rd edition, October 2005.

  API Specification 12F, "Specification for Shop Welded Tanks for Storage of Production Liquids," 12th edition, October 2008.

  API Standard 620, "Design and Construction of Large, Welded, Low-Pressure Storage Tanks," 11th edition February 2008 (including addendum 1 (March 2009), addendum 2 (August 2010), and addendum 3 (March 2012)).

  API Standard 650, "Welded Steel Tanks for Oil Storage," 11th edition, June 2007, effective February 1, 2012, (including addendum 1 (November 2008), addendum 2 (November 2009), addendum 3 (August 2011), and errata (October 2011)).

  API Standard 653, "Tank Inspection, Repair, Alteration, and Reconstruction," 3rd edition, December 2001, (including addendum 1 (September 2003), addendum 2 (November 2005), addendum 3 (February 2008), and errata (April 2008)).

  NACE SP0169-2007, Standard Practice, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" reaffirmed March 15, 2007

- **49 CFR** § 195.553 What special definitions apply to this subpart?

  Active corrosion means continuing corrosion which, unless controlled, could result in a condition that is detrimental to public safety or the environment.

  Buried means covered or in contact with soil.

- **49 CFR § 195.563 Which pipelines must have cathodic protection?**

  (a) . . .

  (b) Each buried or submerged pipeline converted under §195.5 must have cathodic protection if the pipeline—

    (1) Has cathodic protection that substantially meets §195.571 before the pipeline is placed in service; or

    (2) Is a segment that is relocated, replaced, or substantially altered.

(c) All other buried or submerged pipelines that have an effective external coating must have cathodic protection.[1] Except as provided by paragraph (d) of this section, this requirement does not apply to breakout tanks and does not apply to buried piping in breakout tank areas and pumping stations until December 29, 2003.

[1] A pipeline does not have an effective external coating material if the current required to cathodically protect the pipeline is substantially the same as if the pipeline were bare.

(d) Bare pipelines, breakout tank areas, and buried pumping station piping must have cathodic protection in places where regulations in effect before January 28, 2002 required cathodic protection as a result of electrical inspections. See previous editions of this part in 49 CFR, parts 186 to 199.

- **49 CFR § 195.565 How do I install cathodic protection on breakout tanks?**

  After October 2, 2000, when you install cathodic protection under §195.563(a) to protect the bottom of an aboveground breakout tank of more than 500 barrels 79.49m3 capacity built to API Spec 12F (incorporated by reference, *see* §195.3), API Std 620 (incorporated by reference, *see* §195.3), API Std 650 (incorporated by reference, *see* §195.3), or API Std 650's predecessor, Standard 12C, you must install the system in accordance with ANSI/API RP 651 (incorporated by reference, *see* §195.3). However, you don't need to comply with ANSI/API RP 651 when installing any tank for which you note in the corrosion control procedures established under §195.402(c)(3) why complying with all or certain provisions of ANSI/API RP 651 is not necessary for the safety of the tank.

- **49 CFR § 195.571 What criteria must I use to determine the adequacy of cathodic protection?**

  Cathodic protection required by this subpart must comply with one or more of the applicable criteria and other considerations for cathodic protection contained paragraphs 6.2.2, 6.2.3, 6.2.4, 6.2.5 and 6.3 in NACE SP 0169 (incorporated by reference, *see* §195.3).

- **49 CFR § 195.573 What must I do to monitor external corrosion control?**

  (a) . . .

  (d) *Breakout tanks.* You must inspect each cathodic protection system used to control corrosion on the bottom of an aboveground breakout tank to ensure that operation and maintenance of the system are in accordance with API RP 651 (incorporated by reference, *see* §195.3). However, this inspection is not required if you note in the corrosion control procedures established under §195.402(c)(3) why complying with all or certain operation and maintenance provisions of API RP 651 is not necessary for the safety of the tank.

In addition, the administrative orders issued by PHMSA have established precedent for PHMSA's enforcement of the Federal PSR. PHMSA also provides guidance clarifying the intent of certain code sections. This guidance includes frequently asked questions, advisory bulletins, and interpretations and is publicly available on PHMSA's website.[12]

5. Special Permit Process

A special permit is an order that waives compliance with a regulatory requirement if the pipeline operator requesting it demonstrates the need, and PHMSA determines that granting a special permit would not be inconsistent with pipeline safety. Special permits are authorized by 49 USC § 60118(c) and the application process is set forth in 49 CFR § 190.341.[13] PHMSA performs extensive technical analysis on special permit applications and typically conditions a grant of a special permit on the performance of alternative measures that will provide an equal or greater level of safety. PHMSA is committed to public involvement and transparency in considering special permit requests and publishes a notice of every special permit application received in the Federal Register for comment.

Special permits can be used for alternate technologies where an industry consensus standard has not been issued, and special permits are often used before PHMSA adopts new regulations on a new technology or practice. As of the date of the report no operator has asked for a special permit to not install CP for new tanks or prior to modifying a tank.

6. Review of Standards Incorporated by Reference and Other Related Industry Standards

Industry consensus standards are technical standards developed or adopted by domestic and international standards development organizations. PHMSA reviews these industry consensus standards and may incorporate specific standards as deemed appropriate into the Federal PSR by reference. There are currently several published industry consensus standards for tank corrosion control, some of which, as noted

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12 https://www.phmsa.dot.gov/guidance.
13 https://www.phmsa.dot.gov/pipeline/special-permits-state-waivers/special-permits-and-state-waivers-overview.

below, are incorporated by reference (IBR) into the Federal PSR. These include the following:

- **API Recommended Practice (RP) 651: Cathodic Protection of Aboveground Petroleum Storage Tanks** – (IBR in 49 CFR § 195.3) – provides procedures and guidelines for operators to design, construct, install, and operate CP on new or existing ASTs. This RP has the following purpose:

> *"The purpose of this recommended practice is to present procedures and practices for achieving effective corrosion control on aboveground storage tank bottoms through the use of cathodic protection. This RP contains provisions for the application of cathodic protection to existing and new aboveground storage tanks. Corrosion control methods based on chemical control of the environment, or the use of protective coatings are not covered in detail.*
>
> *When cathodic protection is used for aboveground storage tank applications, it is the intent of this RP to provide information and guidance specific to aboveground metallic storage tanks in hydrocarbon service. Certain practices recommended herein may also be applicable to tanks in other services. It is intended to serve only as a guide to persons interested in cathodic protection. Specific cathodic protection designs are not provided. Such designs should be developed by a person thoroughly familiar with cathodic protection practices for aboveground petroleum storage tanks.*
>
> *This RP does not designate specific practices for every situation because the varied conditions in which tank bottoms are installed preclude standardization of cathodic protection practices."*[14]

In accordance with 49 CFR § 195.565 operators are required to install CP to protect the bottom of breakout tanks per API RP 651 requirements. API RP 651 requirements are also included in 49 CFR § 195.573 where the CP system of breakout tanks must be inspected and monitored in accordance with the API RP.

- **API Standard 653 (API 653):** Tank Inspection, Repair, Alteration, and Reconstruction – (IBR into 49 CFR § 192.3) – This standard provides requirements to maintain the integrity of tanks after the tank has been put into service. The standard covers topics beyond the corrosion of the bottom of the tank such as the tank foundation, shell, and roof, but it also sets inspection intervals where tanks must be taken out of service and inspected to the requirements of the standard. These

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[14] API Recommended Practice 651, "Cathodic Protection of Aboveground Petroleum Storage Tanks," 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

inspections include inspection of the bottom of the tank where an operator may find the bottom is corroding faster than anticipated and repairs and alterations to the CP systems may be required. The standard has the following purpose in the document:

> *"This standard covers steel storage tanks built to API 650 and its predecessor API 12C. It provides minimum requirements for maintaining the integrity of such tanks after they have been placed in service and addresses inspection, repair, alteration, relocation, and reconstruction.*
>
> *The scope is limited to the tank foundation, bottom, shell, structure, roof, attached appurtenances, and nozzles to the face of the first flange, first threaded joint, or first welding-end connection. Many of the design, welding, examination, and material requirements of API 650 can be applied in the maintenance inspection, rating, repair, and alteration of in-service tanks. In the case of apparent conflicts between the requirements of this standard and API 650 or its predecessor API 12C, this standard shall govern for tanks that have been placed in service."*[15]

In accordance with 49 CFR § 195.432 operators are required to inspect in-service breakout tanks to API 653. API 653 also sets the pressure testing requirements for tanks in 49 CFR §§ 195.205 and 195.307 to ensure the tank can withstand the pressure of the hazardous liquid to be stored within the tank.

- **NACE SP0193**: External Cathodic Protection of On-Grade Steel Storage Tank Bottoms – While this standard is not directly incorporated into the Federal PSR, it presents guidance for the design, installation, and maintenance of CP for the exterior bottom of steel storage tanks. PHMSA will consider incorporating this standard in the future. The standard has the following purpose:

> *"It is extremely important to maintain the integrity of on-grade carbon steel storage tanks for both economic and environmental reasons. The proper design, installation, and maintenance of cathodic protection (CP) systems can help maintain the integrity and increase the useful service life of on-grade carbon steel storage tanks.*
>
> *The purpose of this standard recommended practice is to outline practices and procedures for providing cathodic protection to the soil side of bottoms of on-grade carbon steel storage tanks that are in contact with an electrolyte.*

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15 API Standard 653, "Tank Inspection, Repair, Alteration, and Reconstruction," 3rd edition, December 2001, (including addendum 1 (September 2003), addendum 2 (November 2005), addendum 3 (February 2008), and errata (April 2008)).

Recommendations for both galvanic anode systems and impressed current systems are included. Design criteria for the upgrade of existing tanks as well as for newly constructed tanks are included. This standard is intended for use by personnel planning to install new on-grade carbon steel storage tanks, upgrade cathodic protection on existing storage tanks, or install new cathodic protection on existing storage tanks."[16]

7. Types of Cathodic Protection Systems for Aboveground Storage Tanks

CP is a commonly applied corrosion preventative technique for ASTs to mitigate soil side tank bottom corrosion. The mechanism of CP is to apply the cathodic current to the metal to be protected and make the metal surface in the electrochemical potential range where corrosion reactions do not occur. The common CP criteria adopted in industry is -0.85V versus a saturated copper/copper sulfate reference electrode.

There are two systems of CP that have been applied for ASTs: 1) galvanic CP system, and 2) impressed current CP system.

7.1 Galvanic Cathodic Protection Systems

A metal which is more active than steel is used as the anode in the galvanic CP system for ASTs. It is buried in the soil and electrically connected to the tank bottom soil side surface to create a galvanic corrosion cell. The anode corrodes and provides cathodic current to protect the tank bottom from corrosion.

> "The commonly used galvanic anodes in soil includes magnesium and zinc in either cast or ribbon form. Galvanic systems are normally applied only to small diameter tanks less than 20-feet, or for tanks with externally coated bottoms."[17]

Figure 7 shows a typical layout of a galvanic CP system.[18]

The advantages of applying a galvanic CP system to prevent soil side corrosion of aboveground tanks include:

- Does not require an external power supply.

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16 NACE SP0193-2016 "External Cathodic Protection of On-Grade Carbon Steel Storage Tank Bottoms", 2016.

17 API Recommended Practice 651, "Cathodic Protection of Aboveground Petroleum Storage Tanks," 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

18 API Recommended Practice 651, "Cathodic Protection of Aboveground Petroleum Storage Tanks," 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

- Relatively easy to install with less capital investment and maintenance cost.
- Typically, unaffected by stray currents.
- Requires less regular monitoring.

The current output from a galvanic system is low, so it is not suitable for larger tanks without external coated bottoms. The use of the galvanic CP system is normally limited to lower resistivity soils as the life expectancy of the anodes can be much shorter in high resistivity soils.

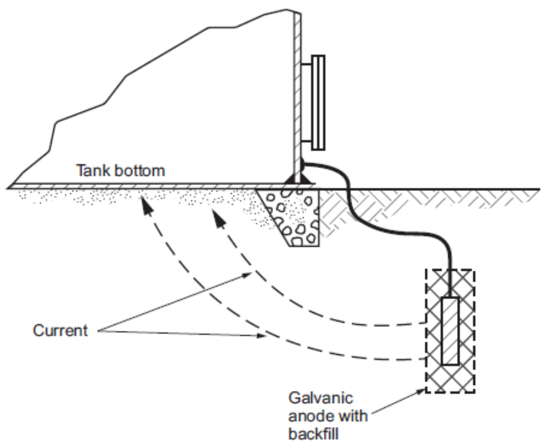

***Figure 7** – Galvanic Cathodic Protection System*

7.2 Impressed Current Cathodic Protection Systems

An impressed current system applies CP current to the soil side of the tank bottom from an external electrical source. The impressed current system uses DC provided by a rectifier that is attached to alternating current (AC) power.

Figure 8 shows a typical layout of the impressed current system.[19] It includes:

- Rectifier
- Anode
- Protected structure (tank bottom)

The rectifier converts AC input current to DC output current that flows into the buried anodes that are connected to the rectifier at the positive terminal. The tank body is

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19 API Recommended Practice 651, “Cathodic Protection of Aboveground Petroleum Storage Tanks,” 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

connected to the negative terminal of the rectifier, and the current flows from the anode to the soil side of the tank bottom in the soil.

> "Impressed current anodes used in soil are made of materials such as graphite, scrap steel, high silicon cast iron, or mixed metal oxides on titanium. Anodes are usually buried in a coke breeze backfill to extend their life and reduce circuit resistance."[20]

The installation and configuration of impressed current anodes include:

- Directly underneath the tank bottom
- Distributed around tank
- In remote anode beds
- In deep anode beds

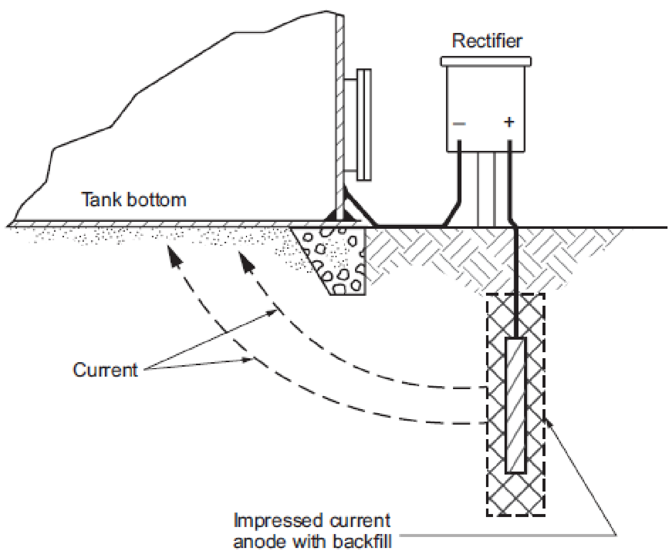

***Figure 8** – Impressed Current Cathodic Protection System*

The advantages of an impressed current system include:

- High current output capable of protecting larger tanks and suitable for almost any soil resistivity.

[20] API Recommended Practice 651, "Cathodic Protection of Aboveground Petroleum Storage Tanks," 3rd edition, January 2007 (incorporated by reference, see 49 CFR § 195.3).

- Adjustable current output from the rectifier to provide the proper level of CP current without damaging the steel or coating properties by overprotection.

When AC power is lost, the tank bottom is not protected by the CP current and corrosion damage could occur on the tank bottom depending on the duration of AC power loss. In addition, the impressed current system normally has interference problems (stray currents) from foreign structures, requiring more frequent monitoring with higher maintenance and operating costs.

It should be noted that there are several situations in which CP systems may be ineffective to protect tank bottom from corrosion:

- "When the liquid stored in the tank is transported, the fill levels of the storage tank change and the bottom plate of the empty tank flexes, creating air gaps between the bottom plate and the tank bed leading to reduced CP effectiveness and potential corrosive conditions for the tank bottoms.
- The poor ionic conductivity within tank bed and failure of anodes.
- Microbiologically influenced corrosion.
- Improper current distribution from the anodes.
- Increased resistance of the tank pad materials.
- Poorly designed CP systems.
- Failure of CP systems before the intended design life."[21]

8. Corrosion Monitoring

Since AST bottoms cannot be easily accessed to see if corrosion is occurring, certain methodologies have been developed to monitor corrosion as described below.

8.1 Corrosion Coupons

Corrosion coupons are used to estimate the corrosion rate by allowing a small sample of metal (the coupon) to be exposed to the corrosive environment. Corrosion coupons are typically made of similar steel used for tank bottoms that are being monitored. The coupons are weighted, measured in three dimensions, and marked prior to being installed in the substrate under the tank bottom. The coupons are retrieved after a pre-determined length of time. Changes of weight and dimension are measured to determine an estimated rate of corrosion rate at the tank bottom.

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[21] *Methodologies to Evaluate Compatibility between Cathodic Protection and Vapor Corrosion Inhibitors for Tank Bottom Applications*. Shukla, Sujay Math and Pavan K. Phoenix, AZ : NACE International, 2018. Corrosion 2018. p. Paper No. 11567.

There are different shapes and sizes of corrosion coupons based on the method of insertion, retrieval, and the environment into which the coupons are installed.

8.2 Electrical Resistance Probes

Electrical resistance (ER) probes can be used to monitor the corrosion rate of soil side tank bottoms by measuring the change in resistance of an exposed steel probe. The probe is made of the same material as the steel of the tank bottom and installed in the tank bottom substrate with the probe surface close to the soil side of the tank bottom.

Metal loss of the probe is calculated by the change of electrical resistance of the probe over time and converted to a corrosion rate representing the corrosion rate of the tank bottom steel in the same environment where the probe is installed.

8.3 Ultrasonic Testing

Ultrasonic testing is a technique used for inspecting tank bottom floor plate thickness. This technology is used in conjunction with other examination tools on breakout tanks under PHMSA jurisdiction when tanks are taken out of service. The process for AST ultrasonic testing is available in API 653 and API 575.

9. PHMSA's Corrosion Related R&D Projects and Other Technologies

Since 2002, PHMSA's research and development (R&D) programs have sponsored more than 100 research projects to investigate corrosion-related threats to pipeline infrastructure and to advance corrosion prevention, mitigation, inspection, and monitoring technologies. This section describes the corrosion prevention/mitigation concepts that were sponsored specifically by the PHMSA Competitive Academic Agreement Program (CAAP). Under the CAAP, research projects are intended to establish a proof of concept and spur innovation by enabling academic research to focus on high-risk, high-reward solutions to pipeline safety challenges that can be "handed-off" for further investigations. The research projects identified below could potentially be developed further on prevention and mitigation of AST bottom corrosion under PHMSA's Core Research Program which is focused on technology development, demonstration, and deployment.

9.1 Corrosion Prevention Coatings

Since 2003, the CAAP has sponsored five R&D projects for developing corrosion prevention coatings. The research was aimed at investigating the potential utilization of the available cutting-edge technologies and developing advanced corrosion prevention and mitigation methodologies.

Completed project topics included:

- Development of nano-coatings[22] to improve coating corrosion resistance, mechanical properties, as well as the coating application process by utilizing advanced nano-scale particles as coating additives.
- Development of smart coatings to integrate the state-of-the-art sensing technologies, CP, and corrosion prevention coating into one system.

(1) Project # 509 Mitigating Pipeline Corrosion Using A Smart Thermal Spraying Coating System

This project was funded in 2013 and completed in 2015. A self-sensing thermal spraying metallic coating[23] was developed during the project proving the concept of simultaneous mitigation and corrosion assessment by applying the developed self-sensing thermal spraying coating. The developed coating is a thermal spraying copper and copper-aluminum bronze coating with long period fiber gratings surface sensors and embedded fiber bragg gratings (FBG) sensors.

The research results were promising for developing the thermal spraying coating system with corrosion monitoring sensors integrated with the corrosion prevention coatings. The research was funded in 2015 (project # 634) for further development of the smart self-sensing coating system.

(2) Project # 510 Mitigating External Corrosion of Pipelines Through Nano-Modified Cement-Based Coatings

This project was funded in 2013 and completed in 2015. This project investigated the improved mechanical properties by replacing cement content with supplementary cementitious materials by up to 50 percent and adding the nano-clays in the coating formulations, which potentially could be used in the coating of tank bottoms during installation.

Research results indicated the cement-based coating could be applied with a simplified process and reduced cost. The developed coating could be further developed to integrate with corrosion inhibitors and sensing systems and implemented with a concrete pad for aboveground storage tank bottom design.[24]

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22 A nano-coating refers to very fine, thin layers of polymeric chemical substances used to impart specific corrosion resistance, chemical and physical properties to a substrate surface.
23 http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=509.
24 https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=510.

*(3) **Project # 634 Mitigating Pipeline Corrosion Using A Smart Thermal Spraying Coating System***

This project was funded in 2015 and completed in 2018 and was a continuation of the research from a previously funded CAAP project (project # 509). The wire arc and cold sprayed Al-Zn coatings with embedded FBG sensors were developed and validated in this project. The developed Al-Zn coatings provided the CP to the substrate steel without the need of an additional CP system.

The developed Al-Zn coating demonstrated superior mechanical property and corrosion resistance. It could be further developed for application to aboveground storage tank bottoms to provide a sacrificial anode type of CP and corrosion monitoring without installing an additional CP and corrosion monitoring sensor system.[25]

*(4) **Project # 635: An Inorganic Composite Coating for Pipeline Rehabilitation and Corrosion Protection***

This project was funded in 2015 and completed in 2018. An inorganic composite coating (Geopolymer[26]) was developed and tested in this project. The developed coating was based off a previously developed alkali aluminosilicate type coating system. The coatings were formulated with various nano-scale additives to improve the corrosion resistance of the coatings by reducing the coating porosities and the adhesion between the coating and the steel substrate.

The developed coating is water based without using solvent. It has zero emission of carbon dioxide (CO_2) and volatile organic compounds (VOC). The test results indicated the developed coating has a high bonding strength with concrete and composite materials that could be implemented for the prevention and rehabilitation of aboveground storage tank bottom corrosion.[27]

*(5) **Project # 722: Development of New Multifunctional Composite Coatings for Preventing and Mitigating Internal Pipeline Corrosion***

This project was funded in 2016 and completed in 2021. A new high-performance multifunctional composite coating was developed and tested in this project. The developed composite coating utilizes the unique properties of high-performance epoxy-based polymer resin and integrates with the nanoparticle reinforcements to mitigate interrelated corrosion-fouling-wear issues.

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[25] https://primis.phmsa.dog.gov/matrix/PrjHome.rdm?prj=634.
[26] Geopolymer is a potassium aluminosolicate coating for corrosion control.
[27] https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=635.

The test results from this project indicate the overall performance of the coating was improved by integration of the three types of nanoparticle reinforcements. The developed coating exhibited superior corrosion resistance and water-repellency, improved mechanical properties, and resistance to fouling and wear. It could be considered for further development to be implemented for the prevention of aboveground storage tank bottom corrosion.[28]

9.2 Corrosion Inhibitors

In addition to coating technologies, the CAAP also sponsored one R&D project on investigating corrosion inhibitors and injection apparatus to mitigate corrosion under insulation (CUI).

(6) Project # 637: Corrosion Under Insulation (CUI): Innovative Solutions to Cold Climate Corrosion Challenges

This project was funded in 2015 and completed in 2017. An inhibitor injection apparatus was designed for injecting inhibitor at pipe-insulations interface. The prototype was developed and tested for this project. The results indicated this inhibitor injection apparatus can be used to inject a solvent-bentonite mixture of corrosion inhibitor into the pipe-insulation interface.

A sodium bentonite corrosion inhibitor was also tested in this project to evaluate its effectiveness on corrosion mitigation. The results indicate sodium bentonite is a promising candidate of corrosion inhibitors for corrosion mitigation with up to 50 percent reduction of the corrosion rate for carbon steel at crevice corrosion conditions. The developed corrosion inhibitor and the injection apparatus could be considered for further development to be implemented with new technologies such as concrete pads and/or other insulation materials to mitigate tank bottom corrosion.[29]

9.3 Surface Treatment

The CAAP also sponsored one R&D project on investigating laser shock peening (LSP) and cleaning technology to improve steel corrosion and cracking resistance.

(7) Project # 570: Laser Peening for Preventing Pipe Corrosion and Failure

This project was funded in 2014 and completed in 2017. The laser cleaning technique was investigated for the effectiveness on surface cleaning. High-energy and low-energy

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[28] https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=722.
[29] https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=637.

LSP systems were developed and tested for effectiveness on improving the mechanical and corrosion resistance of steel.

The development of laser peening surface treatment technology could be implemented to improve the adhesion characteristics of the coating to the tank bottom to improve corrosion resistance.[30]

PHMSA's Pipeline Safety Research Program (PSRP) is collaborative and interactive in funding innovative research and new technology development throughout the industry and funds scientific research to inform pipeline decision-makers. This research results in safety improvements for transportation of energy products by pipelines. Additionally, the PSRP provides scientific and engineering support for PHMSA's safety enforcement and regulatory rulemaking efforts and identifies and develops emerging technologies for the pipeline industry to voluntarily adopt.

In March 2019, PHMSA released a Special Notice for "Identifying Pipeline Safety Research Ideas" in the beta.SAM.gov portal. The ongoing Special Notice invites any interested stakeholder to submit ideas for future research. This notice is open year-round and is revised as needed to reflect initiatives coming from PHMSA or the Administration. PHMSA launched this measure to widen the participation in formulating its future research strategy. A web-based portal was created to support and manage this action[31]. PHMSA encourages pipeline stakeholders to submit topics and safety gaps to be considered for future research.

9.4 Other Corrosion Control Technologies

Vapor corrosion inhibitors (VCIs), also known as vapor phase corrosion inhibitors or vapor phase inhibitors, are types of corrosion inhibitors used to protect ferrous materials and non-ferrous metals against corrosion or oxidation where it is impractical to apply surface treatments. VCIs slowly release chemical compounds within a sealed airspace that actively prevent surface corrosion. VCIs work by absorption and release corrosion inhibiting compound molecules into the air. When these compound molecules come in contact with metal surfaces, the vapors from the VCIs form a very thin molecular layer. This thin layer is designed to inhibit corrosion on the metal surface by preventing air and moisture from coming into contact with the surface. VCIs have been used for many years in other industries, such as for packaging and shipping services. A typical application is to protect stored tools or parts inside bags, boxes, or other storage containers.

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30 https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=570.
31 https://primis.phmsa.dot.gov/rd/gapsuggestions.htm.

Manufacturers of VCIs and operators with non-PHMSA regulated tank facilities have been experimenting with VCIs as a means for protecting the bottoms of aboveground tanks from corrosion for some time. Studies on these experimental projects have shown a reduction in the corrosion rate of the tank bottom. Currently, industry standards for the use of VCIs do not exist.

Studies, including one conducted by Pipeline Research Council International[32] (PRCI) in 2018, have concluded that VCIs can be effective at reducing general corrosion. These studies have also concluded that with VCIs, localized pitting can occur at rates higher than what is considered protected under NACE SP0169 and NACE SP0193,[33] which may require more frequent out of service inspections to ensure a leak does not occur. The recommendations for future activities from PRCI's report included the following:

- Determine the effectiveness including the operational life of VCIs in the field under varying conditions across the range of geographical locations around the country or the world. Using metal mass-loss coupons on tanks with and without VCIs would generate data that could be analyzed to determine under what conditions VCIs would provide sufficient protection to be used without CP.
- Improve in-situ monitoring of VCI performance by developing new monitoring procedures or new monitoring systems. Operators that have used VCIs have tended to use ER probes to estimate the corrosion rate. ER probes are a widely used technique for estimating metal loss, but operators often find large variations depending on probe positions. The number of ER probes and the ideal location of the probes has not been investigated so operators may not be using enough probes or locating the probes where the highest corrosion rate may be occurring. Research or the use of measurement devices from other industries may provide more accurate measurements than using a limited number of ER probes.
- Determine how to best apply VCIs to make sure the entire tank bottom area is protected. Currently, VCIs are commonly applied to existing tanks by mixing the VCI powder into water and injecting that fluid into ports in the ring wall or space under the tank. Aboveground storage tanks can be larger than 250 feet in diameter and injecting VCIs at only one point may not provide ideal protection to the whole tank. Studies that model VCIs spread across the underneath of a tank may provide improved methodologies for VCI distribution.

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32 *Effectiveness of Vapor Corrosion Inhibitors (VCIs) for Corrosion Control on Aboveground Storage Tank Foundations,* Pipeline Research Council International, 2018.

33 The purpose of this standard practice is to present practices for application of CP to control external corrosion of carbon steel on-grade storage tank bottoms that are in contact with an electrolyte. Practices for application of both galvanic anode CP systems and impressed current CP systems are included.

- Determine if bacteria activity or biocides impact the effectiveness of VCIs through laboratory and field studies.
- Determine criteria where CP and VCIs are used together, particularly in highly corrosive environments, and whether these are compatible.

Additionally, API published a Technical Report on VCIs for Storage Tanks[34] in April 2021. The report provides guidance on using VCIs for corrosion protection for ASTs. Specifically, the report provides information on application methods, elements that affect installation and maintenance, monitoring and replenishment, and compatibility to use VCIs and CP together. The report does not provide specific methodologies, nor does it make any conclusions on the effectiveness of VCIs for corrosion mitigation.

In addition to the above-mentioned recommendations from PRCI's report, PHMSA subject matter experts have identified areas that would need to be addressed for consideration of VCIs as an alternative to CP:

- Determine the amount and lifespan of VCIs and spacing of injection locations that are required in an area to mitigate corrosion most effectively. VCI injection and monitoring equipment would need to be installed upon tank construction and would need to be suitable for the soil, loading, temperature, and soil moisture conditions.
- Develop construction and operating procedures for VCI usage, including how the VCIs will be sealed under the tank bottom.
- Determine the degradation rate of VCIs for different tank environments.
- Determine how VCI levels will be maintained throughout the life of the tank and product.
- Determine the appropriate procedures to ensure full coverage of the bottom of the tank floor with VCIs and how this can be tested.
- Determine how the effectiveness of the VCIs will be monitored and at what inspection intervals.
- Describe the effect temperature (operational and ambient) will have on the VCI corrosion protection of the proposed tanks. Describe how an operator will know when additional VCIs are needed and how will the VCIs be recharged.

Another corrosion control practice discussed in the literature is the attempt to isolate the tank bottom so a corrosion cell cannot occur. These designs use a concrete pad with an insulating barrier such as a pad of high-density polyethylene. If electrical isolation can be maintained, the tank bottom should not corrode; however, there have not been any long-term studies on this type of tank design to determine if electrical isolation can be maintained. There are no current standard designs that best implement the use of concrete to prevent or minimize water intrusion between the concrete and tank floor.

Electrical isolation also makes it difficult to monitor the tank bottom to see if corrosion is occurring. Most monitoring devices, such as corrosion coupons used under structures, require an electrical connection, so alternative monitoring may be required. These designs commonly use leak detection integrated into the concrete pad to detect small releases before a large incident occurs.

10. Conclusion

PHMSA currently requires operators install CP on all newly constructed or modified ASTs in accordance with the Federal PSR. The CP systems on ASTs are intended to prevent corrosion on the outside tank bottoms (soil side) and reduce the potential for leaks that could impact people, property, and the environment. Properly installed CP systems are normally very effective at reducing the amount of corrosion on the bottom of a tank. In some instances, due to local soil and moisture conditions, electrical interference, or other circumstances where CP is difficult, other methods of corrosion control may help lower the risk of a leak occurring. However, additional research, development of standards, or consideration through special permits would be needed to assess the effectiveness of these other methods.

PHMSA reviewed the available literature, which indicated that operators of non-regulated tanks have employed several non-traditional corrosion control methods for protection of ASTs. One method reviewed by PHMSA is VCIs, which are a class of chemicals that form a protective barrier on a surface and can reduce the corrosion rate of the protected metal. Research has indicated that use of VCIs may be an effective method for corrosion control to meet the Federal PSR. However, there is currently no industry standard for the use and monitoring of VCIs for tank bottom corrosion control.

Another practice observed in the literature for corrosion control is isolating the tank bottom from a corrosive environment by using a non-conductive membrane or similar material. This approach will typically employ a leak detection system under the tank due to electrical isolation of the tank bottom making it difficult to monitor for potential corrosion. Currently, PHMSA is not aware of any studies on the long-term effectiveness of this practice, and there is currently no industry standard for these types of practice.

PHMSA executes a robust research program that has focused on advancing innovation and new technology development to minimize risks to pipeline facilities and to provide scientific research and data to inform pipeline decision-makers. PHMSA has sponsored several research projects through the CAAP on corrosion prevention/mitigation projects. Some of the concepts proved through the CAAP could be further investigated to determine their effectiveness on preventing corrosion on AST bottoms. Subject to availability of R&D funds, PHMSA could conduct such research under its Core Research Program.

Furthermore, a pipeline operator may apply for a special permit pursuant to 49 CFR § 190.341, to request a waiver of compliance with one or more of the Federal PSR. PHMSA reviews these applications to determine whether granting a special permit would not be inconsistent with pipeline safety. Operators could use the special permit process to propose alternate corrosion control methods for tank bottoms.