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192-0401

Corrosion Reactions

This module will discuss a variety of corrosion types. Each type involves either a chemical reaction or an electrochemical reaction.

Chemical Reaction
Chemicals in the environment react with the metal to create different chemicals (e.g., rust).

Electrochemical Reaction
The environment around the metal results in the creation of an electrical current (flow of electrons). The metal corrodes by giving up electrons to create the electrical flow.

Rust

Rust is one of the first symptoms of corrosion.

Rust is a form of corrosion that affects ferrous metals (irons and steel) only.

Oxidation is the chemical process that causes rust.

Oxidation

Oxidation is the chemical reaction between iron and oxygen.

During oxidation the metal loses electrons, leaving metal ions that carry a net positive charge. The oxygen forms negative ions. The metal and oxygen ions then combine to form oxide. Moisture is necessary to facilitate transport of the electrons

Corrosion Never Stops

Although we can't stop corrosion, we can take steps to slow or reduce it through the use of:

- Cathodic and anodic protection
- Corrosion inhibitors
- Protective pipe coatings
- Appropriate material selection

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A Natural Process

During the corrosion process the impurities in the metal are attacked. The metal reacts with the environment to form a more stable compound. The result is corrosion.

Differences in metals and variations in environment affect corrosion. The higher the purity of the metal, the more resistant it is to corrosion.

Causes of corrosion include:

- **Dissimilar Metals**
- **Dissimilar Soil Types**
- **Dissimilar Pipe Ages**
- **Dissimilar Surface Conditions**
- **Differential Soil Aeration**

Coating Against Corrosion

To provide a barrier to protect the pipe from the corrosive environment, pipes may be coated (or jacketed) with paint, tape, or insulation. The coating functions to prevent electrolytes from contacting the pipe.

Wet/dry conditions are particularly difficult on coatings. These conditions can result in concentration of corrosive species and mechanical action that tend to breakdown protective corrosion films and coatings on the metal surface.

Atmospheric Corrosion

Atmospheric corrosion results from the attack of natural elements on exposed base metal.

Moisture (i.e. rain, dew, sleet, snow, and fog) can collect or form on the pipe. This surface moisture creates the electrolyte required for corrosion to occur. The severity and rate of corrosion will depend on additional atmospheric conditions, such as ambient temperature, humidity, pollution, etc.

Localized Corrosion

Localized corrosion is concentrated in a small area of pipe. Pitting is a form of localized corrosion characterized by small corrosion spots on the pipe's surface

An amount of localized corrosion sufficient to weaken the pipe wall is normally reclassified as general corrosion.

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Generalized Corrosion

Generalized corrosion (also referred to as uniform corrosion) reduces wall thickness over a large area of pipe.

This may be the result of:

- Break down of a passive layer of the surface material
- Expanded localized corrosion sufficient to weaken the pipe wall

Corrosion Cracks

Cracks occasionally occur due to fatigue, stress corrosion, or weld defects. Crack length and depth, along with stress level and pipe material, determine whether an individual crack will fracture or fail.

Stress corrosion cracking, which is environmentally-assisted cracking, results from a combination of normal operating stress and a corrosive environment.

Selective corrosion cracking is a localized corrosion attack along the bond line of welds, creating a groove that is often filled with corrosion products.

Galvanic Corrosion

Galvanic corrosion results when two unlike metals, surrounded by the same electrolyte, are electrically connected. The corrosion is caused by the voltage difference between the two metals.

The material with the highest electrochemical energy is called the anode, while the material with the lowest is called the cathode. The anode will experience corrosion while the cathode does not.

To prevent galvanic corrosion electrical isolation flanges, or bonding wires, are used when joining pipe sections.

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Microbiologically Influenced Corrosion (MIC)

MIC refers to corrosion influenced (or induced) by bacteria. Associated with localized or pitting corrosion, MIC is responsible for a vast amount of natural gas pipeline degeneration.

The microorganisms of interest are mostly bacteria, fungi, algae, and protozans. As the microorganisms colonize they (partially) destroy natural and man made materials such as ductile iron, steel, copper, concrete, plastic, and fiber-reinforced polymeric composites.

Graphitic Corrosion

Graphitic corrosion a form of corrosion that affects gray or ductile cast iron pipe. Through selective leaching, the iron matrix corrodes, leaving behind a porous graphite mass that can be carved with a **pocketknife**. The cast iron thus loses its strength and becomes brittle.

Aboveground Pipe

Pipe corrosion resulting from exposure to oxygen and moisture is called oxidation.

Oxidation is the chemical process in corrosion. Electrons leave the atoms they start with to mingle with oxygen atoms, degrading the base material and forming a corrosion film.

Examples of corrosive films include:

- Rust
- Iron oxide
- Copper patina

Underground Pipe

The conductivity of the soil around buried pipe affects the risk of corrosion.

For example, the pipe's potential for corrosion increases when surrounded by material having a high clay content, since clay is more conductive.

The most corrosive soils are typically those with the lowest pH and highest sulfide and chloride concentration. Alternating wet-dry conditions are particularly difficult, and can lead to the breakdown of protective corrosion films and coatings on the metal surface.

Soil Corrosivity

Although there are no set standards, the classifications shown at the right are generally agreed upon.

Contributing factors affecting the corrosivity of soils to buried pipelines include:

1. **Soil resistivity**
2. **Presence of chlorides and sulfates**
3. **Oxygen content**
4. **pH**

Resistivity (Ohm-Cm)	Corrosivity
Less than 500	Very Corrosive
500 to 1,000	Severely Corrosive
1,000 to 2,000	Moderately Corrosive
2,000 to 10,000	Mildly Corrosive
Greater than 10,000	Progressively Less Corrosive

Soil Resistivity

Soil resistivity is the reciprocal of soil conductivity.

It is important to know how soil resisitivity varies along the route of a (electrically continuous) buried pipeline. Identifying the resisitivity is helpful in predicting relative corrosion rates. Portions of the pipeline in lower soil resisitivity environments may become anodic and therefore corrode faster than other sections of the pipeline.

Internal Corrosion

Although liquid is removed from pipeline quality gas, condensation may still result due to pressure and temperature changes.

- **When the temperature of a gas drops below its hydrocarbon dew point condensation occurs**

Corrosive materials, such as oxygen, carbon dioxide, and hydrogen sulphide, can react with the condensation to corrode the pipeline's inner lining.

External Corrosion

All metal pipes are susceptible to external corrosion:

- Exposure to natural elements may result in atmospheric corrosion
- Polluted rain (acid rain) can accelerate corrosion
- The corrosivity of soil surrounding buried pipe affects corrosion potential
- Microorganisms (such as bacteria, fungi, algae, and protozans) may contribute to corrosion

Corrosion Cell

The different electrical potentials within the pipe material will results in anodic and cathodic areas. Changing the environment around these areas can result in the formation of an electrolytic corrosion cell.
On metal that is uniform in composition, all that is required to start a localized corrosion attack is a drop of water. The drop of water sets up an electrochemical cell because the surface dissolves oxygen from the air. Farthest from the air the oxygen concentration is the lowest. The metal at the center of the droplet becomes the anode and the outer edges the cathode.

Corrosion Inhibitors

A corrosion inhibitor is basically a substance that, when added in a small concentration to an environment, effectively reduces the corrosion rate of a metal exposed to that environment.

Prior to installation a corrosion inhibitor may be applied to the inside of the pipe. After placing the pipe in service, additional internal corrosion protection may be provided by continuous injection or atomization of a corrosion inhibitor into the line.

Pipe Coatings

A variety of polymeric coatings are used to coat the pipe and provide a barrier to protect the pipe from the corrosive environment. These coatings can be sprayed, brushed or rolled on.

Insulating coatings and linings work to prevent corrosion by imposing a dielectric barrier (one which is not able to conduct direct electric current) between the pipe and the corrosive environment.

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Cathodic Protection

Cathodic Protection is a form of corrosion protection that turns the entire pipeline into the cathode of a corrosion cell. The cathodic protection system will provide the required corrosion protection in the event of coating failure.

The design of cathodic protection systems must be based upon local environmental conditions such as soil resistivity.

Cathodic Protection Requirements

According to 49 CFR §192.455:
Buried or submerged pipeline installed after July 31, 1971, must be protected against external corrosion through the use of protective coatings and cathodic protection.

According to *49 CFR §192.457*:
Buried or submerged pipeline that has an "effective external coating" and was installed before August 1,1971 must be cathodically protected. This applies to all pipe except:

- Buried piping at a compressor, regulator, and measuring station
- Cast iron or ductile iron

Soil Characteristics

Soil corrosivity must be taken into account when determining the type of corrosion protection to use. The chemicals present in the soil, moisture content of the soil, and the soil type, all affect soil corrosivity.

The soil's moisture content, clay content, and salinity will determine its resistivity. An environment with a lower soil resistivity may contribute to corrosion growth.

Isolation Devices

If two metals having different electrical potentials were to be joined directly, a corrosion cell would result. For this reason joints must be electrically insulated.

- Electrically insulating couplings may be installed with the correct gasket insulators
- If a non-insulated coupling is installed on cathodically protected pipe, you must maintain cathodic protection through the use of bonding wires (or similar device)

Processed Gas

Gas from a producing well is referred to as "field" or "unprocessed gas." Field gas must be treated to remove contaminants that may cause internal corrosion:

- Water
- Liquids
- Impurities

Once purified, the gas is considered pipeline quality and fit for transportation

Gas Sampling

Routine samples should be taken of the natural gas in the pipeline. Check samples for indications of:

- Corrosion to the interior of the pipeline
- Contaminants that could contribute to MIC (microbiologically influenced corrosion)

Corrosion

Corrosion manifests itself in many forms. If not treated it can result in localized pitting, general corrosion, or be limited to a certain area to form stress cracking. Severe corrosion may cause loss of pipe wall thickness.

Pipe Wall Thickness

If pipe wall thickness is reduced to the point where the pipe could leak, or fails to meet the system MAOP, you must make the decision whether to replace the pipe, repair the pipe, or reduce the operating pressure to correspond with the remaining wall thickness.

Measuring Pipe Wall Thickness

There are a variety of instruments that may be used to measure thickness of the pipe wall. These include:

- **Micrometer**
- **Pipe Thickness Gauge**
- **Ultrasonic Thickness Gauge**
  uses electronic ultrasonic technology

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Measuring Pipe Strength

Following an in-line inspection, the data is interpreted and prepared for analysis. Thousands of anomalies must then beclassified into the following defect categories:

- External corrosion
- Internal corrosion
- Cracks
- Material defects

Active Corrosion

Active corrosion is continuing corrosion that could result in a hazardous condition if not controlled.

In areas of active corrosion you will need to perform leak detection surveys more often than the DOT minimum

Inspection: Aboveground Pipe

Aboveground pipelines should be inspected at intervals in accordance with local O&M manuals. Visually inspect all sides of aboveground pipe for signs of:

- Rust
- Cracked wrap
- Peeling paint

Unless an operator can demonstrate that a corrosive atmosphere does not exist, each aboveground pipe (installed after July 31, 1971) exposed to the atmosphere must be coated or jacketed with a material suitable for the prevention of atmospheric corrosion

Inspection: Exposed Pipe

Whenever any portion of a buried pipeline is exposed, the exposed portion must be examined for evidence of:

- External corrosion
- Coating deterioration

If external corrosion is detected you will need to investigate to determine the extent of corrosion and remedial action required

Inspection: Atmospheric Corrosion

Evaluate onshore pipelines exposed to atmosphere at intervals not exceeding three years. Determine the areas of atmospheric corrosion on the pipeline, and if atmospheric corrosion is found, take remedial measures:

- §192.485
- §192.487
- §192.489

Clean and either coat or jacket the areas of atmospheric corrosion on the pipeline with a material suitable for the prevention of atmospheric corrosion.

Inspection: Belowground Pipe

Unless an operator can demonstrate by tests, investigation, or experience in the area of application, including, as a minimum, soil resistivity measurements and tests for corrosion accelerating bacteria, that a corrosive environment does not exist, buried pipe must be protected against external corrosion.

Belowground piping that is exposed to atmospheric corrosion in utility pits or vaults must also be coated or jacketed.

Inspection: External Corrosion

Inspect the pipe for:

- Damaged pipe
- Corrosion
- Gas leak
- Damaged or disbonded coating
- Discolored or mottled surfaces

Thoroughly investigate bare spots and areas with cracked coating. Verify cathodic protection and investigate locations where the CP reading is below minimal.

Inspection: Pipe Coatings

The DOT requires inspection of coatings at least once every three years.

Premature pipeline corrosion is often due to coating failure. A major cause of coating failure is the presence of flaws in the finished coating, such as:

- Pinholes
- Holidays
- Thin spots

Early inspection for coating flaws will prevent the expense and inconvenience of coating failure.

Inspection: Tape Coating

Wrinkled tape coating forms long, narrow pockets of disbondment. This can result in corrosion "grooves" forming on the pipe surface. This corrosion is sometimes more difficult to detect since it takes on the appearance of the coating wrinkle.

Inspection: Coating Performance

An evaluation of coating performance determines its resistance to the corrosive environment, and its adhesion to the pipe.

Evaluation techniques (such as electrochemical impedance spectroscopy) can be used to assess changes in the coating resistance prior to any visual indications.

Inspection: Coating Disbondment

Coating defects generally take the form of either exposed bare steel or a disbondment in which the coating remains intact but a crevice is formed between it and bare steel.

Defects covered by disbonded coating can be difficult to detect because the coating shields the crevice from cathodic protection.

Inspection: Cathodic Protection

Pipe-to-soil potential measurements are the primary means for monitoring the effectiveness of cathodic protection systems.

Inspection Documentation

Operating and maintenance plans for each pipeline must include a corrosion control plan, including a procedure manual for:

- Operation and maintenance
- Emergency response

Systematic and routine testing and inspection is required for all pipe-type or bottle-type holders. This also includes a provision for detecting external corrosion before the strength of the container has been impaired.

Inspection Records

Operators must maintain a record of each test, survey, or inspection (as required by Subpart I of Part 192). Records must provide sufficient detail to demonstrate the adequacy of corrosion control measures, or that a corrosive condition does not exist

Follow Proper Procedures

Follow inspection/monitoring procedures as outlined in your Company procedure manual.

- Appropriate parts of the manual must be kept at locations where operations and maintenance activities are conducted

Coating Inspection

Wet/dry conditions are particularly difficult since they can result in concentration of corrosive species and mechanical action that tend to breakdown protective corrosion films and coatings on the metal surface.

Inspect for Abnormal Operation Conditions such as:

- **Coating failure**
- **Cathodic disbondment**

Review your company's O&M documentation procedures and follow procedures to report/document detected corrosion

Coatings: EIS Inspection

In situ corrosion sensors use **electrochemical impedance spectroscopy** technology to detect moisture intrusion and degradation of coatings, composites, and adhesive bonds.

- A permanent version attaches an electrode to the surface
- A portable version allows a hand-held probe to be pressed against the surface

All cathodic protection systems must be monitored for:

- Adhering to acceptable levels
- Minimizing effects on adjacent metallic structures for anode systems
- Adhering to electronic isolation guidelines
- Corroding of casings and existing installations
- Preventing arcing in a potentially combustible atmosphere

Pipe Inspection

Internal inspection devices may be used to ensure the pipe's integrity, looking for corrosion, irregularities or thinning of the pipe wall, or other factors that could affect public safety.

External sensors may be installed on the outside of the pipe and used to monitor corrosion growth.

Land and air patrols may be conducted to detect signs of leaks, unauthorized digging or other activities that could affect safety

Corrosion Monitoring Using Coupons

Corrosion coupons may be used to monitor:

- Internal or external corrosion rates
- Cathodic protection system effectiveness

Corrosion coupons provide:

- Details of several types of corrosion
- Physical evidence

Make sure to follow all manufacturer and Company procedures for removal and replacement of internal corrosion coupons

Internal Inspection: Pitting

Pitting is a form of corrosion, which can be serious if allowed to proceed until the pipe leaks. **A pit depth gauge may be used on corrosion coupons or removed pipe sections to determine the extent of internal pitting corrosion.**

If internal corrosion is found, the adjacent pipe must be investigated to determine the extent of internal corrosion.

If the pitting is severe enough to reduce the pipe wall thickness to the point where the pipe could leak you must make repair or replace the pipe section as required.

Internal Inspection: Inline Inspection

Sampling and culturing can be performed to determine extent of internal corrosion. Chemical analysis and pH of corrosion products can give important information relative to the nature of the problem.

Inline pipe inspection systems that traverse through the pipes also provide valuable information on corrosion conditions. These systems are extremely useful in monitoring corrosion in buried or inaccessible pipes.

Smart Pigs

A "pig" is a pipeline inspection gig used to detect pipeline corrosion. "Smart" pigs are robotic in-line inspection (ILI) tools that are driven through the pipe, by the product, and survey the condition of the pipe wall. These "smart" pigs can determine if corrosion is present on either the inside or the outside of the pipe wall.

Inline Inspection

Following an inline inspection, the data is interpreted and prepared for analysis. Thousands of anomalies must then be classified into the following defect categories:

- External corrosion
- Internal corrosion
- Cracks
- Material defects

Title 49 CFR Part 192 requires pipeline operators to use the assessment algorithms of one of two standards to evaluate the remaining strength of the corroded pipe:

- RSTRENG
- ASME/ANSI B31G

Remediation: Internal Corrosion

Whenever any pipe is removed from a pipeline for any reason, the internal surface must be inspected for evidence of corrosion.

If internal corrosion is found, the adjacent pipe must be investigated to determine the extent of internal corrosion.

Types of inspection which may be used include:

- Visual inspection
- Coupon inspection
- Gauges (micrometers, pit depth, etc.)

Remediation: External Corrosion

If external corrosion is found, the adjacent pipe must be investigated to determine the extent of external corrosion. Investigate until no further evidence of corrosion is found.

When replacing a section of buried metallic pipe due to external corrosion, the new pipe section must meet external protective coating and cathodic protection requirements as outlined in §192.241

Remediation: Graphitic Corrosion

If **localized graphitic corrosion** is found to a degree where any leakage might result, the pipe segment must be either:

- Repaired
- Replaced
- Sealed using adequate internal sealing methods

If **generalized graphitic corrosion** is found to a degree where any leakage might result, the pipe segment must be replaced.

Remediation: Localized Corrosion

If localized corrosion pitting has occurred to a degree where leakage might result, you must either:

- **Repair the pipe segment**
- **Replace the pipe segment**
- **Reduce the operating pressure as required by the reduced pipe strength, based on the actual wall thickness in the pits**

Remediation: Generalized Corrosion

If generalized corrosion has resulted in a reduction of pipe wall thickness, and the remaining thickness is less than that required by the system's MAOP, either:

- **Repair segment (if analysis indicates repair will permanently restore serviceability)**
- **Replace the segment**
- **Reduce the operating pressure as required by the reduced pipe strength**

Remediation: MIC Corrosion

Although biocides and inhibitors can be used to fight microbiologically influenced corrosion, one of the most effective actions to mitigate MIC is pigging.

Pipeline pigging involves insertion of a cleaning pig (pipeline inspection gig) into the pipe, which physically removes standing water and accumulated debris in the line

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Identify Potential Threat

An operator must identify and evaluate all potential threats to each covered pipeline segment.

Potential threats include, but are not limited to:

- **Internal corrosion**
- **External corrosion**
- **Stress corrosion cracking**

Gather Data

Operators must gather and integrate data and information concerning the entire pipeline that could be relevant to the covered segment.

Types of data include:

- **Past incident history**
- **Corrosion control records**
- **Continuing surveillance records**
- **Patrolling records**
- **Maintenance history**
- **Internal inspection records**

Finding Corrosion

If an operator finds corrosion on a covered pipeline segment that could adversely affect the integrity of the pipeline; the operator must evaluate and remediate, as necessary, all pipeline segments (both covered and non-covered) where similar corrosion might be found (i.e., with similar material coating and environmental characteristics).

The evaluation and remediation, if remediation is needed, must be completed in a time frame consistent with the operator's operation and maintenance procedures under part 192 for required testing and repair.

Assessment Methods

One or more of the following methods must be used when assessing the integrity of the pipeline segment(s).

- Internal inspection tool or tools capable of detecting corrosion
- Pressure test
- Direct assessment to address corrosion threats
- Other technology demonstrated to meet requirements

Direct Assessment

Direct assessment may be used to address the identified threats of corrosion. If used as the primary method make sure the plan complies with the requirements outlined in 49 CFR §192.923.

The rule allows an operator to use direct assessment either as a primary assessment method, or as a supplement to the other assessment methods.

Assessment Intervals

The required reassessment interval depends on the assessment method and the operating pressure of the pipeline.

If an operator establishes a reassessment interval that is greater than seven years, the operator must within the seven-year period, conduct a confirmatory direct assessment on the covered segment, and then conduct the follow-up reassessment at the interval the operator has established.

Measuring Program Effectiveness

Operators must use performance measures to measure, on a semi-annual basis, whether the program is effective in assessing and evaluating the integrity of each pipeline segment. The operator must also must define and monitor measures to determine the effectiveness of the ECDA process.

Maintaining Records

Operators must maintain, for the useful life of the pipeline, records that demonstrate compliance with the requirements of the integrity management program rule.