

RESEARCH TECHNICAL REPORT

*Corrosion and Corrosion
Mitigation in Fire
Protection Systems*



Corrosion and Corrosion Mitigation in Fire Protection Systems

by

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2nd Edition, July 2014

Project ID 0003040794

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EXECUTIVE SUMMARY

Overall Purpose of Work

The purpose of this technical report is to comprehensively explain corrosion in fire protection systems (FPS). Factors such as pipe weld corrosion, residual water in dry pipe systems, trapped air in wet pipe systems, microbiologically influenced corrosion (MIC), and corrosive water chemistry are discussed. A corrosion resistant fire sprinkler system for highly corrosive exhaust duct is also addressed. This report provides the basis for development of corrosion mitigation strategies of existing FPS and lays out directions for further study on corrosion mitigation and management of FPS.

Summary and Conclusions

A. Corrosion in Fire Protection Systems

1. Corrosion occurs in all sprinkler systems and is one of the major issues for maintenance and operation of Fire Protection Systems such as wet pipe, dry pipe, and preaction systems.
2. Corrosion damage/products and mineral deposits can restrict water flow to sprinklers and impair mechanical operation of FPS equipment, leaving facilities vulnerable to uncontrolled fire loss.
3. Several organizations, such as the National Fire Protection Association (NFPA), the Electric Power Research Institute (EPRI), FM Global, and the European Fire Sprinkler Network have published documents and standards attempting to address these problems. Yet, currently there is no agreed-upon strategy either within the fire protection industry or the National Association of Corrosion Engineers (NACE International) to effectively and efficiently mitigate corrosion in FPS.
4. Corrosion and corrosion-caused pipe leakage in FPS can be due to many factors or the combination of these factors, such as pipe weld corrosion, residual water in dry pipe systems, trapped air in wet pipe systems, corrosive water chemistry, periodic supply of

oxygenated water into the FPS (fresh sprinkler water recharged during regular maintenance), stagnant water, and microbiologically influenced corrosion (MIC).

5. This document comprehensively discusses potential forms of corrosion in FPS, including uniform corrosion, galvanic corrosion, pitting corrosion, crevice corrosion, selective leaching, erosion corrosion, environmentally induced corrosion, intergranular corrosion, MIC, corrosion and premature operation of sprinklers, along with degradation of CPVC (chlorinated polyvinyl chloride) sprinkler piping.
6. This document discusses parameters leading to corrosion and/or leakage of steel piping in FPS, such as tuberculation, water chemistry, sprinkler pipe thickness, weld seam corrosion, trapped air (wet systems), and residual water (dry systems).
7. A corrosion resistant fire sprinkler system for highly corrosive industrial exhaust duct has been developed by FM Global and approved manufacturers. The approved products and system are available for field installation, including corrosion resistant sprinkler nozzles, linear heat detector wires and fire control panel, flexible sprinkler connections, plus other accessories.

Recommendations

A. Corrosion in Fire Protection Systems

Corrosion damage increases the life cycle costs of fire protection significantly and corrosion-caused impairments of FPS can increase the risk of an uncontrolled fire loss; for these reasons it is necessary to have corrosion mitigation strategies for FPS, as detailed in Part B below.

B. Potential Corrosion Mitigation Strategies

1. Orient longitudinal pipe weld seam toward building roof - at least 45° in relationship to the floor (for reference, the weld line points at the floor at 0°) to mitigate pipe weld seam corrosion in the FPS.

2. Fill dry pipe or preaction systems with nitrogen as supervisory gas (e.g., use on-site nitrogen generator) to mitigate galvanized steel pipe corrosion in the dry type FPS.
3. Install an FM Approved air-venting device to remove trapped air in wet pipe systems to mitigate pipe corrosion near air pockets.
4. Use treated water such as municipal water (i.e., avoid untreated raw water) as the source of sprinkler water for better water quality and less corrosion of FPS.
5. Apply only those chemicals (e.g., pipe cutting oil, adhesives, paints, antifreeze, etc.) approved by Lubrizol, FM Global, and UL for hybrid CPVC fire protection systems to avoid potential environmental stress cracking (ESC) failure of CPVC piping material.

C. Future Developments

1. Evaluate the effectiveness of chemical corrosion inhibitors including vapor phase corrosion inhibitors (VCI), organic and inorganic phosphate (PO_4), and biocides under fixed condition for optimization of corrosion mitigation and application variables to reduce potential problems with the application of corrosion inhibitors in FPS.
2. Develop methods for water filtration or treatment (ion exchange or chemical precipitation) of source water to remove aggressive anions from the sprinkler water to reduce water corrosivity. The focus is on proper system design to effectively mitigate corrosion in FPS by evaluating corrosion rate as a function of the Larson-Skold index, water chemistry and oxygen concentration to provide criteria for ion exchange or chemical precipitation performance goals.

ABSTRACT

This technical report comprehensively discusses corrosion in fire protection systems (FPS). Factors such as pipe weld corrosion, residual water in dry pipe systems, trapped air in wet pipe systems, microbiologically influenced corrosion (MIC), corrosive water chemistry, and degradation of CPVC sprinkler piping are discussed. A corrosion resistant fire sprinkler system for exhaust ducts with highly corrosive atmospheres is also addressed.

For steel sprinkler piping, corrosion with leakage is one of the major issues for maintenance and operation of water-based FPS, such as wet pipe, dry pipe, and preaction systems. Repair of corrosion damage due to mechanical failure or water damage adds significantly to the lifecycle cost of sprinkler protection systems in buildings. In addition, buildup of insoluble deposits inside steel sprinkler piping (e.g., tubercles and pipe scale due to corrosion, calcium carbonate and magnesium carbonate deposits due to water hardness) can obstruct water flow in pipes and/or plug sprinklers. Therefore, corrosion damage/products and mineral deposits can impair the effectiveness of sprinkler systems and leave facilities vulnerable to uncontrolled fire loss.

Potential corrosion mitigation strategies in FPS are discussed, such as orienting pipe weld seam toward building roof, filling the dry pipe or preaction systems with nitrogen as supervisory gas, venting trapped air in wet pipe systems, improving water chemistry, along with applications of biocide and corrosion inhibitors. This report provides the basis for development of corrosion mitigation strategies of existing FPS and lays out directions (i.e., Future Developments) for further study on corrosion mitigation and management of FPS.

ACKNOWLEDGMENTS

The authors thank Mr. F. W. Tatar, Mr. B. W. Swinnerton, Dr. G. G. Yee, and Ms. S. Chivukula at FM Global Research, Ms. A. Morcos of FM Global Engineering Standards, especially many CETS and engineers of FM Global Engineering for their contributions to this report. Thoughtful reviews and recommendations from Dr. L. A. Gritzko (VP, Manager of Research), Dr. W. W. Doerr (AVP, Past RRFP Research Area Director), and Dr. F. Tamanini (Acting RRFP Research Area Director) are greatly appreciated.

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1 INTRODUCTION

For steel sprinkler piping, corrosion that results in pipe leakage or obstruction is the most significant issue for owners of water-based fire protection systems (FPS), in terms of both cost and system reliability. Repair of corrosion damage due to mechanical failure or water damage significantly adds to the lifecycle cost of sprinkler protection systems in buildings.^{1,2,3,4,5} In addition, the buildup of insoluble deposits inside steel sprinkler piping (e.g., tubercles and pipe scale due to corrosion, calcium carbonate and magnesium carbonate deposits due to water hardness) can obstruct water flow in the pipe and/or plug sprinklers.^{1,4} Therefore, corrosion damage/products and mineral deposits can impair the effectiveness of sprinkler systems and leave facilities vulnerable to uncontrolled fire loss.

Corrosion and corrosion-caused pipe leakage in FPS are complicated issues. They can be caused by many factors or the combination of these factors, such as pipe weld seam corrosion, residual water in dry pipe systems, trapped air in wet pipe systems, corrosive water chemistry, periodically supplying oxygenated water into the FPS (fresh sprinkler water recharged during regular maintenance), stagnant water, and microbiologically influenced corrosion (MIC).

Many technical articles have been published discussing corrosion issues in FPS.^{6,7,8,9} These documents often look into partial aspects of corrosion in FPS, especially focusing on microbiologically influenced corrosion (MIC).^{7,8,9,10,11} Several organizations such as the National Fire Protection Association (NFPA),^{1,7,9} the Electric Power Research Institute (EPRI),⁶ and FM Global,^{3,4,5} have also published standards and guidelines attempting to address these problems. Yet, there is no agreed-upon strategy within either the fire protection industry or the national corrosion community to effectively and efficiently mitigate corrosion in FPS.

A publication discussing corrosion in FPS and potential corrosion mitigation methods is needed. This document comprehensively explains different types and contributing factors of corrosion that can occur in FPS, such as pipe weld corrosion, water corrosivity, MIC, trapped air (wet systems), and residual water (dry systems); provides the basis for development of corrosion mitigation strategies of existing FPS; and lays out directions for further study on corrosion mitigation and management of FPS.

2 OBJECTIVES

The objectives of this report are summarized as follows:

1. Comprehensively explain different types of corrosion and contributing factors that can occur in FPS, such as pipe weld corrosion, water corrosivity, MIC, trapped air (wet systems), and residual water (dry systems).
2. Discuss potential corrosion mitigation methods in FPS.
3. Provide the basis for development of corrosion mitigation strategies of existing FPS and lay out directions for further study on corrosion mitigation and management of FPS that may yield cost-effective solutions for FM Global clients and the fire protection industry.

3 CURRENT STANDARDS

Several organizations (NFPA, EPRI, FM Global, and European Fire Sprinkler Network) publish documents discussing corrosion issues and corrosion mitigation methods in FPS. The following findings summarize these major documents and the activities of other organizations, including the National Association of Corrosion Engineers (NACE International), Underwriters Laboratory (UL), the American Society for Testing and Materials (ASTM), the European Fire Sprinkler Network, and the International Organization for Standardization (ISO).

3.1 NFPA

NFPA 13 “Installation of Sprinkler Systems”¹² and NFPA 25 “Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems”² partially address corrosion in FPS. The second author of this report is actively participating in NFPA 13 and 25 committees.

Recommendations within NFPA publications are summarized as follows:

1. Where the sprinkler system water is known to have unusual corrosive properties, or conditions that contribute to MIC are present, one of the following is required (NFPA 13 – 24.1.5.1 and 24.1.5.2):
 - a. Install sprinkler pipe that is corrosion resistant - the piping shall have a corrosion resistance ratio (CRR)^{i,ii} of 1 or higher (NFPA 13 – 8.16.4.2.2)
 - b. Treat all water that enters the sprinkler system with an approved corrosion inhibitor and/or biocide. They are to be compatible with system components and, when used together, compatible with each other.
 - c. Monitor the sprinkler system for corrosion.
2. Requirement for dry pipe and preaction sprinkler systems:
 - a. Piping should be pitched towards low point drains (NFPA 8.16.2.3).

ⁱ CRR value: thickness of schedule 40 pipe under the first exposed thread. The “first exposed thread” is the minimum pipe thickness exposed to both interior and exterior corrosion. It occurs at the threaded joint assembly at a line defined by the thread width, just before the pipe engages the fitting.

ⁱⁱ $CRR = (X/X_{40})^3$ - i.e., cube function of thickness ratio, X = pipe thickness (incorporate the minus tolerance to calculate the thinnest thickness), X_{40} = thickness of schedule 40 pipe under the first exposed thread.

- b. An option for controlling corrosion in dry and preaction sprinkler systems is to use nitrogen as a supervisory gas.
3. The following inspections are required:
 - a. All sprinkler system piping should be inspected internally every 5 years for the presence of obstructions created by corrosion.
 - b. All sprinkler system piping and fittings should be inspected externally for leakage and corrosion annually.

3.2 FM GLOBAL

FM Global Property Loss Prevention Data Sheets (DS) 2-0 “Installation Guidelines for Automatic Sprinklers”³ and 2-81 “Fire Protection System Inspection, Testing and Maintenance and Other Fire Loss Prevention Inspections”⁵ discuss certain corrosion aspects in FPS.

The following recommendations summarize current FM Global corrosion mitigation strategies in FPS:

1. Sprinkler weld seams should be oriented towards the building roof to prevent the weld from being located under deposits within the pipe.
2. Sprinkler pipe should be protected against contamination prior to installation.
3. The frequency of sprinkler system draining and refilling should be minimized.
4. Trapped air within the sprinkler system should be minimized.
5. The use of rolled groove fittings should be avoided in dry and preaction sprinkler systems.
6. Internally galvanized pipe should be used for dry and preaction systems.
7. Dry and preaction sprinkler system piping should be pitched towards low point drains.

8. An option for controlling corrosion in dry and preaction sprinkler systems is to use nitrogen as a supervisory gas.
9. Currently, the use of pipe cleaning and water treatment chemicals is not recommended for sprinkler systems.

At present, FM Global is studying corrosion prevention and mitigation strategies for FPS. Note that the first edition of this technical report was originally published in June 2011; additional research results and information (e.g., pipe weld corrosion, on-site nitrogen generator, corrosion resistant fire sprinkler system for highly corrosive environments, etc.) have been added to this report.

3.3 EPRI

In 1999, EPRI published a document titled “Guideline for the Evaluation and Treatment of Corrosion and Fouling in Fire Protection Systems.” This document proposed potential corrosion mitigation methods for FPS, including physical and chemical cleaning of sprinkler piping systems, chemical control of microbial and macro-biological growth, corrosion inhibitor applications, and corrosion monitoring techniques.

The implementation of these methods can be labor intensive and may not be efficient in managing corrosion issues for FPS.

3.4 NACE INTERNATIONAL

NACE International does not have standards related to corrosion in FPS. Two NACE technical committees, “TEG 159X- Building Fire Protection Systems: Corrosion and Deposit Control” and “TG 381 – Fire Protection Systems,” are developing corrosion mitigation methods and documents in building FPS. The first author of this report is actively participating in these NACE committees.

3.5 EUROPEAN FIRE SPRINKLER NETWORK

A report titled “Corrosion in Sprinkler Systems” was published by the European Fire Sprinkler Network in 2013.¹³ It briefly describes corrosion related issues and risks for the FPS.

3.6 ASTM, UL, AND ISO

Currently, ASTM, UL, and ISO do not have standards and/or committees attempting to mitigate corrosion in FPS.

4 CORROSION IN FIRE PROTECTION SYSTEMS

Corrosion involves the reaction between a metal or alloy and its environment. It is an irreversible interfacial process, which causes the gradual deterioration of metal surface by water (or moisture) and corrosive chemicals. In aqueous or humid environments, corrosion is an electrochemical reaction in nature; it involves electron (e^-) transfer between anodic and cathodic reaction sites. For corroding metals, the anodic reaction is the oxidation (i.e., loss of electrons) of a metal to its ionic state:

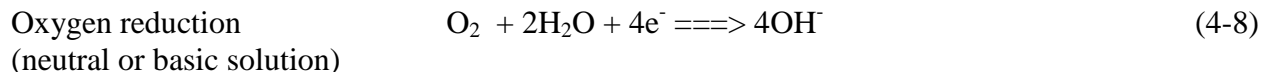
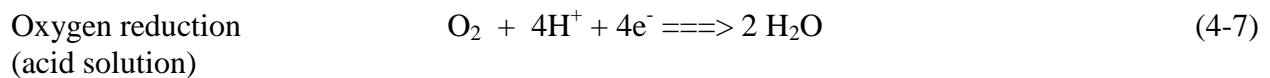
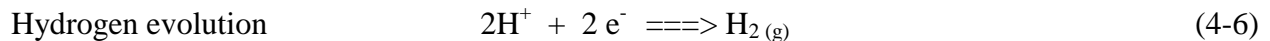


Examples:



The cathodic reaction is a reduction (i.e., gain of electrons) process. For metal corrosion, cathodic reactions like reactions 4-6 to 4-8 are frequently encountered. In acid solutions, hydrogen evolution and oxygen reduction reactions (reactions 4-6 and 4-7) are the main cathodic reactions. In neutral or basic pH solutions, oxygen reduction reaction (reaction 4-8) is the primary cathodic reaction.

Cathodic reactions:



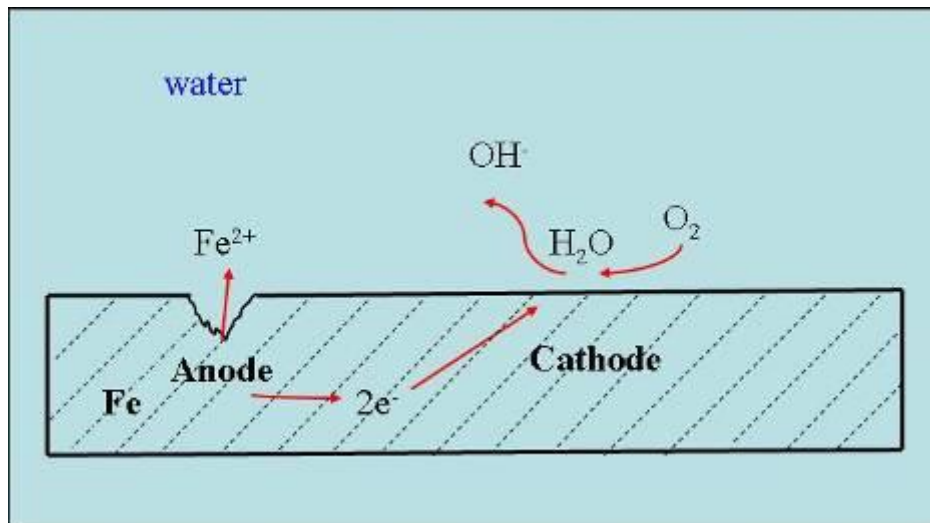


Figure 4.1 A schematic illustration of iron (Fe) corrosion in water. The Fe dissolves into Fe²⁺ at the anode, liberating electrons (e⁻) to react with O₂ and water to form hydroxide ions (OH⁻) at the cathode (oxygen reduction reaction).

Figure 4.1 shows a schematic illustration of iron (Fe) corrosion in water. The Fe dissolves into Fe²⁺ at the anode, liberating electrons (e⁻) reacting with O₂ and water to form hydroxide ions (OH⁻) at the cathode (oxygen reduction reaction). In general, when a FPS is supplied with sprinkler water containing oxygen, corrosion of steel or galvanized steel pipe (anodic reaction) in the FPS will occur and continue, until oxygen in the water (cathodic reaction) is depleted by the corrosion reactions.

4.1 FORMS OF CORROSION

While corrosion for metals can occur in many forms, it is generally characterized as eight or nine forms depending on how corrosion is defined.¹⁴ In addition, the degradation of chlorinated polyvinyl chloride (CPVC) sprinkler piping is discussed in Section 4.5.

These forms of corrosion include:

1. Uniform (or general) corrosion;
2. Galvanic or two-metal corrosion;
3. Pitting corrosion;

4. Crevice corrosion;
5. Selective leaching;
6. Erosion corrosion;
7. Environmentally induced cracking;
8. Intergranular corrosion;
9. Microbiologically influenced corrosion (MIC).

It should be noted that MIC is a corrosion phenomenon, which has been studied relatively recently and can lead to pitting corrosion and/or failure.¹⁵ For the purpose of this document, discussion of corrosion forms is specifically focusing on corrosion issues in FPS.



Figure 4.2 Uniform corrosion of steel sprinkler pipe joints (2 inch dia.) in a wet pipe system caused by water leakage past their thread joints.

4.1.1 Uniform Corrosion

Uniform corrosion is described as “(1) A type of corrosion attack (deterioration) uniformly distributed over a metal surface. (2) Corrosion that proceeds at approximately the same rate over a metal surface. Also called general corrosion.”¹⁶ Figure 4.2 shows uniform corrosion of steel sprinkler pipe joints (2 inch dia.) in a wet pipe system. The uniform reddish-brown corrosion product [i.e., rust, hydrated iron(III) oxides $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ and iron(III) oxide-hydroxide

(FeO(OH))] is apparent outside the fitting/pipe joint interface, indicative of water leakage past the joint and subsequent corrosion of the pipe threads and the pipe surface adjacent to the threads.

4.1.2 Galvanic Corrosion

Galvanic corrosion or two-metal corrosion is described as “Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.”¹⁷ The less noble metal in the two-metal couple becomes the anode with a higher corrosion rate than it would experience if alone, while the more noble metal becomes the cathode with slower corrosion than if alone.¹⁸



Figure 4.3 Photograph showing galvanic corrosion damage of a less noble steel connection (anode) contacting a large noble stainless steel plate (cathode) inside a high humidity environmental chamber.

Figure 4.3 shows galvanic corrosion damage of a less noble steel connection (anode) contacting a large noble stainless steel plate (cathode) inside a high humidity environmental chamber

without proper electrical insulation between these two metals. The deposits shown in Figure 4.3 are the corrosion products of the steel connection.

Galvanic corrosion can also be found in areas where steel sprinkler pipe connects to copper alloy (brass or bronze) components like valves and couplings, if the contact between the two metal components is not properly insulated. It should be noted that, although sprinkler heads are made of copper alloy, the ratio of the surface area of sprinkler head (cathode, small surface area) in contact with steel pipe (anode, large surface area) is not sufficient to cause severe steel pipe corrosion. Note that the sprinkler is never in direct contact with the steel pipe – it touches a steel or cast iron/ductile iron fitting on the steel pipe.

4.1.3 Pitting Corrosion

Pitting corrosion is described as “Localized corrosion of a metal surface, confined to a point or small area that takes the form of cavities.”¹⁹ It is a type of corrosion with extensive corrosion at localized areas, while the rest of the surface corrodes at a much lower rate. Rapid corrosion of metal (anodic reaction) occurs inside a pit, while cathodic reaction such as oxygen reduction takes place at adjacent surfaces.

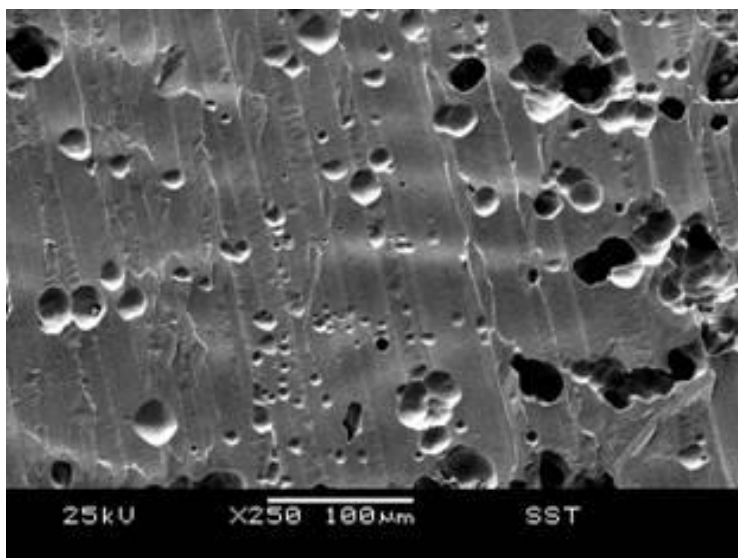


Figure 4.4 SEM photograph showing pits on a metal surface.

Figure 4.4 shows an scanning electron microscope (SEM) image of pits on a metal surface. It is noted that corrosion took place locally at many pits, while other areas on the metal surface are relatively intact.²⁰ The solution inside a pit can be very aggressive (e.g., acid with pH ~2 and Cl⁻), which increases the metal dissolution rate and is often called an autocatalytic process.

Pitting is a destructive form of corrosion and is difficult to detect, since pits are often covered with corrosion products such as tubercles. Formation of tubercles plays an important part in corrosion of sprinkler piping systems (discussed in Section 4.2). Figure 4.5 shows examples of through-wall pinhole leakage by pitting corrosion at the bottom of two nominal pipe size (NPS) 3 (3.5 inch OD) steel sprinkler pipes. Two other tubercles are apparent at the roll-grooved end of the pipe at left. Pit growth frequently follows the direction of gravity (e.g., leakage caused by pitting corrosion at the bottom of a sprinkler pipe). “Since the dense, concentrated solution within a pit is necessary for its continuing activity, pits are most stable when growing in the direction of gravity.”¹⁴ It should be noted that this kind of localized corrosion is also called under-deposit corrosion.

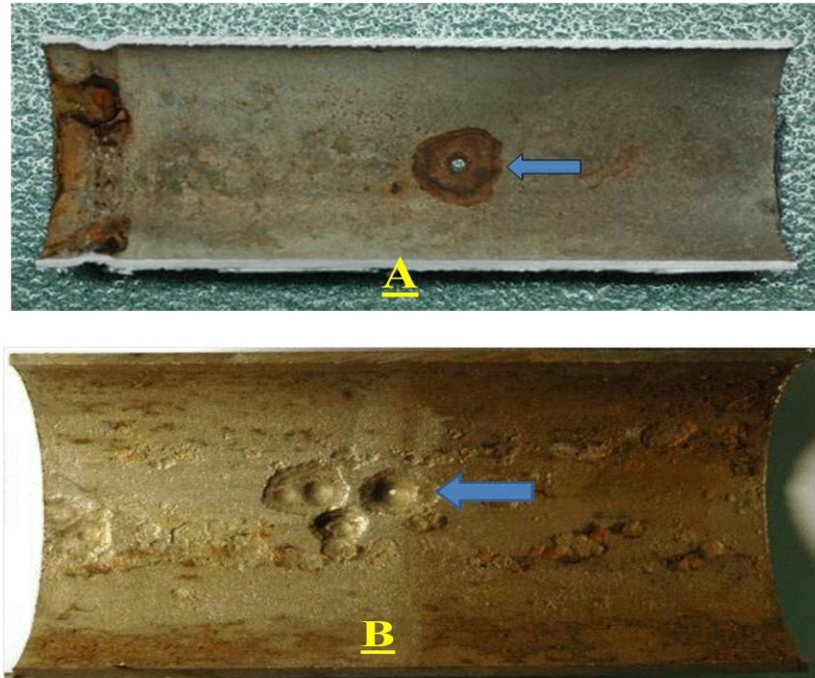


Figure 4.5 (A) Through-wall leakage of pitting at the bottom of a NPS 3 (3.5 inch OD) galvanvanized steel sprinkler pipe in a dry pipe system. (B) Through-wall leakage of pitting at the bottom of a NPS 3 black steel sprinkler pipe in a wet pipe system.

In Figure 4.5 (A), the arrow highlights the former presence of a large tubercle beneath which the galvanvanized steel pipe wall was penetrated by pitting corrosion at the through-wall penetration in a dry system; in Figure 4.5 (B), the arrow highlights the through-wall penetration of a NPS 3 black steel pipe by pitting corrosion in a wet system. Tuberculation is described as “The formation of localized corrosion products scattered over the surface in the form of knoblike mounds called tubercles.”¹⁶

4.1.4 Crevice Corrosion

Crevice corrosion is described as a “Localized form of corrosion that occurs within crevices and other shielded areas on metal surfaces exposed to a stagnant corrosive solution. This form of corrosion usually occurs beneath gaskets, in holes, in surface deposits, and in thread and groove joints. Crevice corrosion is also referred to as gasket corrosion, deposit corrosion, and under-

deposit corrosion.”¹ This form of corrosion is often caused by concentration differences of oxygen and/or chlorides inside and outside the crevice areas.

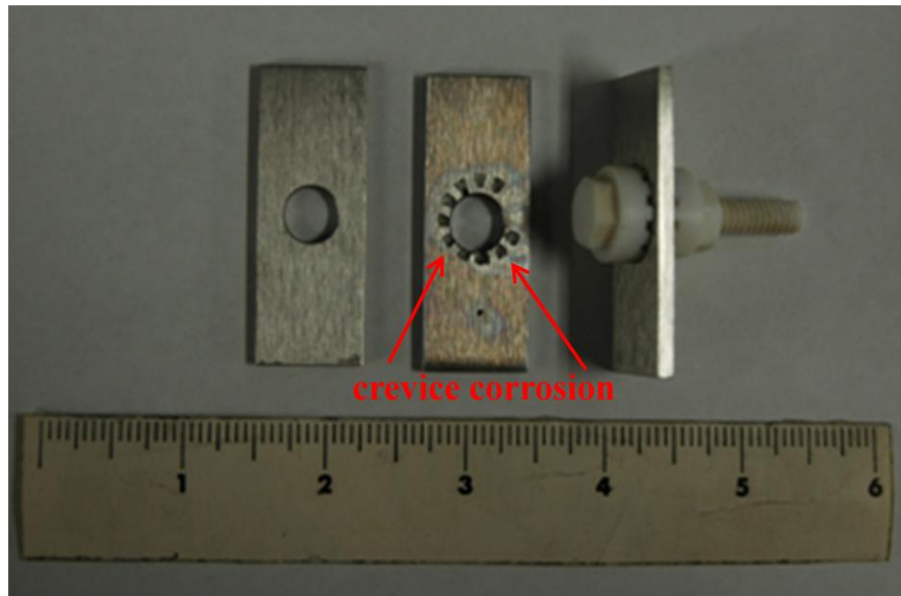


Figure 4.6 Photograph showing localized crevice corrosion attacks on a metal coupon (middle) underneath a PTFE artificial crevice washer at 75°C after 48 hours of exposure.

Figure 4.6 shows localized crevice corrosion attacks on a metal coupon (middle) underneath a polytetrafluoroethylene (PTFE) artificial crevice washer at 75°C after 48 hours of exposure.

4.1.5 Selective Leaching

Selective leaching is described as “Corrosion in which one element is preferentially removed from an alloy, leaving a residue (often porous) of the elements that are more resistant to the particular environment.”²¹ For instance, two common examples of selection leaching in FPS are (A) dezincification of brass (Cu-Zn alloy) sprinkler with selective leaching (corrosion) of Zn from brass, and (B) graphitic corrosion of grey cast iron water pipe with corrosion of iron (anode) matrix leaving a porous graphite (cathode) structure in fire water underground main lines.

Figure 4.7 shows a ruptured underground water main (identified as gray cast iron, 8-inch diameter) with cement lining on the main's inside diameter. The circled area in Figure 4.7 exhibits graphitic corrosion on the outside surface of the main due to its exposure to mildly aggressive groundwater and soils. Generally, high moisture content in the surrounding soil is required for graphitic corrosion to occur.



Figure 4.7 Photograph showing a ruptured underground water main (8 inch dia.) with circled area indicative of graphitic corrosion.

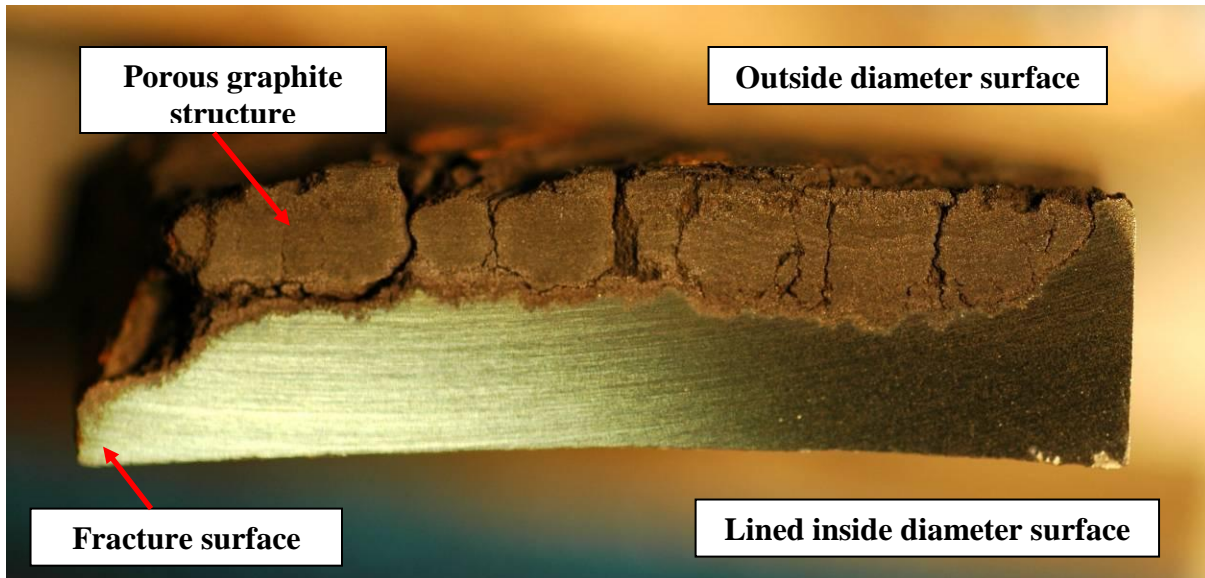


Figure 4.8 Photograph showing the cross section for part of the water main in Figure 4.7. Almost the entire wall thickness of the pipe has been penetrated by graphitic corrosion attack at the far left fracture face.

Figure 4.8 shows a cross section for part of the water main in Figure 4.7. It is noted that almost the entire wall thickness of the pipe has been penetrated by graphitic corrosion attack at the far left fracture surface, while the pipe's inside diameter surface with cement lining is in good condition.

4.1.6 Erosion Corrosion

Erosion corrosion is described as “Destruction of metals or other materials by the abrasive action of moving fluids, usually accelerated by the presence of solid particles or matter in suspension. When corrosion occurs simultaneously, the term erosion-corrosion is often used.”²² Erosion usually appears in a directional pattern as grooves, waves, gullies, round holes, and valleys.

Figure 4.9 shows the pitting and erosion corrosion of elongated corrosion pits following water flow direction at a domestic water line (3/4 inch dia.). A number of leaks occurred in this copper domestic water line. Pitting corrosion initially occurred at a number of areas on the waterside of the copper tubing. Erosion-corrosion then resulted due to excessive localized water velocities

and/or turbulence. A sudden change in flow direction, such as would occur at an elbow, would be expected to increase the local turbulence. Within both the second elbow and the second horizontal tube, smooth, hollowed-out areas consistent with erosion-corrosion were observed.

The black and greenish materials shown in Figure 4.9 are different forms of copper corrosion products, such as cupric oxide (CuO , black), cuprous oxide (Cu_2O , reddish-brown), and malachite [$\text{Cu}_2(\text{CO}_3)(\text{OH})_2$, blackish green].²³ It should be noted that corrosion of copper piping in FPS can be caused by aggressive water quality/chemistry parameters²³, such as sprinkler water with pH values ranging from 7.0 to 7.7, stagnant water with air pocket supplying dissolved carbon dioxide (CO_2) and oxygen (O_2), dissolved anions (chloride and sulfate), low alkalinity and by residual soldering flux during fabrication of copper pipe joints.^{24,25}



Figure 4.9 Photograph showing erosion corrosion (elongated corrosion pits following water flow direction) in a copper domestic water line.

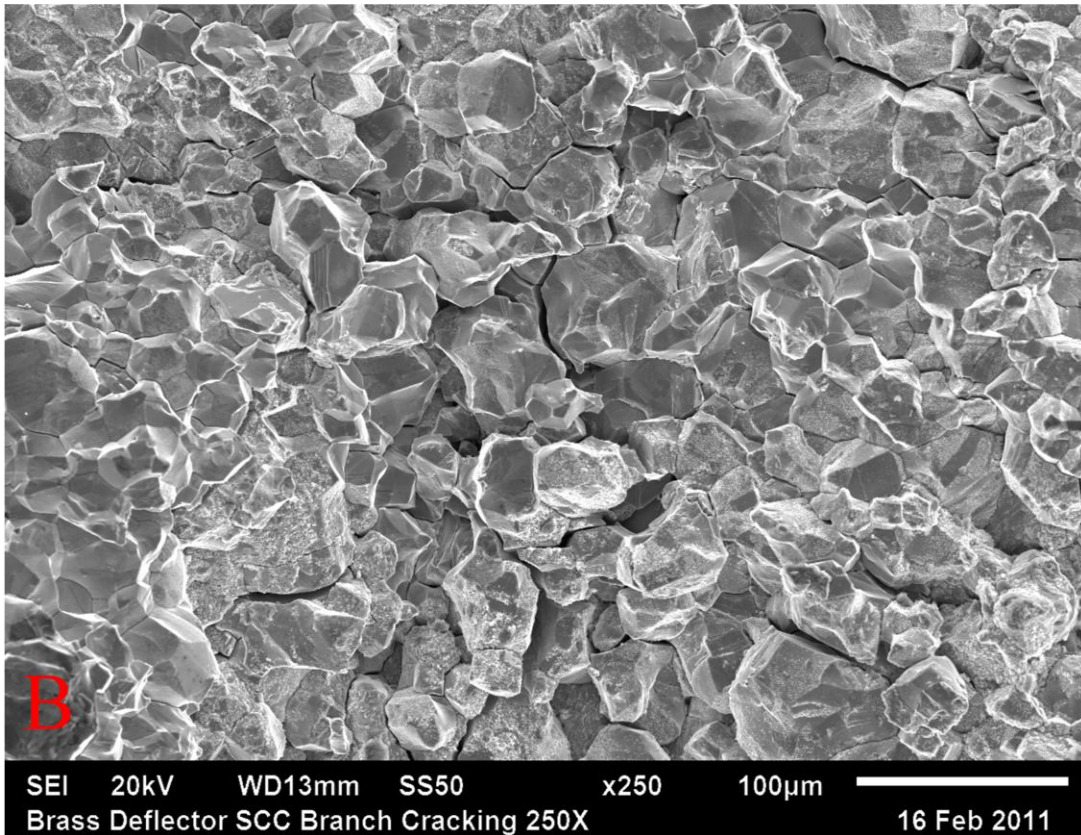
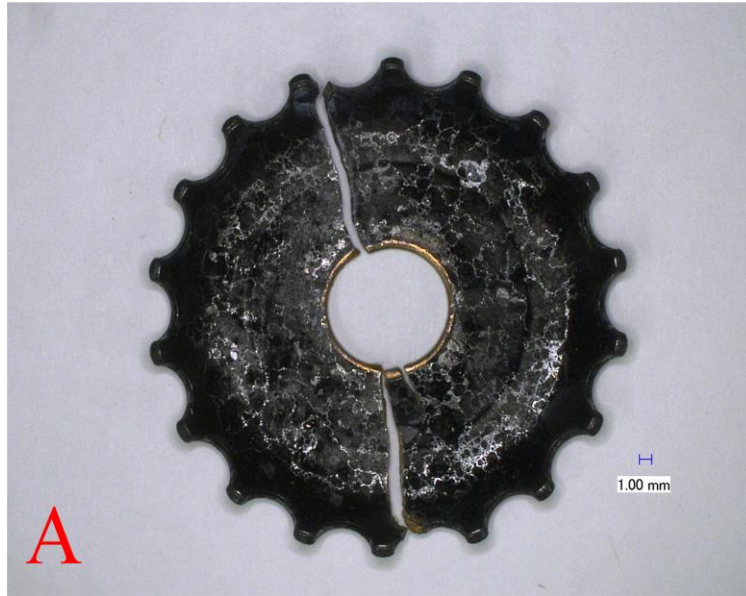


Figure 4.10 (A) Photograph showing SCC failure across the deflector of a brass sprinkler after the ammonia SCC testing. (B) SEM photograph of cracking morphology for fracture surface on the deflector in Figure 4.10 (A).

4.1.7 Environmentally Induced Cracking

Environmentally induced cracking is described as “Brittle fracture of a normally ductile material in which the corrosive effect of the environment is a causative factor.”²² Stress corrosion cracking (SCC), corrosion fatigue cracking (CFC), and hydrogen-induced cracking (HIC) are the three distinct types of failure related to environmentally induced cracking. These types of stress cracking failures require the simultaneous action of corrosive environment and sustained stress. It is noted that SCC failures of brass sprinklers have occurred in the field.

Brass sprinklers can experience SCC failure under ammonia atmosphere. Ammonia SCC testing is used in FM Global Approval Standards (e.g., “Automatic Control Mode Sprinklers for Fire Protection Class Number 2000”) to evaluate the SCC resistance of copper-based (e.g., brass) sprinklers. Figure 4.10 (A) shows SCC failure across the deflector of a brass sprinkler after ammonia SCC testing. Figure 4.10 (B) displays an image of cracking morphology for fracture surface on the deflector in Figure 4.10 (A), taken by scanning electron microscope (SEM, JEOL JSM-6610LV). The cracking morphology showing intergranular cracking (fracture) is a typical characteristic of SCC where grain boundaries in the brass deflector were attacked by ammonia, resulting in brittle fracture.

4.1.8 Intergranular Corrosion

Intergranular corrosion (IGC) is described as “Corrosion occurring preferentially at grain boundaries, usually with slight or negligible attack on the adjacent grains. It is also called intercrystalline corrosion.”²⁶ Grain boundaries are sites for precipitation and separation of phases in metals, which make them chemically different from the grain matrix. Thus, selective dissolution (corrosion) of grain boundaries or surrounding areas by corrosive environment without attacking grain matrix is called IGC.

Figure 4.11 shows IGC and cracking of steel where the corrosion and cracking occurred along grain boundary areas without corroding the steel grain matrix.

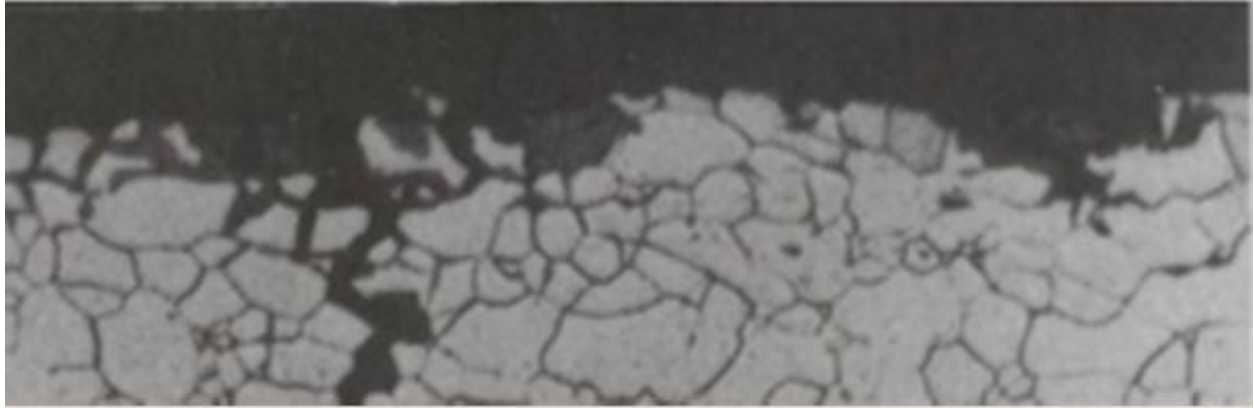


Figure 4.11 Photomicrograph showing intergranular corrosion of steel surface where corrosion and cracking occurred along grain boundaries without corroding the steel grain matrix.

4.1.9 Microbiologically Influenced Corrosion (MIC)

4.1.9.1 Definition

Microbiologically influenced corrosion (MIC) is described as “corrosion that is influenced by the presence and activities of microorganisms and/or their metabolites (the products produced in their metabolism).”²⁷ This type of corrosion is caused by formation of biofilm on metal surfaces. Within the biofilm, metabolism activities of microorganisms (e.g., bacteria, fungi and algae) influence electrochemical conditions on the metal/solution interface, where metal corrosion can be initiated or accelerated.^{28,29,30,31}

4.1.9.2 Damage by MIC

MIC is reported to be responsible for 10-20% of the damage caused by corrosion³² or 10-30 % of corrosion in all piping systems in the United States.³³ Activities of microbes and corrosion of carbon steel piping systems may form tubercles or nodule deposits on pipe surfaces, leading to obstruction of water flow and blockage of valves or sprinklers in FPS when activated. It should be noted that stagnant water and dead ends of sprinkler piping in FPS could provide quiescent environments conducive to microbial activities.

4.1.9.3 Fundamental Model and Mechanism

Figure 4.12^{34,28,35,36} illustrates a model for biofilm/MIC development, which can be described as follows:

1. A conditioning film develops on the metal surface due to adsorption of organic materials (yellow layer), which leads to the adhesion of “pioneer” bacterial species (green and purple colored bacteria) on the conditioning film.
2. Additional microorganisms (red, turquoise, yellow, and yellow-green colored bacteria) develop colonies and complex consortia (stratified zones of anaerobes living without oxygen, facultatives living with or without oxygen, and aerobes living with oxygen), forming a biofilm, followed by accumulation and entrapment of particles (brown), dead cells, ions, and chelation of metals from water.

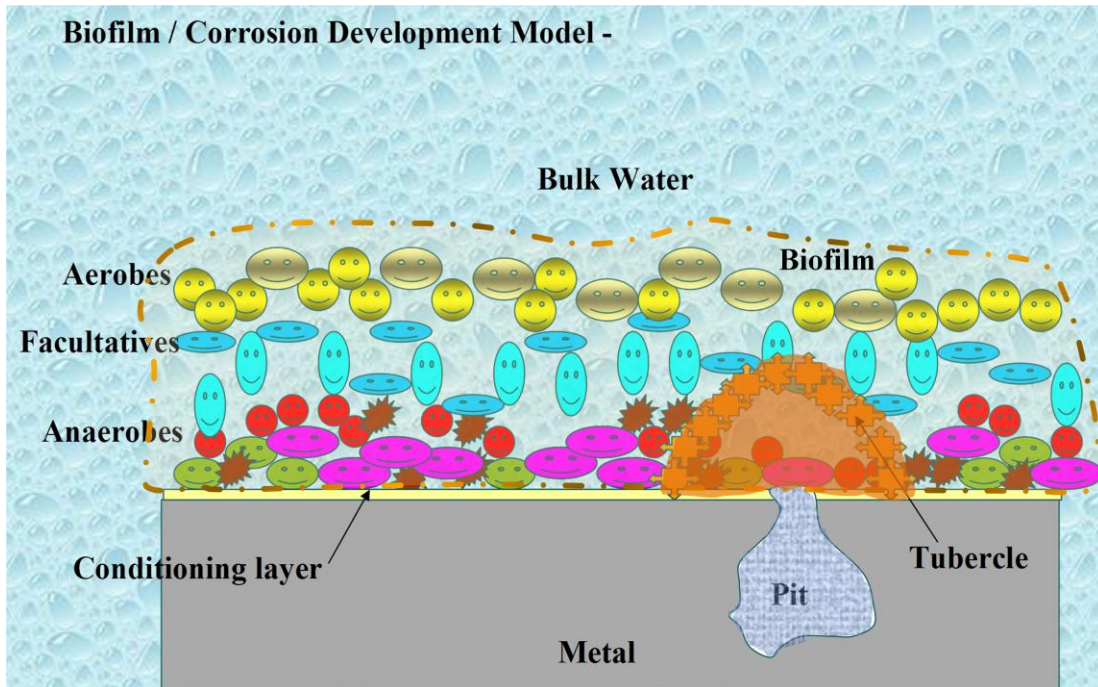


Figure 4.12 Illustration of the biofilm/microbiologically influenced corrosion development model.

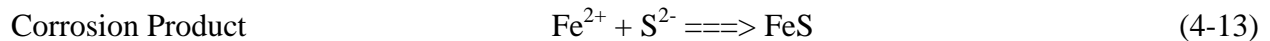
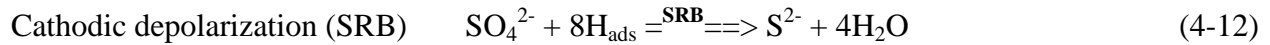
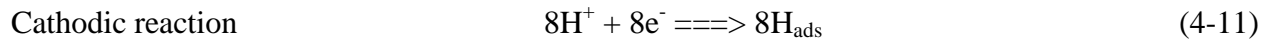
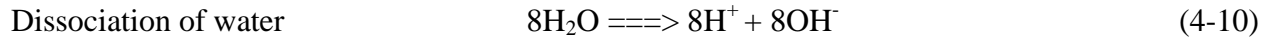
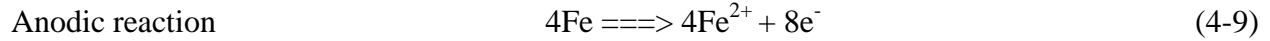
3. The metabolic activities of biofilm induce local water chemistry changes (e.g. ions, pH, O₂ concentration, corrosion potential) at the metal surface, and thus influence electrochemical processes occurring at the metal/solution interface, leading to MIC: metal dissolution (e.g., pitting) and tubercle formation.

The formation of a conditioning film on metal surface enables planktonic (floating) bacteria from the bulk water to develop colonies and complex consortia with other types of bacteria and become sessile (anchored) on the metal surface. Representative microorganisms linked to MIC are described as follows:

- Sulfate-reducing bacteria (SRB);
- Acid-producing bacteria (APB);
- Iron-oxidizing bacteria (IOB);
- Slime-forming bacteria (SFB);
- Sulfur-oxidizing bacteria (SOB);
- Nitrate-reducing bacteria (NRB).

SRB are anaerobic (living without oxygen) and they reduce sulfate (SO₄²⁻) to sulfide (S²⁻). Some example genera are: *Desulfovibrio*, *Desulfuricans*, *Desulfobacter*, and *Desulfohalobium*. SRB are commonly implicated in causing MIC. APB are anaerobic but can also survive aerated environments and they create organic acids such as acetic, succinic, and isobutyric, which can stimulate SRB growth. IOB are aerobic (with oxygen) and they can oxidize ferrous ions II (Fe²⁺) to form orange-red tubercles of iron oxides or hydroxides (Fe³⁺). Some example species include: *Crenothrix polyspora*, *Sphaerotilus natans*, *Gallionella ferruginea*, and *Siderocapsa treubii*. SOB bacteria are aerobic and they oxidize sulfur to sulfate. Example genera are: *Thiobacillus*, *Thiodendron*, *Beggiatoa*, and *Sulfolobus*. NRB reduce nitrate (NO₃⁻) to ammonia (NH₃). Also, any given species may exhibit more than one of these traits. It should be noted that SRB and APB are commonly implicated as groups of bacteria causing MIC in FPS as well as steel pipeline corrosion failures.^{1,37,39}

The following equations were proposed to explain the classical mechanism of MIC caused by SRB¹⁵:



Equations 4-9 to 4-11 describe the anodic and cathodic reactions for steel corroding in aqueous environments; equations 4-12 to 4-14 have been linked to the activity of sulfate-reducing bacteria (SRB). The hydrogen atom in equation 4-12 is stripped off by SRB using its enzyme hydrogenase through a process called cathodic depolarization; the removed hydrogen then can be used by SRB in reducing sulfate (SO_4^{2-}) to sulfide (S^{2-}), allowing the corrosion process to continue. As a result, corrosion products, including iron sulfide (FeS) and iron hydroxide ($\text{Fe}(\text{OH})_2$), are formed, shown in equations 4-13 to 4-15. It is noted that modifications to this original mechanism have been proposed;^{15,38} yet, these fundamental equations still play a significant role in explaining the MIC mechanism by SRB.

4.1.9.4 MIC Assessment

Microorganisms are ubiquitous, but detecting MIC-related bacteria in sprinkler water (planktonic) and/or corrosion product samples (sessile) does not necessarily confirm that MIC has occurred in an FPS. As discussed in Section 4.1.3 (Pitting Corrosion), pinhole leakage caused by pitting corrosion underneath a tubercle is frequently observed, which could be influenced by microorganisms (i.e., MIC). However, pitting corrosion and pinhole leakage can also be caused by other types of corrosion mechanisms, such as non-microbial pitting under

tubercle (discussed in Section 4.2), crevice corrosion, aggressive water chemistry (Cl^- , SO_4^{2-} , pH, O_2 concentration, etc.), metallurgical microstructures, and manufacturing issues.

It is necessary to evaluate chemical (chemical information of environments and identification of corrosion products), microbiological (numbers and types of microorganisms), metallurgical (distribution and morphology of corrosive attacks), and operational data to identify biotic factors as primary contributors to corrosion damage.^{39,40} For FPS, it is often difficult to distinguish contributing factors for corrosion of sprinkler piping between biotic (presence of biological factors, i.e., MIC) and abiotic (absence of biological factors, i.e., non-MIC) factors, both affecting pitting corrosion and tubercles.

In many cases, the presence of MIC-related bacteria may exert some influence on corrosion of FPS, but not as the major corrosion contributor. Therefore, it is necessary to evaluate all corrosion parameters discussed in this section before determining the causes of corrosion in FPS. For example, residual water and dissolved oxygen in galvanized steel pipe are the leading cause of corrosion and/or leakage for dry and preaction type FPS (discussed in Sections 4.3.1.2 and 5.3)⁴¹, even though several types of bacteria can often be detected in their sprinkler water. Table 4.1 shows bacteria culture testing of water samples in a preaction system. SRB was not found in these water samples; yet, other types of bacteria such as aerobic, anaerobic, iron related ($\sim 1.4 \times 10^5$ cfu/mlⁱⁱⁱ), and slime forming ($\sim 1.3 \times 10^5$ cfu/ml) were detected.

Table 4.1 Bacteria culture testing of water samples.

Type of Bacteria	Source Water	System Water
SRB	Negative	Negative
Iron Related	1.4×10^5 cfu/ml	1.4×10^5 cfu/ml
Aerobic	1×10^2 cfu/ml	Negative
Anaerobic	Positive	Positive
Slime Forming	1.3×10^5 cfu/ml	1.3×10^5 cfu/ml

ⁱⁱⁱ cfu = colony forming units

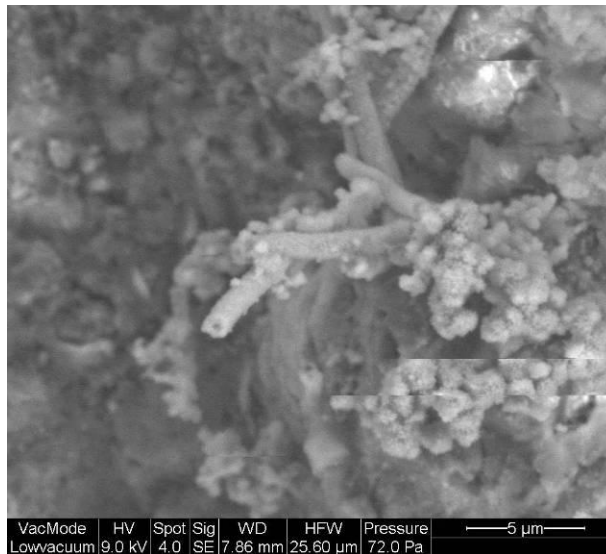


Figure 4.13 Representative SEM image of corroded steel with bacteria. The corrosion product, drinking straw-like structure, may be due to *Leptothrix ochracea*, iron-oxidizing bacteria on corroded steel pipe.

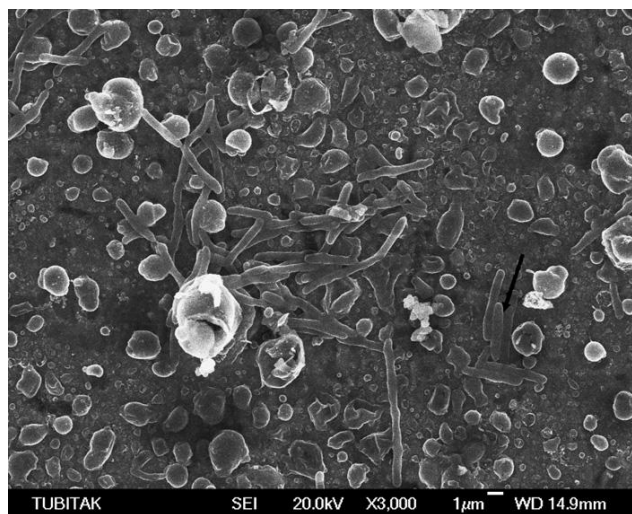


Figure 4.14 Representative SEM image of rod-shaped *Desulfovibrio* sp., sulfate-reducing bacteria on the galvanized steel surface after 8 hours of incubation.⁴² (Courtesy of Elsevier, August, 2011)

4.1.9.5 Example of MIC

Figures 4.13 and 4.14 show representative SEM images of corroded steel with bacteria, indicating bacterial involvement in the corrosion process (i.e., MIC). Figure 4.13³⁴ displays an image of corroded steel pipe with corrosion product containing a drinking straw-like structure, which may be due to *Leptothrix ochracea* (iron-oxidizing bacteria). Figure 4.14⁴² displays rod-shaped *Desulfovibrio* sp. (SRB) on the galvanized steel surface after 8 hours of incubation. Figure 4.15 is an example of a 4 inch dia. corroded/leaked steel pipe with many tubercles formed inside the pipe. MIC caused by SRB was identified to be a likely contributing factor to pipe corrosion, based on testing results of SRB immunoassay, lead acetate sulfide tests, water chemistry analyses, and corrosion/metallurgical evidence (discussed in Section 5.5).



Figure 4.15 Photograph showing a corroded/leaked steel sprinkler pipe (4 inch dia.) with many tubercles. MIC caused by SRB was identified to be a likely contributing factor to pipe corrosion.

4.2 TUBERCULATION

Tuberculation is described as “The formation of localized corrosion products scattered over the surface in the form of knoblike mounds called tubercles.”¹⁶ Tuberculation is a major form of

corrosion for steel sprinkler systems. Formation of tubercles can be influenced by biotic (presence of biological factors, i.e., MIC) and by abiotic (absence of biological factors, i.e., non-MIC).⁴³ Tubercles are frequently observed in steel and galvanized steel pipe, and are capable of obstructing water flow in pipes and/or plugging sprinklers. A localized region of metal loss or pitting is often observed underneath these tubercles, which can lead to through-wall leakage of sprinkler pipes, as shown in Figure 4.16 (A and B) and Figure 4.17 (A and B).



Figure 4.16 Photograph showing tubercles and pinhole (circled) leakage of steel sprinkler pipe in wet pipe systems. (A) Tubercles heavily formed inside a steel sprinkler pipe (4 inch dia.). (B) Pinhole (circled) leakage on a steel sprinkler pipe.

4.2.1 Tubercles

4.2.1.1 Wet Pipe System – Steel Sprinkler Pipe

Figure 4.16 (A and B) shows tubercles and pinhole (circled) leakage of steel sprinkler pipe in wet pipe systems. Tubercles heavily formed inside a steel sprinkler pipe (4 inch dia.) are seen in Figure 4.16 (A); reddish-brown ferric hydroxide ($\text{Fe}(\text{OH})_3$) corrosion product covers tubercle surfaces. Figure 4.16 (B) displays corrosion at the base of a tubercle, which ultimately led to the observed through-wall pinhole leakage, which is circled in red.

4.2.1.2 Dry Pipe and Preaction Systems – Galvanized Steel Pipe

Figure 4.17 (A and B) shows tubercles and pinhole (circled) leakage of galvanized steel sprinkler pipe in dry pipe systems. Tubercles heavily formed inside a galvanized steel sprinkler pipe (4 inch dia.) are seen in Figure 4.17 (A); corrosion products such as white zinc oxide (ZnO) and zinc hydroxide ($\text{Zn}(\text{OH})_2$) cover non-tubercle surfaces. Figure 4.17 (B) shows corrosion at the base of a tubercle, which ultimately led to the observed through-wall leakage.

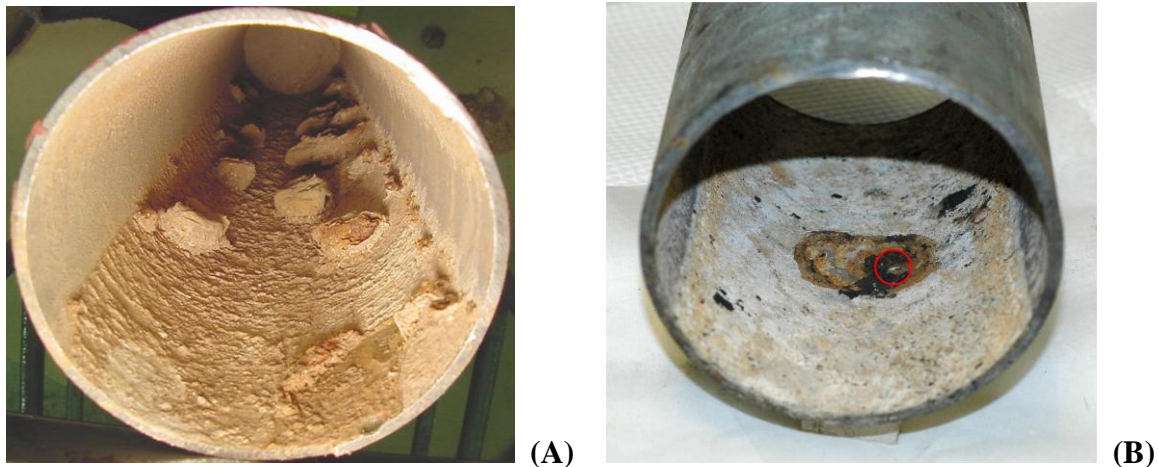


Figure 4.17 Photograph showing tubercles and pinhole (circled) leakage of galvanized steel sprinkler pipe in dry pipe systems. (A) Tubercles heavily formed inside a galvanized steel pipe (4 inch dia.). (B) Through-wall (circled) leakage underneath a tubercle (removed) on a galvanized steel pipe.

4.2.2 MIC Tubercles

The formation and growth of tubercles controlled by biotic factors (MIC) has previously been discussed in Section 4.1.9.

4.2.3 Non-MIC Tubercles

The formation and growth of non-MIC tubercles are controlled by water chemistry and flow via electrochemical reactions. In FPS, factors like oxygenated sprinkler water, aggressive water chemistry (e.g., raw or untreated water, high Cl^- high SO_4^{2-} ion concentration, discussed in Section 4.3), stagnant water, and dead-end branch lines provide an environment conducive to non-MIC tubercles. It was reported that the majority of tubercles studied in the literature is likely related to non-MIC tubercles.⁴³ Note that stagnant water and dead ends of sprinkler piping in FPS could also provide quiescent environments conducive to microbial activities as discussed in Section 4.1.9.

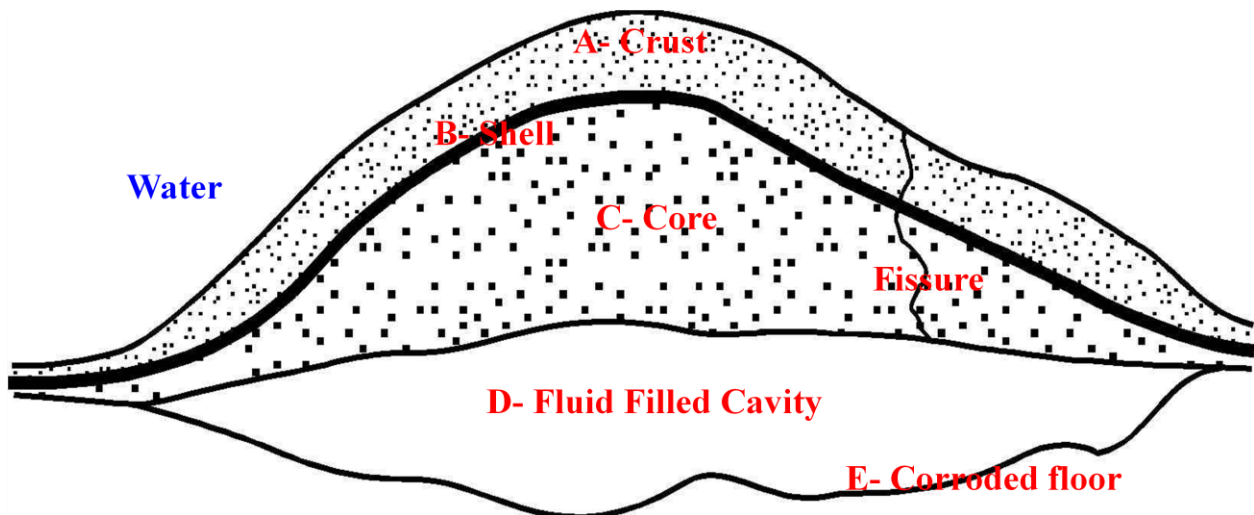


Figure 4.18 Schematic drawing illustrating five common structural features of non-MIC tubercles including (A) Outer Crust, (B) Inner Shell, (C) Core Material, (D) Fluid-Filled Cavity, and (E) Corroded Floor.

4.2.3.1 Common Features

Non-MIC tubercles are highly structured with complex chemical composition. Their structure and growth can be interrelated in many ways. Figure 4.18 is a schematic drawing, which illustrates five common structural features of non-MIC tubercles including Outer Crust, Inner Shell, Core Material, Fluid-Filled Cavity, and Corroded Floor.^{43,44,45}

A. Outer Crust

Outer crust is a friable red, orange and brown-like layer composed of ferric hydroxide (Fe(OH)₃, major component), carbonates, silicates, and other precipitates, forming the top layer of a tubercle. Equation 4-16 describes ferrous hydroxide (Fe(OH)₂) generated inside the tubercle diffused outward through fissures and reacted with dissolved oxygen in water, forming ferric hydroxide (Fe(OH)₃).



B. Inner Shell

The inner shell is a region separating high dissolved oxygen concentration outside the tubercle, thus creating a low oxygen environment inside the tubercle. Black magnetite (Fe₃O₄) is mostly found in this region. Magnetite of the inner shell is a good conductor, which promotes electron passage from the corroding floor as well as the cathodic reaction (oxygen and water), as described in equation 4-17.



C. Core Material

The bulk of the tubercle is found in the core, mainly consisting of ferrous hydroxide (Fe(OH)₂) formed by equation 4-18.



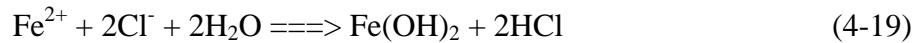
Reaction of ferrous ion (Fe^{2+}) with anions such as carbonate (CO_3^{2-}) forming small amounts of siderite (FeCO_3) can also occur.

D. Fluid-Filled Cavity

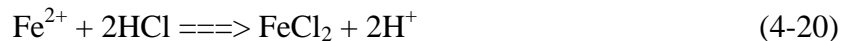
A fluid-filled cavity is normally formed below the core material. The shape of the cavity is irregular and its size is also varied. The acid anions such as Cl^- and SO_4^{2-} inside the tubercle can create an acidic environment that may prevent the precipitation of oxides and hydroxides, resulting in the formation of the fluid-filled cavity. In addition, the acidic environment can promote the hydrogen evolution reaction (equation 4-6), which may also contribute to cavity formation in the tubercle.

E. Corroded Floor

Iron corrodes, forming ferrous ion (Fe^{2+} , Equation 4-2). If Cl^- is present in this region, hydrolysis can reduce the pH value as shown in equation 4-19.



Hydrochloric acid (HCl) will further increase the corrosion rate, as described in equation 4-20.



Similarly, sulfate (SO_4^{2-}) can increase the corrosion rate as Cl^- inside a tubercle, but to a lesser extent.

Figure 4.19 shows the cross section of several non-MIC tubercles in a NPS 4 Schedule 10 steel sprinkler pipe. Irregular shapes of cavities are visible inside two larger tubercles. The orange and brown-like layers of corrosion product are likely to be hydrated iron(III) oxides $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ and iron(III) oxide-hydroxide ($\text{FeO}(\text{OH})$) and the black layers of material could be magnetite (Fe_3O_4). In this case, intermittently charging oxygenated water into the system may have created oxygen concentration cells and changed the local water chemistry in the steel pipe, resulting in promoting the growth of tubercles.



Figure 4.19 Photograph showing the cross section of non-MIC tubercles in a NPS 4 Schedule 10 steel sprinkler pipe. Irregular shapes of cavities are visible inside two larger tubercles.

4.3 WATER QUALITY/CHEMISTRY

The corrosivity of sprinkler water in FPS is significantly influenced by water quality and chemistry parameters, such as concentration of dissolved gases (O_2 , CO_2), dissolved anions (chloride, sulfate, etc.), pH, alkalinity (HCO_3^- and CO_3^{2-}), solids (hardness and deposits), and microorganisms. In particular, if raw water or untreated water is used as the source of sprinkler water, metal parts used in FPS are more susceptible to waterside corrosion damage – due to higher concentration of anions, solids, microorganisms, etc. in raw water.

4.3.1 Dissolved Gases (O₂ and CO₂)

Dissolved oxygen (O₂) concentration in sprinkler water is the major factor influencing corrosion inside steel sprinkler piping systems. As shown in Equations 4-7 and 4-8, oxygen concentration is the controlling factor for cathodic reactions to occur; consequently, higher dissolved oxygen concentration increases corrosion rate for steel sprinkler piping systems. Under the corrosion products or tubercles, there is a limited amount of oxygen as compared to directly outside the corrosion products/tubercles. This oxygen concentration gradient establishes a sustained driving potential for the localized corrosion of steel pipe to continue.

In addition, dissolved carbon dioxide (CO₂) reacting with water to form a weak carbonic acid (H₂CO₃) is mildly corrosive toward steel pipe, as shown in Equation 4-21.



4.3.1.1 Wet Pipe System

In a wet pipe system, after oxygen in the initially charged sprinkler water is consumed through pipe corrosion, corrosion in the system will be minimized if no other factors are present here (e.g., aggressive ions, intermittently recharging oxygen into the system, or microorganisms) that can induce steel pipe corrosion. In addition, the pH of sprinkler water in most FPS normally varies from weak acid (pH 5-7) to mild basic solution (pH 7-10), indicating that oxygen reduction reaction (Equation 4-7 or 4-8) is the controlling cathodic reaction for steel pipe corrosion.

Figure 4.20 shows steel pipe in a wet pipe system with limited corrosion forming a layer of black magnetite (Fe₃O₄) on its internal pipe surface. This magnetite layer was created when oxygen in the initial aerated water reacted with the steel pipe and was depleted. Limiting the oxygen supply and reducing its concentration in FPS can substantially mitigate corrosion.



Figure 4.20 Photograph showing steel pipe in a wet pipe system with limited corrosion after forming a layer of black magnetite and depleting oxygen inside this piping system.

4.3.1.2 Dry Pipe or Preaction Systems

For dry pipe or preaction systems, galvanized (zinc coated) steel pipe is specified. If these galvanized steel piping systems can be maintained “dry” (free of water), pipe internal corrosion will not occur. However, field installed dry systems often encounter inadequate pitching and/or draining issues, trapping residual water from system commissioning and trip testing in the piping (filled with air), thus resulting in high concentrations of dissolved oxygen and carbon dioxide in trapped water. Dissolved oxygen (main cause) and carbon dioxide in water can increase corrosion rate for galvanized steel pipe (with zinc then steel corrosion). Note that if an air dryer is not used on the system air compressor, water can be introduced via condensation.

Zinc coating prevents corrosion of underlying steel pipe by forming a physical barrier due to formation of corrosion resistant films on the pipe surface such as zinc oxide (ZnO), zinc hydroxide (Zn(OH)_2), and zinc carbonate (ZnCO_3)^{46,47} and by acting as a sacrificial anode, if this

barrier is damaged. With trapped water, the zinc layer corrodes first, followed by a local penetration point where zinc is depleted and the underlying bare steel is exposed.

As the zinc continues to dissolve surrounding the point of penetration and the bare steel area expands, the remaining zinc “throwing power” ultimately becomes inadequate to protect the steel. The exposed steel begins to experience localized corrosion (pitting) attack, forming a tubercle. The dissolved oxygen concentration gradient between the bulk water surrounding the tubercle and the water in direct contact with the metal surface beneath the tubercle (due to depletion of dissolved oxygen compared with the bulk water) is typically the driving force for such under-deposit pitting corrosion. The area (pit) underneath the tubercle (oxygen depleted, anodic–iron corrosion) becomes a small anode compared to the larger surrounding cathode (oxygenated, cathodic–oxygen reduction) and further increases pitting corrosion rate. In addition, the solution inside a pit can be very aggressive (e.g., acid with pH ~2 and Cl⁻), which increases the metal dissolution rate and is often called an “autocatalytic” process. Eventually, the continued and autocatalytic pitting corrosion of steel penetrates the pipe wall, leading to leakage.

Figure 4.21 shows NPS 4 galvanized steel pipe (4.5 inch OD) with through-wall leakage. Residual water filled about 40% of the pipe’s volume in service. Under the waterline, white rust (zinc corrosion) and well over a dozen reddish-brown tubercles of various sizes are evident on the bottom half of the pipe.

It should be noted that new dry or preaction systems can develop through-wall corrosion pinhole leakage within 2-3 years after initial installation, due to residual water causing corrosion in galvanized steel pipe.

4.3.1.3 Scale Formation

Dissolved calcium and magnesium salts in sprinkler water (if hard water is used) can react with bicarbonate (HCO_3^-), forming a thin film (scale) composed of calcium carbonate (CaCO_3 mostly found) and magnesium carbonate (MgCO_3) under neutral or alkaline environments. This film offers certain protection against corrosion inside sprinkler piping. However, it is possible that

larger and thicker scales formed inside copper sprinklers could plug orifices.² In addition, it is noted that no scales can form in soft water environments.

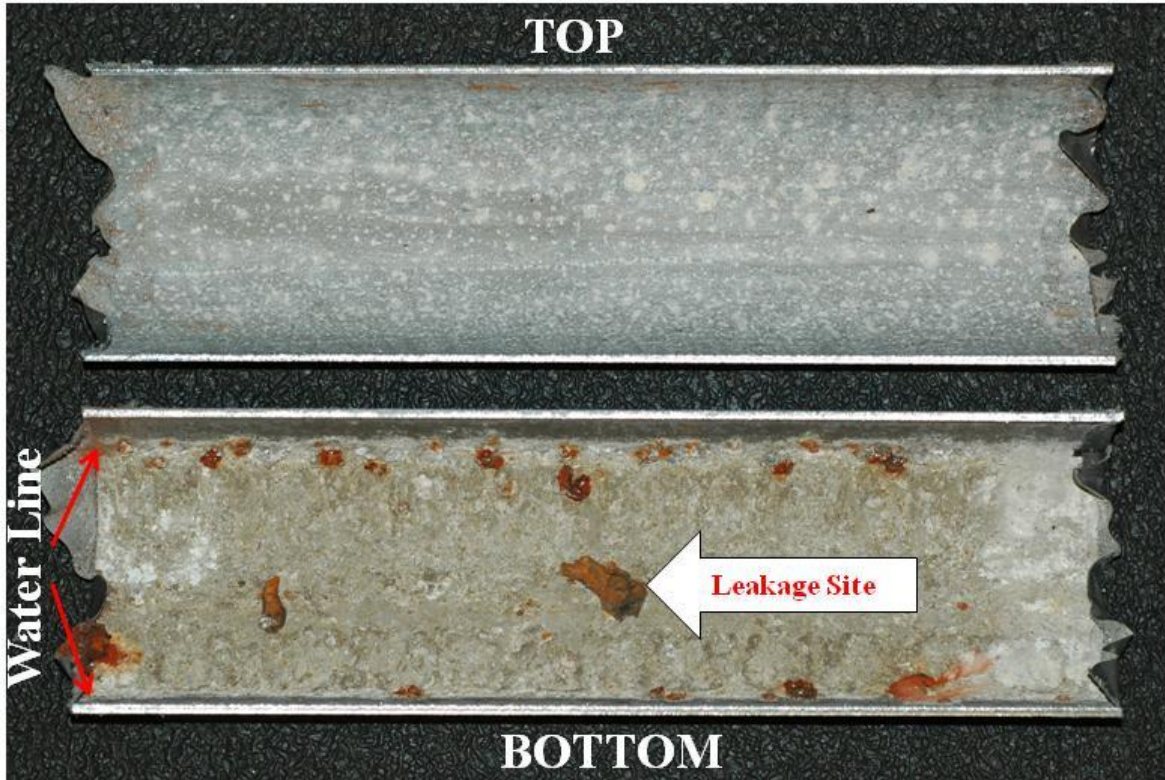


Figure 4.21 Photograph showing NPS 4 galvanized steel pipe (4.5 inch OD) with a through-wall leakage. Residual water filled about 40% of the pipe's volume in service. Under the waterline, white rust and well over a dozen reddish-brown tubercles of various sizes are evident on the bottom half of the pipe.

Indexes are available to evaluate the scaling tendency of water in piping systems, such as the Langelier saturation and Ryznar stability indexes used in the cooling-water industry by calculating pH and alkalinity relationship.⁴⁸ There is no definite correlation between these indexes and corrosion of steel in water, and they do not consider the effects of chloride and sulfate anions on steel pipe corrosion. Thus, these indexes are not used in water chemistry analysis of sprinkler water often containing these anions.

4.3.1.4 FM Global Loss Experience

Figure 4.22 shows that dry-type sprinkler systems (dry and preaction) are involved in the majority (59%) of obstructed sprinkler-system fire losses, based on FM Global loss data (history, 1982-2001) analysis described in “Understanding the Hazard: Dry-Pipe Sprinkler Systems Flushing Investigations.”⁴⁹ It should be noted that this loss data analysis for dry systems predominantly involves black steel pipe. The hard and dense corrosion tubercles in black steel pipe were found to be the most frequent obstructing material. It is recommended to use galvanized steel pipe for dry or preaction systems, to minimize the likelihood that sprinklers become clogged when activated to control or to extinguish fires.⁴¹

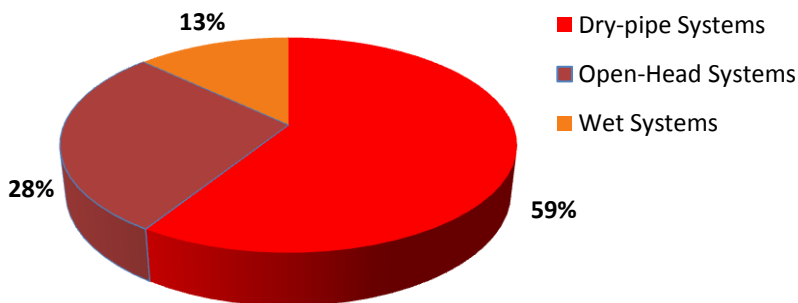


Figure 4.22 Sprinkler systems involved in Obstructed-Pipe Fires: (Losses reported to FM Global 1982-2001).

4.3.2 Dissolved Salts

Water containing aggressive anions such as chloride (Cl^-) and sulfate (SO_4^{2-}) stimulates pipe corrosion similar to other localized corrosion mechanisms (pitting and crevice corrosion) discussed previously. Both chloride and sulfate anions can adsorb on the metal surface, interfere with the formation of passive films on metal surface, lower solution pH in pits, crevices, and tubercles, and consequently enhance metal corrosion.

The Larson-Skold index has been used as one of the parameters (e.g., pH, dissolved gases, anions, alkalinity, and scaling tendency) in measuring some qualitative information about

corrosivity of water toward mild steel. The index is based on evaluation of corrosion for mild steel lines transporting Great Lakes waters.⁵⁰ This index is the ratio of chloride (Cl^-) and sulfate (SO_4^{2-}) concentration (equivalents per million, epm) to alkalinity as bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) as shown in equation 4-22.

$$\text{Larson-Skold index} = (\text{epm Cl}^- + \text{epm SO}_4^{2-}) / (\text{epm HCO}_3^- + \text{epm CO}_3^{2-}) \quad (4-22)$$

The Larson-Skold index is reported to be interpreted by the following guidelines⁴⁸:

- “Index \ll 0.8 chlorides and sulfate probably will not interfere with natural film formation
- 0.8 \ll index \ll 1.2 chlorides and sulfates may interfere with natural film formation. Higher than desired corrosion rates might be anticipated
- Index \gg 1.2 the tendency towards high corrosion rates of a local type should be expected as the index increases.”

It is noted that the Great Lakes have bicarbonate-rich waters, the alkalinity of which ranges from 46 parts per million (ppm) of carbonates in Lake Superior to 113 ppm in Lake Michigan.⁵¹ This index may not be applicable for water with low or extreme alkalinity conditions beyond the range of original data.⁴⁸

4.4 SPRINKLER PIPE THICKNESS (SCHEDULE)

The thickness of steel sprinkler pipe plays an important role in determining its service life, if the pipe corrosion rate is relatively constant. Schedule 40 pipe was the most popular size of sprinkler pipe for FPS. However, thinner types of pipe, such as Schedule 10 or 5, are commonly installed in FPS now, especially for dry or preaction systems.

Table 4.2 compares the nominal wall thickness of Schedule 10 versus Schedule 40 steel pipe of different pipe sizes. If a linear corrosion rate is assumed to occur equally on all pipe sizes, NPS 1 Schedule 10 pipe would be expected to have a service life about 82.0% that of NPS 1 schedule

40 pipe; NPS 6 Schedule 10 pipe would be expected to have a service life about 47.9% that of NPS 6 Schedule 40 pipe. This indicates that by using thinner pipe, service life of sprinkler pipe in FPS can be significantly reduced. This is particularly pronounced for pipe diameters greater than NPS 3; for these larger sizes, the service life of Schedule 10 pipe is only about half that of Schedule 40 pipe.

Table 4.2 Comparison of nominal wall thickness of Schedule 10 versus Schedule 40 steel pipe.

Nominal Pipe Size (NPS) Diameter Inch	Schedule 10 Wall Thickness Inch	Schedule 40 Wall Thickness Inch	Schedule 10/Schedule 40 Wall Thickness Ratio %
1	0.109	0.133	82.0
2	0.109	0.154	70.8
3	0.120	0.216	55.6
4	0.120	0.237	50.6
6	0.134	0.280	47.9
8	0.148	0.322	46.0
12	0.180	0.406	44.3
16	0.250	0.500	50.0

4.5 DEGRADATION OF CHLORINATED POLYVINYL CHLORIDE (CPVC) SPRINKLER PIPING SYSTEMS

4.5.1 Types of Plastic Failure

Plastic materials have been widely utilized in a variety of processing and construction industries due to their corrosion resistance properties, long-term durability, ease of production and installation, etc.^{52,53} However, similar to metals, plastic products do suffer degradation and failure in service. Figure 4.23 characterizes causes of plastic failures based on failure analysis of 5,000 plastic products.⁵⁴ In Figure 4.23, it is noted that environmental stress cracking (ESC) is the most common cause, being responsible for 25% of plastic failures.

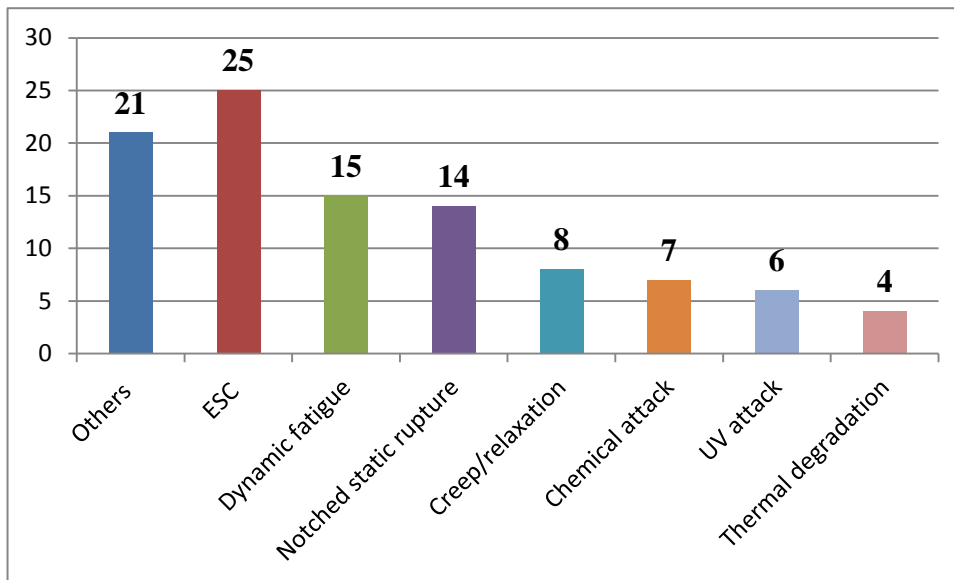


Figure 4.23 Causes of plastic failure – percentage.

CPVC pipe and fittings have been successfully used in fire protection systems for more than 30 years.⁵⁵ Some compatibility issues between CPVC material and its service environments are known and have been addressed by Lubrizol Corporation in its “FBC™ System Compatible Program”.⁵² This program is designed to test chemical compatibility of Lubrizol’s CPVC products with a broad range of chemicals, which may come in contact with CPVC in the field. In addition, UL (Underwriters Laboratories), FM Global, Lubrizol, NSF International (National Sanitation Foundation) and the fire protection industry have formed a STP 2732 committee to write the UL 1821B standard titled “Evaluating Compatibility of Products with CPVC Piping” for CPVC fire protection system.

4.5.2 Environmental Stress Cracking (ESC) Mechanism

As shown in Figure 4.23, ESC is the most common cause of plastic failure. Absorption of organic chemicals into a plastic can reduce its yield strength.^{55,56,57} This absorption process is accelerated when the plastic is under applied stress (especially tensile stress). The absorbed organic chemicals along with applied stress weaken intermolecular bonds of plastics, leading to local bonding cleavage, thereby reducing the strength of the material. The ISO 220088-1:2006

(E) “Plastics – Determination of resistance to environmental stress cracking (ESC) – Part 1: General guidance” standard illustrates the underlying mechanisms for ESC as the following:⁵⁸

- 1) “Formation of microvoids in specimens by microscopic stress concentration after applying stress.
- 2) Formation and subsequent growth of macrovoids caused by the breakdown of intermolecular bonds in intervoids that is produced by the action of a chemical environment, and formation of crazes which are composed of interconnected voids and fibrils.
- 3) Growth of the crazes caused by the breakdown of the fibrils due to the applied stress and contact with a chemical environment.
- 4) Finally, a crack starts at the tip of the craze, leading to brittle failure.”

Organic fluids with modest hydrogen bonding, such as aromatic hydrocarbons, halogenated hydrocarbons, ketones, aldehydes, esters, ethers, and nitrogen and sulfur containing compounds, can be absorbed into the plastics with the assistance of applied stress.^{52,59} They are likely to be ESC agents. Examples of ESC agents include paints, adhesives, cleaning agents, lubricants, residual oil (including pipe cutting oil), solvent cements, plasticizers, inks, aerosol sprays, leak detection fluids, lacquers, surfactants, etc.

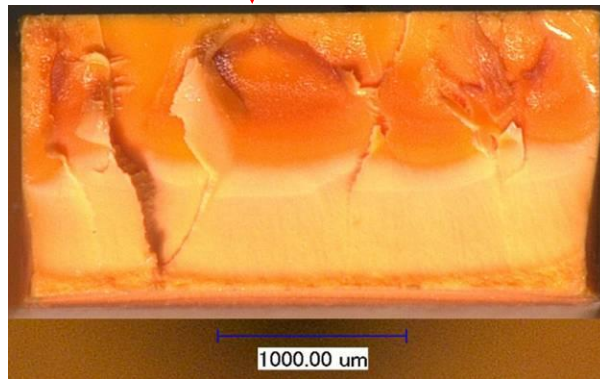
Because of their relatively open structure, glassy amorphous thermoplastics, like polyvinyl chloride (PVC), CPVC, polycarbonate (PC), and polymethyl methacrylate (PMMA), are more susceptible, in general, to ESC failure than semi-crystalline thermoplastics like polyethylene (PE) and polypropylene (PP) or thermosetting plastics like polyimide (PI) and epoxy resin. Closely packed crystalline regions of plastics act as penetration barriers to chemicals; thus, the cracking can be reduced by the crystalline region.

Figure 4.24 (A) shows five CPVC type V tensile specimens on a 1% strain jig for ESC testing of coating chemicals on black steel pipe.⁶⁰ Figure 4.24 (B) displays the fracture surface side view of a type V tensile specimen exposed to an ESC agent. The dark orange/glassy^{55,47} region indicates that the ESC agent has diffused into the specimen and the tensile stress has accelerated the diffusion process of this chemical; thus, eventually led to ESC fracture of the specimen.



(A)

Exposed Surface



(B)

Figure 4.24 Photographs showing (A) five CPVC type V tensile specimens on a 1% strain jig for ESC testing of coating chemicals on black steel pipe and (B) the fracture surface side view of a type V tensile specimen – ESC agent diffused into the specimen from exposed surface (top).

4.5.3 Other Failure Modes

CPVC pipes and fittings are mainly fabricated by extrusion and injection molding processes, respectively. They are known to have knit lines (weld lines) as a result of incomplete fusion of polymers. The knit lines' interface decreases the mechanical strength of CPVC components, and is more susceptible to attack by ESC agents.⁶¹ It is noted that there are many other failure modes of CPVC components in fire protection systems that have been reported. For example, improper installation, manufacturing and materials defects, operation and handling errors, are listed as contributing to CPVC failure in service.

5 FIELD CORROSION/LEAKAGE EXAMPLES

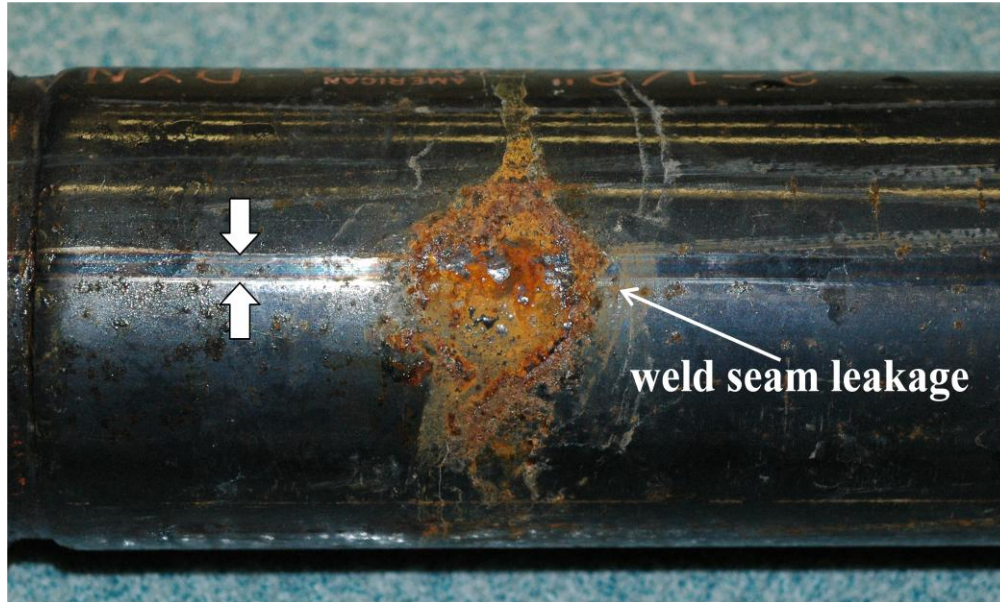
5.1 WELD SEAM CORROSION AND LEAKAGE

Preferential corrosion of weld seam (i.e., “grooving corrosion” or “knife-edge corrosion”) in steel pipe welded by electric-resistance welding (ERW) process is a common failure mode for fire protection sprinkler systems.⁶² This kind of corrosion may be attributed to formation of unstable iron sulfides along with high residual stresses and microstructure changes around weld seam areas (i.e., causing anodic sites for corrosion to occur).⁶³ Such areas are created during the pipe manufacturing process and they include the weld seam and other heat-affected zones.⁶⁴ Corrosion and/or leakage of sprinkler pipe surrounding the weld seam area at the pipe bottom is frequently observed in the field due to low corrosion resistance and near-bottom (6 o’clock) orientation of the weld seam. For example, localized corrosion underneath tubercles and corrosion scale (e.g., under-deposit or pitting) requires aggressive, concentrated solution (e.g., pH ~ 2 and Cl⁻) to grow actively, often growing in the direction of the gravity force field. “Since the dense, concentrated solution within a pit is necessary for its continuing activity, pits are most stable when growing in the direction of gravity.”¹⁴ Note that if the pipe weld is oriented above the 9 o’clock position toward the building roof (e.g., 9 o’clock to 12 o’clock positions), pitting corrosion can be expected to be less severe for not growing in the direction of the gravity force field (e.g., upward).

In practice, the weld seam is commonly located near the pipe bottom or at the 6 o’clock position for installed FPS, contrary to recommended FM Global practice noted earlier in Section 3.2. Corrosion and/or leakage of sprinkler pipe surrounding the weld seam area at the pipe bottom is frequently observed in the field due to low corrosion resistance and near-bottom orientation of the weld seam, in conjunction with corrosion following gravity phenomena.

5.1.1 Wet Pipe System

Figure 5.1 (A) and (B) shows leakage on an NPS 2½ steel sprinkler pipe in a wet pipe system. The weld seam leakage site and the location of the weld seam are indicated by arrows in Figure 5.1 (A). Figure 5.1 (B) shows the waterside of the pipe in the region corresponding to the leakage site, after removal of corrosion products. Preferential attack surrounding the weld seam is severe.



(A)



(B)

Figure 5.1 Photographs showing (A) Weld seam leakage site on a NPS 2½ sprinkler pipe with the location of the weld seam indicated by arrows. (B) The waterside of the pipe in the region corresponding to the leakage site, after removal of corrosion products. Preferential attack surrounding the weld seam is severe.

Figure 5.2 shows an example of preferential grooving corrosion on a pipe weld seam with a 1 mm pinhole leak in a wet pipe system, after removing corrosion products inside an NPS 3 pipe.



Figure 5.2 Photograph showing preferential grooving corrosion on pipe weld seam with a 1 mm pinhole leak in a wet pipe system, after removing corrosion products inside an NPS 3 pipe.

5.1.2 Dry Pipe or Preaction Systems

Figure 5.3 shows grooving corrosion of a longitudinal through-wall leakage in a galvanized steel pipe along its weld seam in a preaction system. The leak occurred beneath a large tubercle (shown in Figure 4.21) along the pipe's approximate 6 o'clock installed position. Figure 5.4 shows another preferential grooving corrosion attack surrounding the weld seam area for a preaction system, near the pipe's 6 o'clock (bottom) installed position.

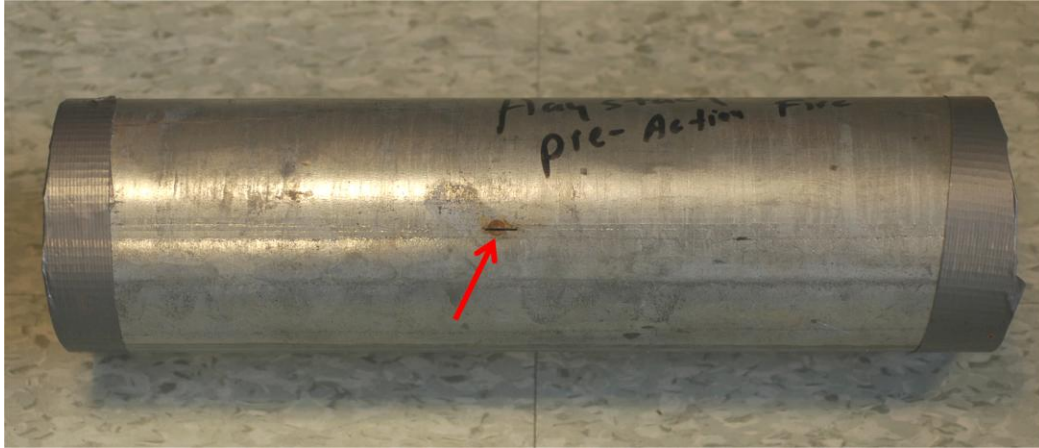


Figure 5.3 Photograph showing the outside of the bottom half of the pipe in Figure 4.21. The arrow points a longitudinal through-wall leakage site on the pipe in a preaction system.



Figure 5.4 Photograph showing preferential grooving attack surrounding the weld seam area in a preaction system.

5.2 TRAPPED AIR IN WET PIPE SYSTEMS

Figure 5.5 shows the leakage section of a pipe where the air gap filled approximately 40% of the volume in a wet pipe system, providing the oxygen source for steel pipe corrosion. The through-wall leakage site is indicated and the two parallel lines point to the air pocket boundary in the pipe. Note the significant tuberculation/corrosion products/deposit buildup in the bottom half of

the pipe. The leakage arrow points to a large tubercle, beneath which the leakage site was located.

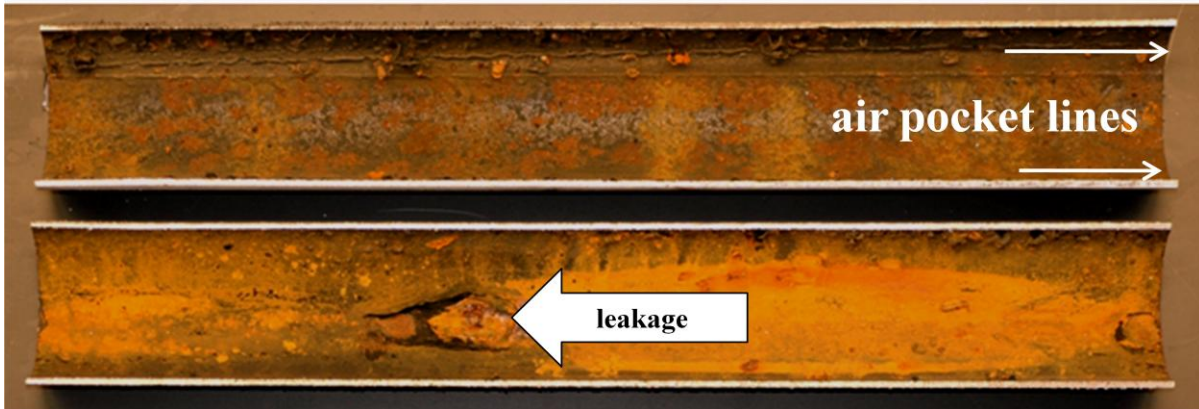


Figure 5.5 Photograph showing the leakage section of a pipe where the air gap filled approximately 40% of the volume in a wet pipe system.

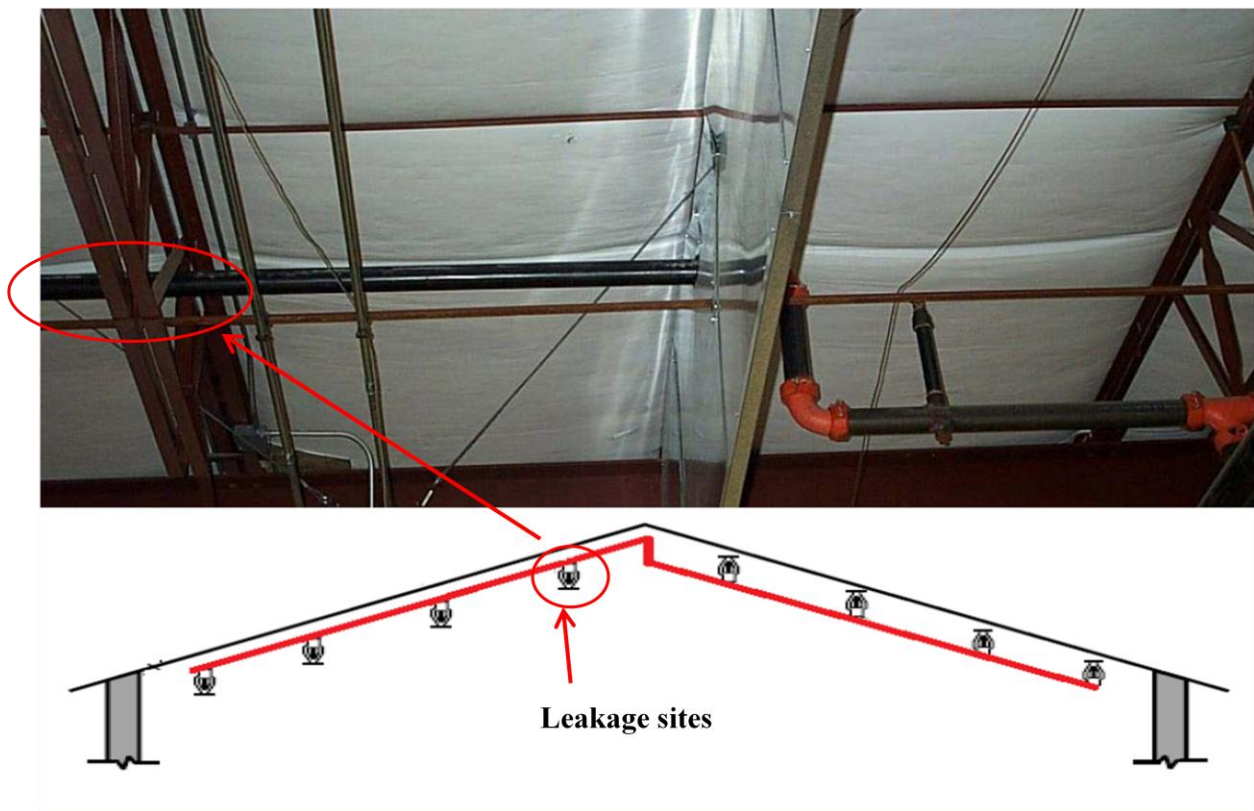


Figure 5.6 Photograph showing leakage sites in a wet pipe system due to trapped air.

Figure 5.6 shows leakage sites of a wet pipe system due to trapped air. The leakage sites were at the left in the picture and near the roof bar joist as indicated. They were 10-15 ft to the left of the highest point in the system.

5.3 RESIDUAL WATER IN DRY PIPE OR PREACTION SYSTEMS

Residual water in dry pipe or preaction systems is the leading cause for corrosion and leakage of galvanized steel pipe in these systems. The presence of the air gap above the residual water results in high dissolved oxygen and carbon dioxide contents in the water and makes it corrosive to galvanized steel sprinkler pipe. Figure 5.7 shows corrosion of galvanized steel pipe (NPS 6, Schedule 10) where residual water filled about 40% of the pipe's volume in a dry pipe system.



Figure 5.7 Photograph showing corrosion of galvanized steel pipe (NPS 6, Schedule 10) where residual water filled about 40% of the pipe's volume in a dry pipe system.

It should be noted that new dry and preaction systems can develop through-wall corrosion leakage within as little as 2 years after installation, due to residual water in galvanized steel pipe. In accordance with FM Global practice noted in Section 3.2, dry and preaction sprinkler system piping should be pitched towards low point drains.

5.4 WATER CORROSIVITY ANALYSIS

As discussed in Section 4.3, parameters like dissolved oxygen (O_2), dissolved anions (chloride, sulfate, etc.), pH, alkalinity (HCO_3^- and CO_3^{2-}), and solids (hardness and deposits) are needed to give an overall assessment of sprinkler water corrosivity toward steel components such as sprinkler piping in FPS.

Figure 5.8 shows four water samples collected from a wet pipe system for water corrosivity analysis. Samples #1 and #2 were source water samples, while Samples #3 and #4 were fire pump line samples, respectively. The two source water samples were clear, while the fire pump water samples had a light brown and a light yellow color, respectively.

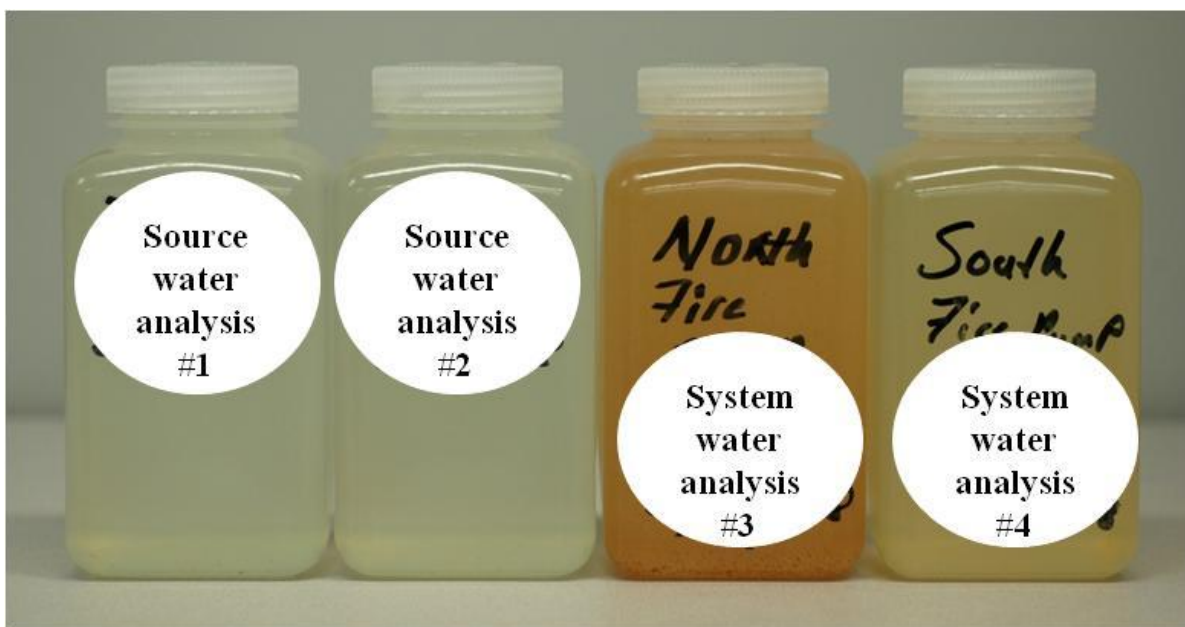


Figure 5.8 Photograph showing four water samples removed from a wet pipe system. Samples #1 and #2 were source water samples, while Samples #3 and #4 were fire pump line samples, respectively. The two source water samples were clear, while the fire pump water samples had a light brown and a light yellow color, respectively.

Chemical analyses were conducted on the four water samples in Figure 5.8; results are presented in Table 5.1. The findings were then evaluated to determine the corrosivity of the water samples to any carbon steel components with which they might come into contact. The Larson-Skold index of the water samples, calculated from their chloride, sulfate, and alkalinity values, were all determined to be over 4.77.

The tendency towards high corrosion rates of a local type should be expected as the index increases above 1.2, along with chloride concentration (>91 ppm) in these water samples. Thus, the sprinkler water in this analysis was considered to be corrosive to steel sprinkler piping.

Table 5.1 Water analysis results.

Sample	pH	Total Hardness as CaCO ₃ (ppm)	Total Alkalinity as CaCO ₃ (ppm)	Total Dissolved Solids (ppm)	Calcium (ppm)	Magnesium (ppm)	Cl ⁻ , NO ₃ ⁻ , and SO ₄ ²⁻ anions			Larson-Skold Index
							chloride	nitrate	sulfate	
Water #1	6.8	79	61	490	24	4.6	110	0.18	190	7.06
Water #2	6.9	81	61	500	25	4.6	91	<0.09	200	6.73
Water #3	6.9	95	79	550	29	5.3	110	2.7	240	6.26
Water #4	6.9	88	83	530	27	5.0	97	3.54	180	4.77

5.5 WATER CORROSIVITY AND MIC ANALYSES

5.5.1 Example I

Figure 5.9 shows four water samples in a wet pipe system. Source water analysis samples #1 and #2 are source water samples, while system water analysis samples #3 and #4 are system water samples. The two source water samples are brown and light tan, and the two system water samples are yellow and reddish-brown. This facility's wet pipe fire protection system was 4-5 years old after showing pipe leakage. Two feeder line pipe samples, and two source and two sprinkler system water samples, were received for analysis. Results of water chemistry and SRB analysis are shown in Table 5.2.

The immunoassay sulfate reducing bacteria analysis of the sprinkler water samples showed that the concentration of SRB was negative (below the test's detection limit - 10^3 cells/ml), i.e., $< 10^3$ SRB bacteria were present in each 1 ml of water. Consistent with these findings, the results of the lead acetate sulfide analyses of both the sprinkler and source water samples were negative. There was also no significant reduction observed in the sulfate concentration in the sprinkler waters compared with the source waters. These results indicated that planktonic SRB concentration was below detectable limit.

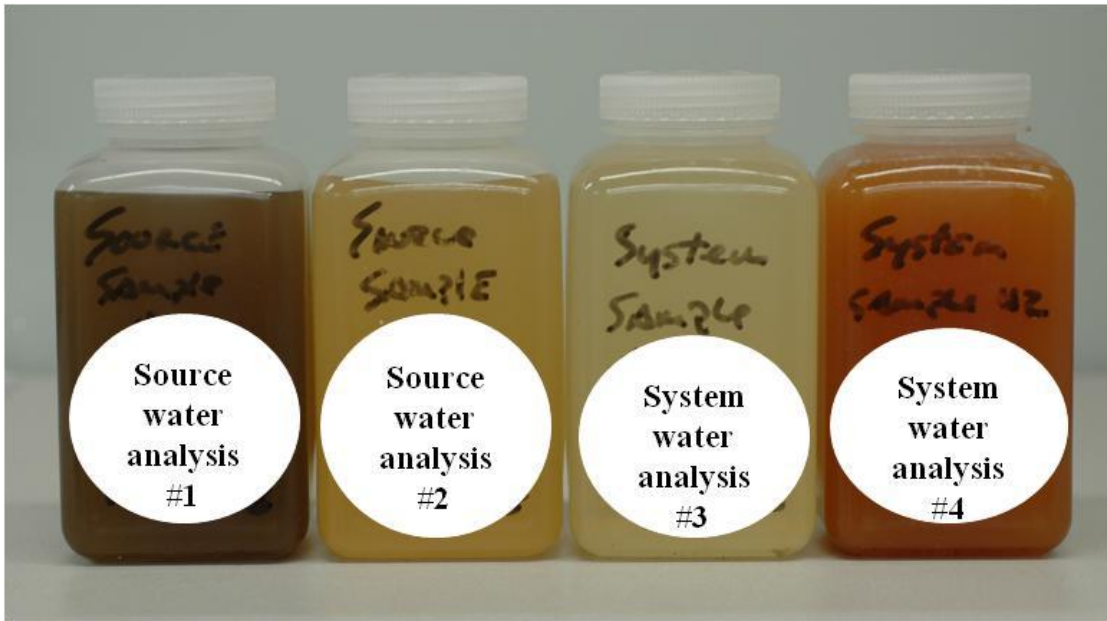


Figure 5.9 Photograph showing the four water samples in a wet pipe system. samples #1 and #2 are source water samples, while samples #3 and #4 are system water samples.

In contrast to the results obtained from the water samples, the immunoassay SRB and sulfide tests of the tubercle/deposit buildup specimens removed from the feeder line pipe samples were weakly to moderately positive (10^3 to 10^4 cells/ml). These results indicated the presence of sessile SRB on the wall of the sprinkler pipe tested. The detection of sessile bacteria indicated the establishment of a microbial colony on the pipe, which may have caused pipe corrosion.

Table 5.2 Water and sprinkler pipe analysis results.

Sample	Water Line	pH	Total Hardness as CaCO ₃ (ppm)	Total Alkalinity as CaCO ₃ (ppm)	Total Dissolved Solids (ppm)	Ca (ppm)	Mg (ppm)	Cl ⁻ , NO ₃ ⁻ , and SO ₄ ⁻² anions (ppm)			Larson-Skold Index ¹	SRB ²	Sulfide ²
								chloride	nitrate	sulfate			
Water #1 ³	N/A	8.1	13	25	150	3.2	1.2	43.0	0.84	10.0	3.47	--	-
Water #2 ³	N/A	8.4	13	25	180	3.2	1.2	34.0	0.84	8.0	2.75	--	-
Water #3 ³	N/A	9.2	13	30	140	3.1	1.2	33.0	0.58	6.0	2.15	-	-
Water #4 ³	N/A	9.0	12	25	180	3.0	1.2	32.0	0.53	7.0	2.56	-	-
Pipe #1 Top ³	Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+	++
Pipe #1 Bot ³	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+	+
Pipe #2 Top ³	Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+	++
Pipe #2 Bot ³	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+	+

¹ The Larson-Skold index is computed from the sample's chloride, sulfate, and alkalinity values. A high value (> 0.8) indicates that a protective carbonate scale might not form on a steel component exposed to this water. Due to the low alkalinity (25-30 ppm) of water samples in this analysis, values of Larson-Skold index are reported for reference only.

² +++ = strong indication, ++ = moderate indication, + = weak indication, - = below detection limit or negative result; -- = not tested; N/A = Not Applicable.

³ Water #s 1 and 2: Source Water; Water #s 3 and 4: System Water. Pipe #1 Top: Tubercle/deposit buildup removed adjacent to Pipe #1's air gap; Pipe #1 Bot: Tubercle/deposit buildup removed from the bottom of Pipe #1 (diametric to the air gap); Pipe #2 Top: Tubercle/deposit buildup removed adjacent to Pipe #2's air gap; Pipe #2 Bot: Tubercle/deposit buildup removed from the bottom of Pipe #2 (diametric to the air gap).

A portion of the pipe sample #1 in Table 5.2 is shown in Figure 5.10. Extensive tuberculation and deposit buildup are apparent. In the center of the photo, along a longitudinal band, the degree of tuberculation and deposit buildup is greatly diminished, indicating the former presence of an air pocket in the pipe. The trapped air filled up about 5-10% of the pipe's volume. The air pocket would lead to high dissolved oxygen content in the water, increasing the likelihood of under-deposit pitting corrosion of steel from the differential oxygen concentration phenomena.



Figure 5.10 Photograph showing extensive tuberculation and deposit buildup for a portion of the Pipe Sample #1 in Table 5.2.

In summary, corrosive water, trapped air, and MIC were identified as the causes contributing to pipe corrosion and/or leakage in this fire protection system.

5.5.2 Example II

Figure 5.11 shows three water samples in a wet pipe system. Source water analysis sample #1 is the source water sample, while system water analysis samples #2 and #3 are system water samples from the 2-inch drain and the inspector test connection, respectively. This wet pipe system was over 12 years old, and no leakage had been reported in the system.

Figure 5.12 is a photograph showing an NPS 1¼ branch line pipe removed from the system. Visual examination of the inside diameter surfaces of the pipe revealed that it was in relatively good

condition. The pipe sample did not exhibit leakage indications. Some tubercles/corrosion products/deposit buildup was detected on the waterside of the pipe, but the amount of this material was not significant.



Figure 5.11 Photograph showing the three water samples in a wet pipe system. Sample #1 is from source water. Samples #2 and #3 are system water samples.



Figure 5.12 Photograph showing an NPS 1¼ branch line pipe sample.

Table 5.3 shows SRB and APB test results of sprinkler pipe and water samples. The APB test kit results for the three water samples and the two tubercles/corrosion products/deposit buildup specimens were concluded to be strong; yet, SRB were negative and only showed very low activity in water sample #2.

Table 5.3 Sprinkler pipe and water SRB and APB test results.

Sample	SRB	APB
Water #1 ³	Negative	Strong
Water #2 ³	Very Low	Strong
Water #3 ³	Negative	Strong
Pipe #1 ³	Negative	Strong
Pipe #2 ³	Negative	Strong

¹ SRB = sulfate-reducing bacteria.

² APB = acid-producing bacteria.

³ Water #1 – source water: “suction tank sample”; Water #2 – system water: “2-inch drain sample”; Water #3 – system water: “inspector test connection sample”; Pipe #1 – branch line pipe sample: “tubercles/corrosion products/deposit buildup”; Pipe #2 – branch line pipe sample: “tubercles/corrosion products/deposit buildup.”

Table 5.4, which shows the results of the corrosivity analysis performed on the three water samples, indicates that they are all very corrosive to any carbon steel sprinkler components with which they might come into contact.

Table 5.4 Sprinkler Pipe and Water Chemical Analysis Results.

Sample	pH	Total Hardness as CaCO ₃ (ppm)	Total Alkalinity as CaCO ₃ (ppm)	Total Dissolved Solids (ppm)	Ca (ppm)	Mg (ppm)	Cl ⁻ , NO ₃ ⁻ , and SO ₄ ²⁻ anions (ppm)			Larson-Skold Index ¹
							chloride	nitrate	sulfate	
Water #1 ²	7.5	240	108	740	65	19	140	<0.44	190	4.47
Water #2 ²	7.0	220	115	700	50	23	140	<0.44	220	4.53
Water #3 ²	8.2	150	29.7	600	24	22	130	0.53	180	15.2
Pipe, #1 ²	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pipe, #2 ²	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

¹ The Larson-Skold index is computed from the sample’s chloride, sulfate, and alkalinity values. A high value (> 0.8) indicates that a protective carbonate scale might not form on a steel component exposed to this water.

² Water #1 – source water: “suction tank sample”; Water #2 – system water: “2-inch drain sample, system #3”; Water #3 – system water: “inspector test connection sample, system #3”; Pipe #1 – branch line pipe sample: “tubercles/corrosion products/deposit buildup”; Pipe #2 – branch line pipe sample: “tubercles/corrosion products/deposit buildup.”

In summary, corrosive water and MIC were identified as the causes contributing to pipe corrosion in this fire protection system.

5.6 CORROSION AND PREMATURE OPERATION OF SPRINKLERS

Figure 5.13 shows six intact (top, #1-6) and one prematurely-operated (bottom, #7) sprinkler heads removed from the mechanical room housing boilers and air-handling units inside a building. The #7 sprinkler's fusible link halves had separated during a premature operation incident.



Figure 5.13 Photograph showing six intact (top, #1-6) and one prematurely operated (bottom, #7) sprinkler heads. The #7 sprinkler's fusible link halves had separated during the premature operation incident.

A photograph showing a side view of the fusible link halves from Sprinkler #1 is presented in Figure 5.14. The copper-based alloy halves are covered with a bluish-green corrosion product/deposit. A significant gap is also present between the link halves. The exposed surface of

the fusible solder visible between the link halves has a rough surface, consistent with corrosion attack.

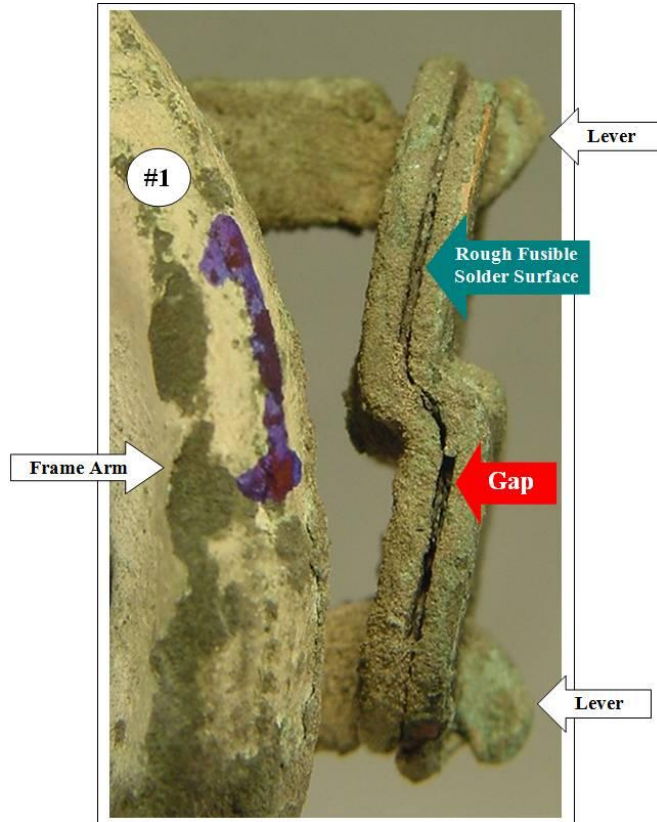


Figure 5.14 Photograph showing a side view of the fusible link halves from Sprinkler #1. A significant gap is present between the two link halves. The exposed surface of the fusible solder visible between the link halves has a rough surface, consistent with corrosion attack.

A close-up photograph of the fracture surface (solder side) of the link half from the prematurely operated sprinkler is shown in Figure 5.15. The white arrows highlight white deposits/buildups and the green arrows bluish-green corrosion products/deposit buildups. The small red circle area was analyzed with Xray microfluorescence technique.

The presence of the bluish-green areas on the fracture face indicates that the environment surrounding the sprinkler head had penetrated the soldered joint. Before the separation incident,

the edges of the joined link halves would thus have been expected to exhibit a gap similar to that shown in Figure 5.14 for Sprinkler #1. Such a gap, likely caused by corrosion attack of the solder, would have allowed the ingress of environmental gases and moisture into the joint.

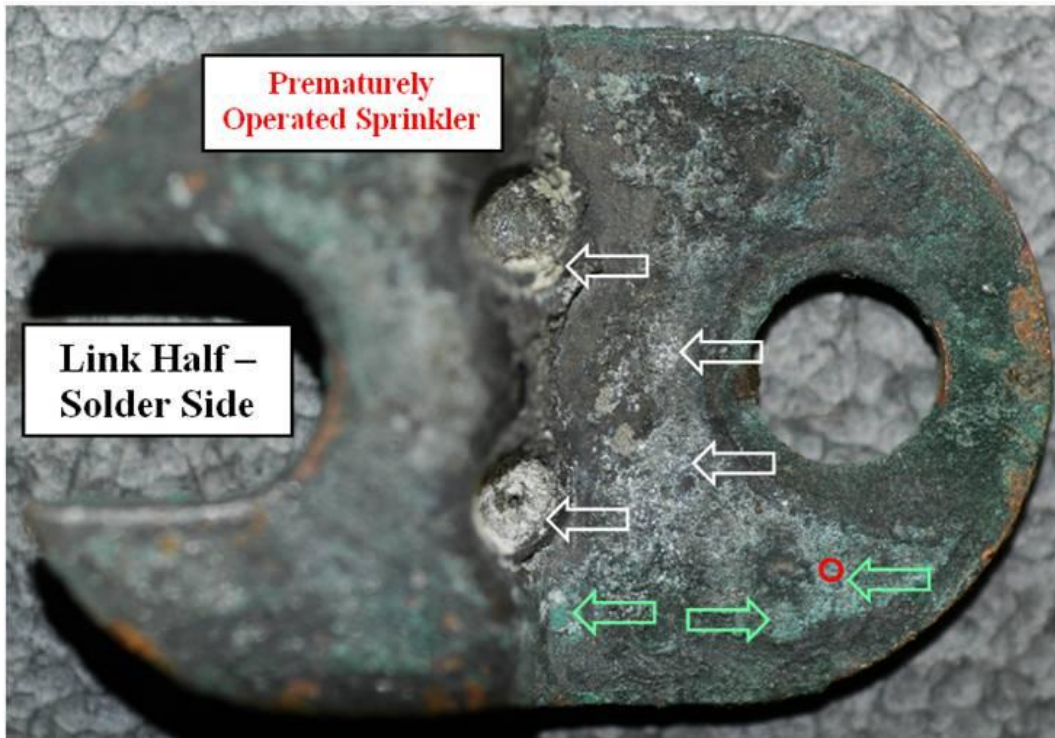


Figure 5.15 Close-up photograph of the fracture surface (solder side) of the link half from the prematurely operated sprinkler.

Figure 5.14 is the Xray microfluorescence spectrum of the bluish-green corrosion products/deposit buildup area circled (red) in Figure 5.15 and its standardless (semi)quantitative chemical analysis results of the XRMF spectrum. The Cu, Zn and Fe spectrum peaks in Figure 5.16 are associated with brass sprinkler compositions; the Bi, Sn and Cd peaks are from the fusible solder. The Zn and Cl spectrum peaks are related to the presence of a zinc chloride flux residue on the fusible solder.

In summary, the cause of the failure of the sprinkler head was the combined effects of the presence of trapped flux within the soldered joint, as well as the penetration of environmental gases and moisture into the joint that caused corrosion of the fusible solder. These preexisting

and in-service deterioration conditions weakened the joint, which ultimately led to its separation due to time-dependent creep.

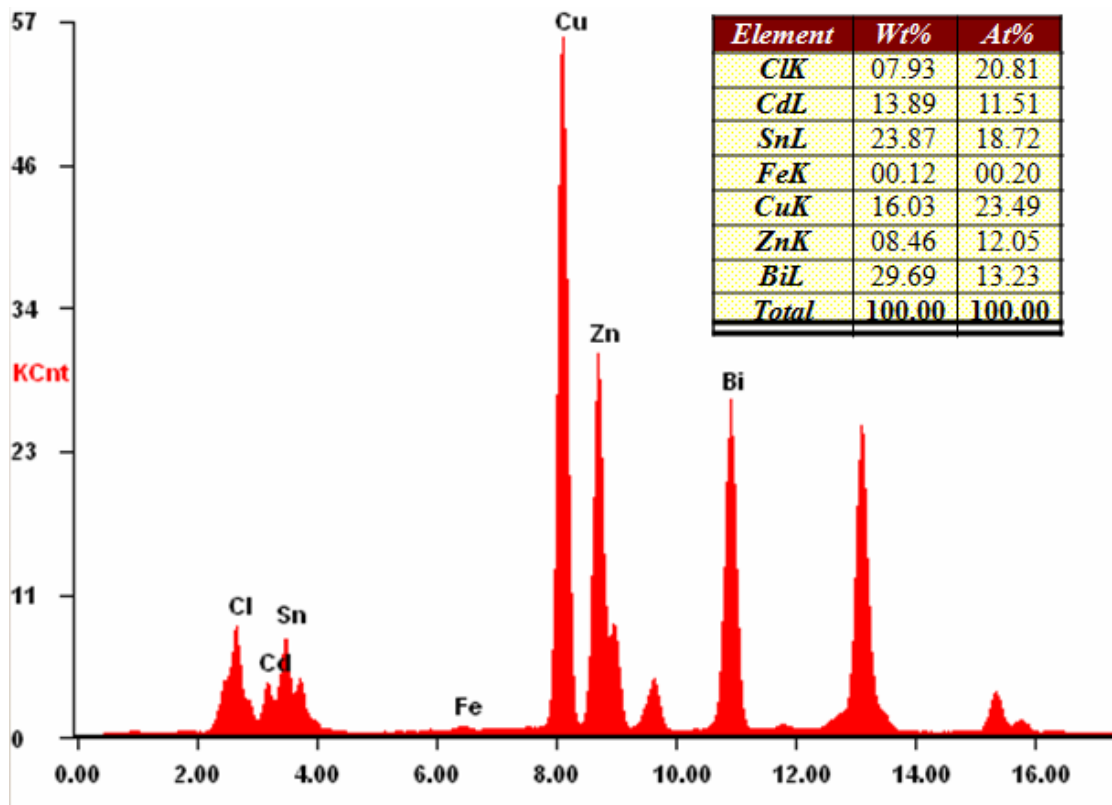


Figure 5.16 X-ray microfluorescence spectrum of the bluish-green corrosion products/deposit buildup area circled (red) in Figure 5.15 and its standardless (semi)quantitative chemical analysis results of the XRMF spectrum.

6 CORROSION MITIGATION

Corrosion and corrosion-caused pipe leakage in FPS are complicated issues. They can be caused by many factors or the combination of these factors, such as pipe weld corrosion, residual water in dry pipe systems, trapped air in wet pipe systems, corrosive water chemistry, periodically injecting oxygen into FPS (fresh sprinkler water recharged during regular maintenance), stagnant water, dead legs of pipe, and MIC.

It is beneficial to start corrosion mitigation strategies by first tackling the most frequently occurring factors, such as pipe weld corrosion, residual water in dry pipe systems, trapped air in wet pipe systems, and oxygen in sprinkler water issues. Then, deal with corrosive water chemistry, stagnant water, and MIC factors, which may require pipe cleaning, corrosion inhibitor applications, and biocide treatments.

6.1 PIPE WELD SEAM MANAGEMENT

As discussed in Section 5.1, preferential corrosion of weld seam is common for electric-resistance welded steel pipe in FPS, especially if the weld seam is located near the pipe bottom or at the 6 o'clock position in the installed FPS. Use of stress relieved steel pipe (Grade B in accordance with ASTM A795/A795M-13) or avoidance of installation of the pipe weld seam near the 6 o'clock position could be beneficial in reducing pipe weld seam corrosion.

FM Global Data Sheet 2-0 states, "To help reduce the potential for accelerated internal pipe corrosion of longitudinally-welded black steel pipe, install such pipe with the weld line rotated at least 45° in relationship to the floor (for reference, the weld line points at the floor at 0°)." Sprinkler weld seams should be oriented towards the building roof (180°) to prevent the weld from being located under deposits within the pipe.

Figure 6.1 shows metallographic images of weld protrusion of pipe sections oriented in the (A) 9 o'clock (side) and at (B) 6 o'clock (bottom) directions after 12 months of exposure in aerated artificial sea water.⁶³ After 12 months of dynamic testing, the corrosion (metal loss) of the weld

located at the 6 o'clock (bottom) position is 2.7 times higher than that of the weld located at the 9 o'clock (side) position (77.7% vs. 29.1 %).⁶³

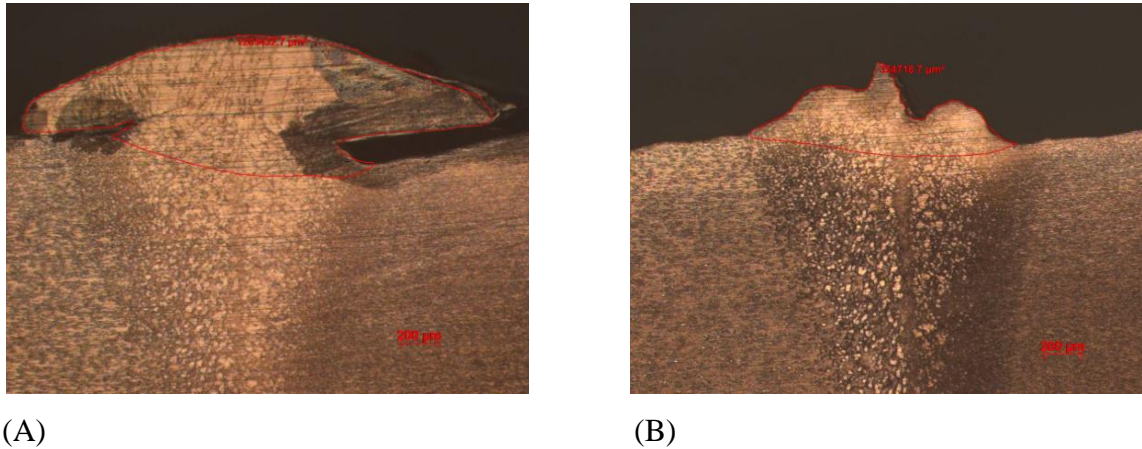


Figure 6.1 Metallographic images showing weld protrusion of pipe sections oriented at the (A) 9 o'clock and (B) 6 o'clock position (50X magnification).

To mitigate pipe weld corrosion in fire protection systems, it is recommended to: (A) orient the pipe weld seam above the 9 o'clock position (side) toward the building roof, to prevent the weld seam from being located at the 6 o'clock position (bottom) and to reduce pipe weld corrosion rate of electric-resistance welded steel pipe; (B) select steel sprinkler pipe without irregularly shaped finger-type pipe weld for better corrosion resistance of the weld seam area; and (C) reduce the frequency of introducing oxygen-rich water into the steel sprinkler piping system (e.g., periodic inspector testing) to decrease the corrosion rate of the steel.

6.2 DRY PIPE OR PREACTION SYSTEMS

6.2.1 Residual Water

The corrosion and leakage of pipe systems caused by residual water in dry pipe or preaction systems is discussed in Section 5.3. Draining residual water from these dry systems after performance of hydrotesting or maintenance inspection is the most effective way of mitigating corrosion. In practice, this can be difficult due to inadequate pitching of the pipe or use of pendent sprinkler drops that prevent all water from being drained from the system.

6.2.2 Supervisory Nitrogen Gas

Another corrosion mitigation approach is to fill the dry pipe or preaction systems with nitrogen gas from gas cylinders or an on-site nitrogen generating system. FM Global Data Sheets 2-1⁶⁵ and 2-81⁶⁶ recommend the use of nitrogen gas as the supervisory gas where corrosion is a concern. Filling these systems with nitrogen gas can remove oxygen and decrease oxygen-related electrochemical reactions. This technique could mitigate corrosion in these dry systems based on several field trials.

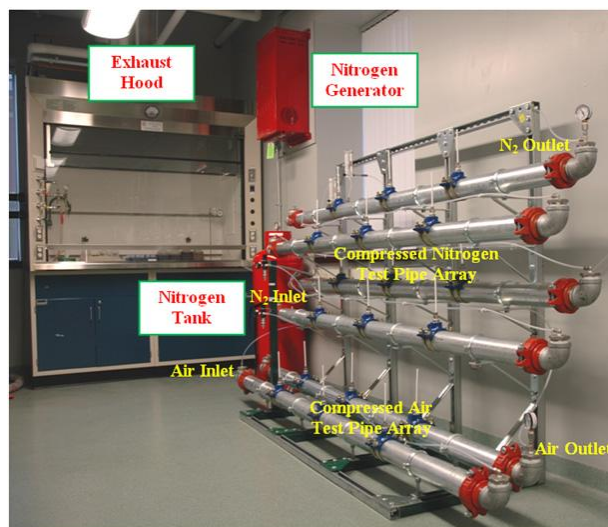


Figure 6.2 Photograph showing an overall view of the compressed nitrogen corrosion test apparatus.

Figure 6.2 is a photograph showing an overall view of a corrosion test apparatus with pressurized nitrogen and compressed air (house air) at 40 psi (0.28 MPa) and 0.2 L/min. flow rate in the pipe test racks.⁶⁷ Initially, a test rack was designed and assembled to support the six pipes containing the test coupons. The other major components that comprise this apparatus – namely, the nitrogen generator, the nitrogen receiver (storage tank), the pipe test rack containing the compressed nitrogen pipe array (top four pipe rows), and the exhaust hood – have been highlighted. The bottom two pipes visible in Figure 6.2 comprise the compressed air test pipe array, which is fed by compressed air available to the laboratory.⁶⁷

Figure 6.3 (A) and (B) shows photographs of galvanized steel pipe half-filled with tap water in (A) house air and in (B) compressed nitrogen, after nearly 6 weeks exposure. For comparison, whitish zinc corrosion products covered the bottom half of the house air-filled pipe in Figure 6.3 (A); yet, only limited zinc corrosion products covered bottom half of the compressed nitrogen-filled pipe in Figure 6.3 (B). This indicated that compressed nitrogen can reduce corrosion of galvanized steel pipe containing trapped water.^{67,68}

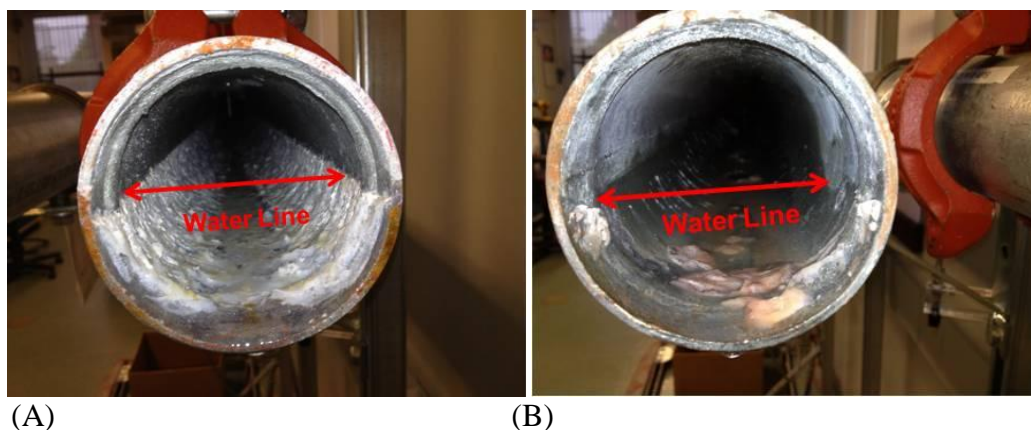


Figure 6.3 Photographs showing galvanized steel pipe half-filled with tap water in (A) house air and in (B) compressed nitrogen for nearly 6 weeks.

The corrosion rates (CR) of galvanized steel coupons in tap water and purged with either house air or nitrogen are shown in Table 6.1. In nitrogen, coupon corrosion rates ranged from 0.25 to 0.54 mpy; in house air (HA), coupon corrosion rates ranged from 0.29 to 1.15 mpy. The values of corrosion rate ratio (CR in HA/CR in N₂) ranged from 1.16 to 2.14. The corrosion rates (CR) of carbon steel coupons in tap water and purged with either house air or nitrogen are also shown in Table 6.1. In nitrogen, coupon corrosion rates ranged from 0.11 to 0.14 mpy; in house air, coupon corrosion rates ranged from 2.96 to 5.90 mpy. The corrosion rate ratio (CR in HA/CR in N₂) ranged from 21.1 to 50.9. Note that the lower corrosion rates of carbon steel (2.96 mpy at 12 months) or galvanized steel (0.29 mpy at 10 months and 0.37 mpy at 12 months) coupons after 10-12 months exposure in house air were likely caused by corrosion products covering the

coupon surfaces and lower oxygen concentration for the 10-12 month coupons located near the bottom of the test coupon assemblies, hence reducing corrosion.

The reduction of corrosion rate for galvanized steel coupons in compressed nitrogen (CR ratio, HA/N₂ -1.16 to 2.14) was less than the reduction of corrosion rate for carbon steel coupons in the same environment (CR ratio, HA/N₂ -21.1 to 50.9). This was caused by corrosion of the zinc coating on galvanized steel coupon as a sacrificial anode to protect underlying carbon steel from corrosion. Therefore, after depletion of zinc coating via long-term exposure in house air (i.e., without N₂ supervisory gas), accelerated corrosion (pitting) of steel can be expected due to the effect of dissolved oxygen concentration gradient, as described in Section 4.3.1.2.

In summary, testing results in Table 6.1 demonstrate the effectiveness of using an on-site nitrogen generator to mitigate corrosion of galvanized steel pipe in dry and preaction fire sprinkler systems by reducing oxygen concentration in these systems.

Table 6.1 Corrosion rates (CR) of galvanized and carbon steel coupons based on weight loss measurements.

Exposure Time (Month)	Corrosion Rate (MPY)									
	Galvanized Steel					Carbon Steel				
	N2	STDev	HA	STDev	CR Ratio HA/N2	N2	STDev	HA	STDev	CR Ratio HA/N2
2	0.54	0.27	1.15	0.06	2.14	0.11	0.02	5.60	1.59	50.91
4	0.44	0.25	0.70	0.04	1.59	0.13	0.02	5.90	0.65	45.38
10	0.25	0.10	0.29	0.03	1.16	0.14	0.02	5.90	0.57	42.14
12	0.29	0.13	0.37	0.04	1.28	0.14	0.01	2.96	0.77	21.14
N2: Nitrogen, 0.2 l/min, 40 psi										
HA: House Air, 0.2 l/min, 40 psi										

6.3 WET PIPE SYSTEMS

The corrosion and leakage of a wet pipe system caused by trapped air inside the pipe is discussed in Section 5.2. Minimizing air pockets in wet pipe systems is recommended. An air release valve,⁶⁹ which is capable of venting trapped air in the pipe, can mitigate this kind of corrosion.

Note that control of the frequency of introducing oxygenated fresh water into the piping system can also mitigate corrosion of wet pipe systems.

6.3.1 Supervisory Nitrogen Gas

Similar to the dry pipe or preaction systems, nitrogen gas can also be used as a supervisory gas to reduce oxygen concentration in fire water for wet systems. Preliminary laboratory testing data have shown effective corrosion mitigation of steel coupons in wet FPS with continuous flow of nitrogen gas.⁶⁷ Yet, there are parameters required to be further studied for field application including the combined use of an air venting device, flow rate of nitrogen gas, etc.

6.4 CORROSIVE WATER CHEMISTRY

Section 5.4 describes a case of sprinkler water with high Larson-Skold index (>4.77) along with chloride concentration (>91 ppm) in the water samples. The sprinkler water in this analysis was considered to be corrosive to steel sprinkler piping. In addition, this water was from a raw water source. Thus, it is recommended to use treated water such as municipal water as the source of sprinkler water for better water quality and less corrosion of FPS.

Filtration or treatment (ion exchange or chemical precipitation) of source water to remove aggressive anions from the sprinkler water may be beneficial. However, proper system design and experimental testing data are needed to confirm system effectiveness before field applications.

6.5 MIC

Due to the complexity of MIC diagnosis and biocide applications, it is necessary to further study effective MIC mitigation techniques before recommendations can be provided.^{6,34,35} It is noted that MIC is not the leading cause of corrosion in FPS based on an FM Global internal study.⁷⁰

6.6 CORROSION INHIBITORS

Corrosion inhibitors are regularly used in many industries to mitigate corrosion, such as boiler water treatment, cooling water systems, and wastewater treatment.⁷¹ Each service environment requires special combinations of corrosion inhibitors to effectively and efficiently mitigate corrosion. For example, organic and inorganic phosphate (PO_4) compounds have been used to inhibit ferrous alloy corrosion; oxidizing chemicals like chlorine and hydrogen peroxide along with non-oxidizing chemicals like quaternary amines (quats) have been used as biocides for MIC control and as corrosion inhibitors; vapor phase corrosion inhibitors (VCI) like amine-based compounds have been used to inhibit corrosion of metallic components.^{71,72,73}

For FPS, systematic study and field testing data associated with using corrosion inhibitors to mitigate corrosion in these systems are not available, besides the published guidelines.⁶ In addition, compatibility tests of these chemicals with other materials used in FPS, such as CPVC and other types of plastic piping, sprinkler heads, O-rings, rubber gaskets, should be carried out before their field applications. Therefore, further study associated with corrosion inhibitor applications for corrosion mitigation in FPS is needed.

6.7 CORROSION MONITORING

There are many recommended methods for monitoring corrosion in sprinkler systems, such as coupon measurements, internal visual inspections, ultrasonic thickness measurements, etc. The effectiveness of some of these techniques may be questionable. Since most severe corrosion and damage areas are often localized, detection of these areas would be difficult utilizing an ultrasonic thickness measurement or using coupon exposure measurements.

Internal visual examination using a borescope or video-borescope would appear to be a practical method for evaluating corrosion in an FPS when the system is accessible with such a device.

6.8 CORROSION-RESISTANT FIRE SPRINKLER SYSTEM FOR INDUSTRIAL EXHAUST DUCT

Many plants remove smoke, fumes and/or dust generated during industrial processes via exhaust ductwork systems, some of which are made of plastics or fiber-reinforced plastics (FRP) that can be ignitable. Damage to these exhaust ductwork systems caused by fire can lead to interruption of plant operations for an extended period with substantial financial losses, as shown in Figure 6.4 (A) and (B).^{74,75,76} Due to the extremely corrosive environments (e.g., acid fumes like HNO_3 , HCl , H_2SO_4 , and HF/HNO_3) inside many combustible exhaust ducts (e.g., ducts made with fiberglass-reinforced plastic [FRP], polypropylene [PP], or chlorinated polyvinyl chloride [CPVC]), sprinkler systems have not been successfully designed and installed to protect against fires originating within these ducts.^{77,78} A fire can originate outside the exhaust system and be drawn into the ductwork, or originate inside the ductwork. The potential ignition sources include electrical short circuits, hot work, friction, and spontaneous ignition of duct deposits. FM Global presently addresses protection of plastic ductwork and associated plastic equipment (e.g., scrubbers and electrostatic precipitators) in Data Sheet 7-78: Industrial Exhaust Systems.



(A)



(B)

Figure 6.4 Photographs of fire incidents. (A) An unsprinklered steel pickling facility with plastic ductwork system, and (B) An unsprinklered facility with corrosive environment.

Feedback from the industry has indicated that the types of corrosion-resistant sprinklers currently used are limited in their applications and generally not suited for the environments typically found in many highly corrosive atmospheres, such as flue gas desulphurization systems, metal acid pickling ducts, chemical industry exhaust systems, power generation industry exhaust systems, and pulp and paper industry exhaust systems.

A fire protection system in the FRP exhaust duct of an HF/HNO₃ steel pickling line has been developed for field application as shown in Figure 6.5.⁷⁹ This new fire protection system is designed to protect FRP or other combustible plastic ducts with corrosive atmospheres. This system is comprised of corrosion-resistant sprinkler nozzles (see Figure 6.6),⁸⁰ linear heat detector (LHD) wires and fire control panel, flexible sprinkler connections, plus other accessories. It is designed to be suitable to protect combustible exhaust ducts from fires in extremely corrosive environments, such as high concentrations of H₂SO₄, HCl, HNO₃, and HF acids, as well as smoke.⁷⁹



Figure 6.5 Representative photograph showing part of the fire protection system protecting the main FRP exhaust duct.

The design of this system was based on results from laboratory and field tests along with data from manufacturers of sprinklers, heat detectors, flexible sprinkler connections, and a fire system installer who would design this new fire protection system. It should be noted that the HF/HNO₃ mixed acid pickling environment is likely to be the most corrosive exhaust environment in which this kind of fire protection system will be used, based on previous testing data.



Figure 6.6 Photograph showing a corrosion-resistant nozzle with ethylene chlorotrifluoroethylene (ECTFE) coating, rounded deflector, and Teflon-based plug.

FM Global Property Loss Prevention Data Sheet 7-78, “Industrial Exhaust Systems,” FM Global Approval Standards 2021/2025, “Automatic and Open Water-Spray Nozzles for Installation in Permanently Piped Systems,” and 3210, “Heat Detectors for Automatic Fire Alarm Signaling” have been updated to provide guidelines and approved manufacturers for the installation of a fire sprinkler system suitable for HF/HNO₃ and other highly corrosive exhaust duct environments.^{81,82}

7 SUMMARY AND CONCLUSIONS

A. Corrosion in Fire Protection Systems

1. Corrosion occurs in all sprinkler systems and is one of the major issues for the maintenance and operation of wet pipe, dry pipe, and preaction systems.
2. Corrosion damage/products and mineral deposits can restrict water flow to sprinklers and impair mechanical operation of FPS equipment, leaving facilities vulnerable to uncontrolled fire loss.
3. Several organizations, such as the National Fire Protection Association (NFPA), the Electric Power Research Institute (EPRI), FM Global, and the European Fire Sprinkler Network, have published documents and standards attempting to address these problems. Yet, currently there is no agreed-upon strategy either within the fire protection industry or the National Association of Corrosion Engineers (NACE International) to effectively and efficiently mitigate corrosion in FPS.
4. Corrosion and corrosion-caused pipe leakage in FPS can be caused by many factors or the combination of these factors, such as pipe weld corrosion, residual water in dry pipe systems, trapped air in wet pipe systems, corrosive water chemistry, periodic supply of oxygenated water into the FPS (fresh sprinkler water recharged during regular maintenance), stagnant water, and microbiologically influenced corrosion (MIC).
5. This document comprehensively discusses potential forms of corrosion in FPS, including uniform corrosion, galvanic corrosion, pitting corrosion, crevice corrosion, selective leaching, erosion corrosion, environmentally induced corrosion, intergranular corrosion, MIC, corrosion and premature operation of sprinklers, along with degradation of CPVC (chlorinated polyvinyl chloride) sprinkler piping.
6. This document discusses parameters leading to corrosion and/or leakage of steel piping in FPS, such as tuberculation, water chemistry, sprinkler pipe thickness, weld seam corrosion, trapped air (wet systems), and residual water (dry systems).

7. A corrosion-resistant fire sprinkler system for highly corrosive industrial exhaust ducts has been developed by FM Global and approved manufacturers. The approved products and system are available for field installation, including corrosion-resistant sprinkler nozzles, linear heat detector wires and fire control panel, flexible sprinkler connections, plus other accessories.

8 RECOMMENDATIONS

A. Corrosion in Fire Protection Systems

Corrosion damage increases the life cycle costs of fire protection significantly, and corrosion-caused impairments of FPS can increase the risk of an uncontrolled fire loss; for these reasons it is necessary to have corrosion mitigation strategies for FPS, as detailed in Part B below.

B. Potential Corrosion Mitigation Strategies

1. Orient longitudinal pipe weld seam toward building roof - at least 45° in relationship to the floor (for reference, the weld line points at the floor at 0°) to mitigate pipe weld seam corrosion in the FPS.
2. Fill dry pipe or preaction systems with nitrogen as supervisory gas (e.g., use on-site nitrogen generator) to mitigate galvanized steel pipe corrosion.
3. Install an FM Approved air-venting device to remove trapped air in wet pipe systems to mitigate pipe corrosion near air pockets.
4. Use treated water such as municipal water (i.e., avoid untreated raw water) as the source of sprinkler water for better water quality and less corrosion of FPS.
5. Apply only those chemicals (e.g., pipe cutting oil, adhesives, paints, antifreeze, etc.) approved by Lubrizol, FM Global, and UL for hybrid CPVC fire protection systems to avoid potential environmental stress cracking (ESC) failure of CPVC piping material.

C. Future Developments

1. Evaluate the effectiveness of chemical corrosion inhibitors including vapor phase corrosion inhibitors (VCI), organic and inorganic phosphate (PO₄), and biocides under fixed condition for optimization of corrosion mitigation and application variables to reduce potential problems with the application of corrosion inhibitors in FPS.

2. Develop methods for water filtration or treatment (ion exchange or chemical precipitation) of source water to remove aggressive anions from the sprinkler water to reduce water corrosivity. The focus is on proper system design to effectively mitigate corrosion in FPS by evaluating corrosion rate as a function of the Larson-Skold index, water chemistry, and oxygen concentration to provide criteria for ion exchange or chemical precipitation performance goals.

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