TECHNICAL REPORT :
CORROSION IN DRY AND PREACTION SYSTEMS: PRELIMINARY RESULTS OF LONG-TERM CORROSION TESTING UNDER COMPRESSED AIR AND NITROGEN SUPERVISION

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INTRODUCTION

The inclusion of recommendations for use of galvanized steel pipe in dry and preaction systems in the NFPA 13 installation standard initiated decades of widespread adoption. Currently, new dry and pre-action installations are almost exclusively constructed using hot dip galvanized, schedule 10 piping and rolled groove couplings. The premise for recommending its use is based on the principle of cathodic protection, in which the piping's internal zinc coating is sacrificially corroded while protecting the underlying steel. Although based on solid corrosion science, cathodic protection has proved to be ineffective on galvanized pipe surfaces that are partially wetted and exposed to the stagnant water conditions found in many problematic dry or preaction systems.

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CORROSION BASICS

Unlike galvanized outdoor structures, which are wetted intermittently, the low points in sprinkler piping (where water and condensate accumulate) are constantly wetted and the zinc corrosion product deposits remain where they are formed. Initially, the zinc coating cathodically protects the underlying steel, but as the zinc is oxidized, the zinc corrosion products are deposited on the metal surface. This, in combination with a decrease in the efficiency of the cathodic protection due to coverage of the metal surface by non-conductive oxide, eventually results in localized penetration of the zinc coating and corrosion of the underlying steel.

Numerous owners of galvanized pipe systems have experienced premature failure due to multiple pinhole leaks in as little as three years after commissioning. In all of these instances, subsequent investigations revealed a common set of conditions:

- Multiple pockets of trapped water
- Lack of adequate means to completely drain the system after initial hydrotesting
- Localized tubercles at breaches in the zinc coating with underlying pits penetrating into the steel base material
- Intact zinc coating covering surfaces surrounding the localized tubercles

Based on data collected during more than a decade's experience with such systems, galvanized piping that is partially filled with water will only be cathodically protected by the sacrificial zinc coating until localized penetration of the zinc coating occurs and the underlying steel is exposed. As the corrosion reaction progresses, the penetration rate of the localized pitting increases due to the occlusion resulting from the growing mound of corrosion products covering the pit. As a result of the reduction in the availability of oxygen in the bottom of the pit (referred to as differential aeration by corrosion engineers), changes in the local chemistry and pH occur, which cause an increase in the rate of local oxidation of the steel and lead to an "electrochemical drill" effect. Localized corrosion of the exposed steel then proceed at a rapid pace. This is due to a phenomenon known as the "area effect", where the large area of intact zinc coating surrounding the local penetration acts as a cathode and the small area of exposed steel acts as an anode. These areas of localized corrosion usually manifest themselves at the six o'clock position and water/air interface in the form of distinctive reddish-brown nodules of iron oxide covering the site of localized corrosion in the steel. The presence of these deposits also creates conditions occluding the underlying steel from the bulk solution, thereby accelerating the rate of localized corrosion with the creation of a differential aeration cell (also referred to as a concentration cell). By this mechanism, the oxygen under the deposits is consumed, while the surrounding exposed area remains cathodic relative to the area under the deposits. This further accelerates the rate of the localized corrosion. The presence of tubercles is often misinterpreted as evidence that the damage is the result of microbiologically influenced corrosion (MIC). However, more than a decade's worth of accumulated results of microbiological culturing of deposit samples collected from affected pipe from all over the United States show that the corrosion cannot be attributed to the actions of bacteria[2].

Once localized pits are established, they continue to grow by a self-sustaining, or autocatalytic process. The propagation of pits involves the dissolution of metal and the maintenance of a high degree of acidity at the bottom of the pit by the hydrolysis of the metal ions in solution. Anodic metal dissolution in the pit ($Metal \rightleftharpoons Metal^{n+} + ne^-$) is balanced by the cathodic, oxygen reduction reaction on the surrounding surface ($O_2 + 2H_2O + 4e^- \rightleftharpoons 4OH^-$). Due to the increasing concentration of metals cations in the pit, negative ions in solution such as chloride Cl^- migrates into the pit to maintain charge neutrality. In the case of chloride, the metal chloride (MCl) is hydrolyzed by combining with water to form a metal hydroxide and free acid. The presence of the acid lowers the local pH, which causes accelerated localized dissolution of the metal. This process has been found to be much more pronounced and severe in galvanized steel pipe than in black steel pipe. This is due to a fundamental difference in the observed corrosion mechanisms in black steel as compared to galvanized steel. The absence of any protective coating on black steel in this type of environment typically results in even and uniform thinning of the steel pipe wall, unlike the very localized and fast penetrating pitting on galvanized pipe. As such, practical industry experience has shown that even though corrosion occurs, the rate of penetration and time to failure is considerably slower and more predictable in black steel than in galvanized steel.

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2 Van Der Schijff OJ. MIC in Fire Sprinkler Systems— Field Observations and Data. NACE International, Corrosion 2008 Conference and Expo, New Orleans, LA, March 16–20, 2008.

(As time passes and a thicker layer of corrosion products develop on the black steel, the corrosion mechanism is likely to change to a localized mechanism with the development of localized tubercles with underlying pits. However, this typically happens much later in the service life of black pipe and only if the two-phase compressed air/water condition persists.)

CORROSION PREVENTION STRATEGIES

Prevention of such corrosion can be achieved as follows:

1. By completely removing all residual water and moisture from the dry or preaction system, thereby rendering the internal pipe surfaces completely dry. This effectively eliminates the availability of an electrolyte, which is a prerequisite for corrosion to occur. However, industry experience with this remedy has shown that it is virtually impossible to achieve completely dry conditions within the sprinkler piping. These systems are routinely flooded for initial and periodic hydrotests resulting in significant amounts of water remaining in the piping due to inadequate sloping or lack of drainage points. Additionally, the internal profile of commonly used rolled grooves for pipe fittings create a natural "trap" for moisture, even if the pipe is sloped in accordance with the requirements of NFPA 13. That combined with the availability of an inexhaustible source of oxygen in the compressed supervisory air to sustain the corrosion reaction, renders this method marginally effective at best.
2. By replacing supervisory compressed air with high purity, inert, dry, supervisory nitrogen gas, the thermodynamic driving force for the cathodic oxygen reduction reaction is effectively removed and corrosion slow down to a negligible rate. This method is based on an understanding of basic electrochemical theory. It has proven to be very effective in many galvanized pipe installations that previously had failed within three years after their original installation.

LONG-TERM EXPOSURE TESTING

Long-term exposure tests have been conducted to compare the performance of black steel and galvanized sprinkler pipe in compressed air and nitrogen gas environments over the past two years. Our intention is that these tests will be continued for the next several years. The test environment is comprised of half-filled black and galvanized steel sprinkler pipe sections, which are individually subjected to either compressed air or 98% nitrogen supervision. This real-world experiment, consisting of materials that are currently used in dry and preaction sprinkler installations, has been conducted under carefully controlled and monitored conditions. These tests provide the first science-based data for evaluation of the effectiveness of nitrogen gas supervision. A composite of images of the test setup is shown in Figure 1.

At designated time intervals, 1-foot sections of the pipe assemblies have been removed from each of the pipe assemblies for evaluation. Each section was examined and photodocumented in the as-found condition, cleaned with inhibited acid oxide remover and reevaluated and photodocumented. The corrosion penetration depth of pits on the galvanized steel was measured using a pit gauge and the maximum depth was recorded and reported. To conduct an accurate remaining wall thickness evaluation for black steel samples, a half-ring, approximately ½-inch wide, was sectioned transversely from the section of pipe on a band saw. The sample was ground on a metallurgical grinding wheel with successively finer grit sanding paper to produce a 600-grit cross-sectional pipe wall surface.

Figure 1. Long-term exposure test setup.

Each half-ring pipe section was subsequently examined with the aid of a stereomicroscope under a magnification power of 5X. Following the photo-documentation of the wall, thickness markers were placed on the digital image utilizing a digital measurement system with an accuracy of 1 x 10^{-5} inches (only three decimal places are reported). Based on the difference between remaining wall thickness and the nominal thickness for this diameter of pipe, the corrosion penetration rate was calculated. Since two different corrosion mechanisms were observed, the collected data was normalized by calculating the corrosion penetration rate for each of the pipe samples. This was based on the highest value of observed wall thinning for black steel and the deepest measured pit for galvanized steel. Test results after respective exposure periods of 497 days, 759 days, and 780 days are presented in Table 1

Table 1. Corrosion penetration rates.

Pipe Material	Supervision	Exposure time (Days)	Uniform wall loss or Pit depth (inches)	Penetration Rate (mils/yr)	Average Penetration Rate (mils/yr)
Black steel	Compressed Air	497	0.009	6.6	
Black steel	Compressed Air	759	0.022	10.6	8.4
Black steel	Compressed Air	780	0.017	8.0	
Black steel	98% Nitrogen	497	0.004	2.9	
Black steel	98% Nitrogen	759	0.003	1.4	2.5
Black steel	98% Nitrogen	780	0.007	3.3	
Galvanized steel	Compressed Air	497	0.028	20.6	
Galvanized steel	Compressed Air	759	0.034	16.4	17.97
Galvanized steel	Compressed Air	780	0.036	16.9	
Galvanized steel	98% Nitrogen	497	0	0	
Galvanized steel	98% Nitrogen	759	0.003	1.4	1.57
Galvanized steel	98% Nitrogen	780	0.007	3.3	

Examination of the tested black steel pipe spool samples under compressed air supervision showed uniform loss in thickness of the pipe wall in the portion of the pipe that was submerged in water. No localized pits were noted. The corresponding galvanized steel pipe spool samples showed localized pits underlying locations where brown to black nodules or tubercles had formed. Representative images of the pipe samples after removal of corrosion product deposits are presented in Figure 2 through Figure 5. The test results confirm that the corrosion mechanism in black steel pipe is of a uniform nature in this particular test environment. Wall thinning occurs evenly in the wetted portion of the partially filled pipe. (Field observations of long-term service, failed black steel pipe, have shown pinholes associated with localized pits. However, it has been observed that such pits only occur after development of differential aeration cells under a thick layer of corrosion product deposits and/or tubercles. As shown by the reported results of the exposure testing, the mechanism for the initial several years is uniform corrosion resulting in relatively uniform thinning of the pipe wall.)

In galvanized pipe, corrosion of the underlying steel occurs at localized breaches in the zinc coating. Localized pits penetrate into the base metal, while the surrounding material shows only superficial corrosion of the zinc coating. Measurements of wall loss (black steel), and pit depth (galvanized steel) under air supervision, and subsequent calculation of the respective corrosion penetration rates in thousands of an inch per year (mils/yr) yielded average rates of 8.4 mpy for black steel and 17.97 mpy for galvanized steel. Under 98% nitrogen gas supervision, these rates dropped to 2.5 mpy (black steel) and 1.57 mpy (galvanized steel), representing a reduction in corrosion rates of 70% for black steel and 92% for galvanized steel. This translates into a projected extension of service life from 14 to 48 years for Schedule 10 black steel pipe (nominal wall 0.120") and from 7 to 79 years for Schedule 10 galvanized steel pipe (nominal wall 0.125"), which both exceed normal design life of approximately 40 years. It must be noted that the extrapolation of the calculated corrosion penetration rate to predict service based on pit depth is a simplification that is usually not supported by actual in-service experience. The autocatalytic nature of established pit is known to cause acceleration of the penetration rate as the pit grows deeper, resulting in non-linear penetration rates. Several instances of failure of galvanized pipe within 3 to 4 years after installation are documented fact. Time will tell if this trend will be borne out by this ongoing experiment. The aforementioned exposure testing is ongoing and results will be reported as they become available over the course of the next several years. However, based on these results, it is already apparent that the replacement of supervisory compressed air with high purity nitrogen effectively inhibits internal corrosion of sprinkler piping and could significantly extend the service life of sprinkler pipe.

Figure 2. Black steel piping after 498 days exposure while half-filled with water and compressed air supervision. Note uniform thinning of pipe wall and absence of any localized pits.

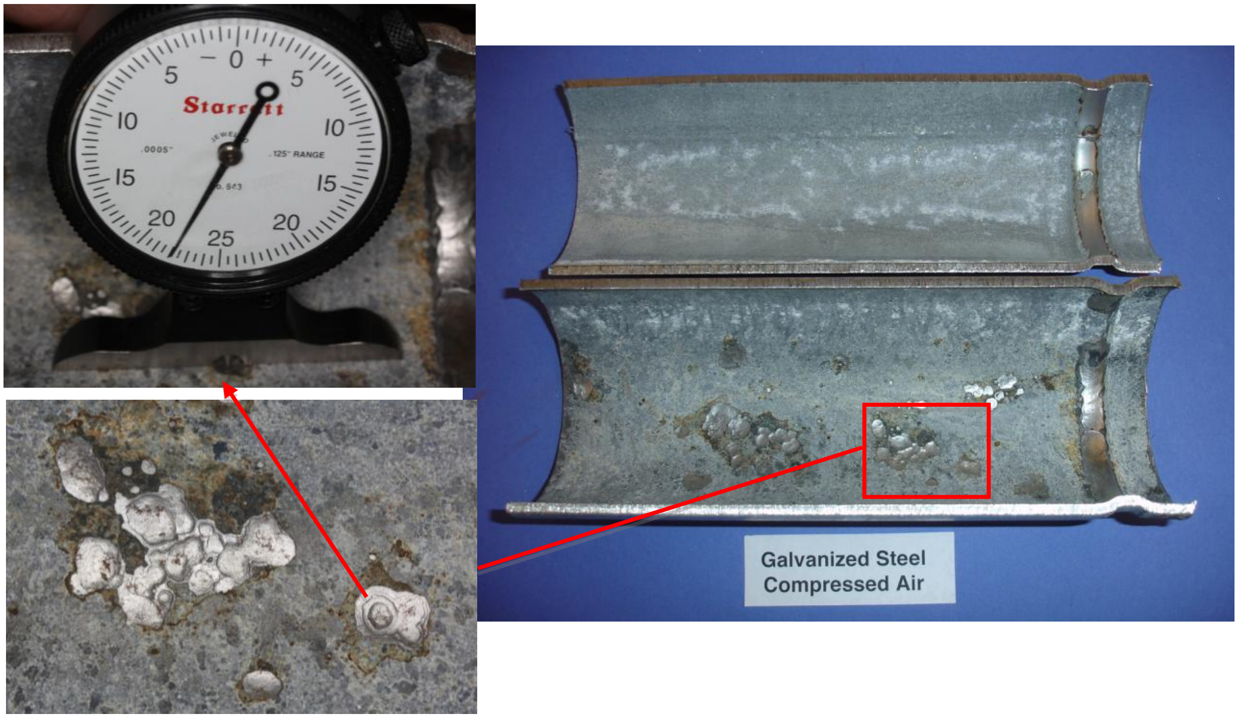

Figure 3. Galvanized piping after 498 days exposure while half-filled with water and compressed air supervision. Note localized pitting at locations where zinc coating has been breached.

Figure 4. Black steel piping after 498 days exposure while half-filled with water and 98% nitrogen supervision. Note uniform appearance of pipe wall and absence of any localized pits.

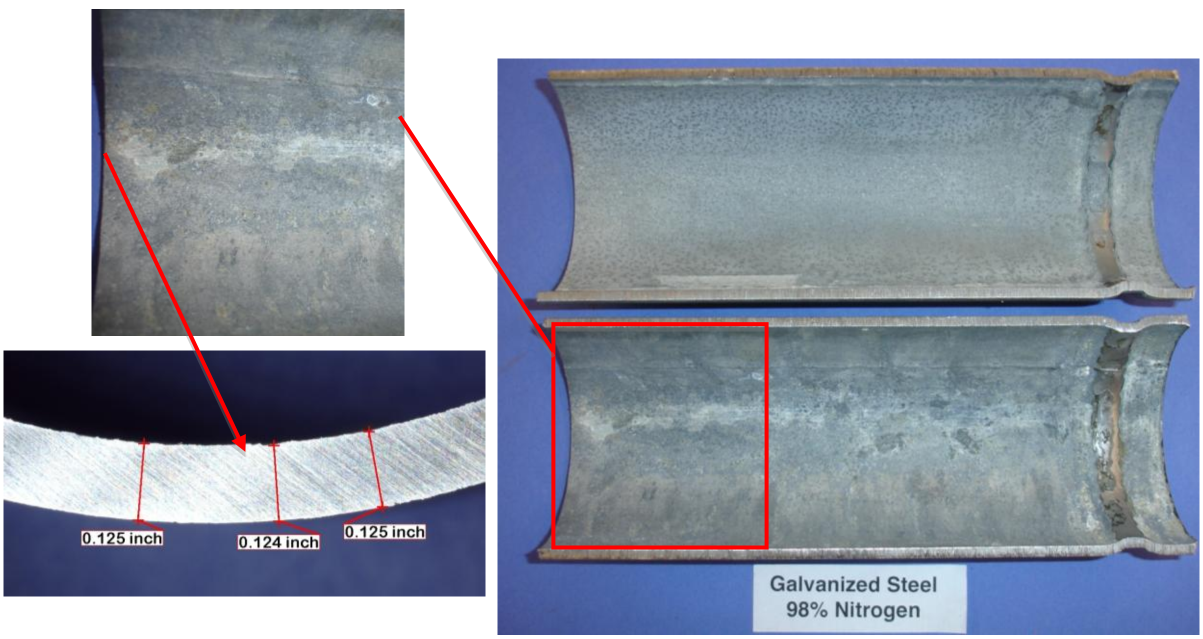

Figure 5. Galvanized piping after 498 days exposure while half-filled with water and 98% nitrogen supervision. Note absence of localized breaches in zinc coating except for rolled groove.

POTENTIAL COST SAVINGS

The results presented above raise the question whether there is indeed a compelling reason for using galvanized steel instead of black steel under nitrogen supervision. A cost comparison between black steel and galvanized steel is presented in Table 2. A typical sprinkler system with a capacity of 1,750 gallons of water represents an approximate additional cost of $12,600 if schedule 10 galvanized steel is used instead of schedule 10 black steel. The cost differential is even greater if schedule 40 pipe is used (which is often specified by owners who have experienced severe corrosion of dry and/or preaction FPS in the past), amounting to approximately $17,900.

Table 2. Cost comparison between black steel and galvanized steel sprinkler piping.

	Schedule 10 Piping			Schedule 40 Piping		
*Total Building Piping Capacity (gallons)	Galvanized	Black Steel	(Δ) Cost Savings	Galvanized	Black Steel	(Δ) Cost Savings
250	$7,000	$3,500	$3,500	$8,900	$4,400	$4,500
750	$21,000	$10,500	$10,500	$26,700	$13,200	$13,500
1,750	$37,000	$24,400	$12,600	$48,900	$31,000	$17,900
3,000	$72,000	$41,900	$30,100	$93,400	$53,200	$40,200
6,000	$132,000	$83,700	$48,300	$173,400	$106,500	$66,900
12,000	$264,000	$167,400	$96,600	$346,800	$212,400	$134,400
18,000	$384,000	$251,000	$133,000	$506,800	$318,800	$188,000

Figures are based on the use of 23% Main (3”-6” piping) and 77% Branch (1”-3” piping). All costs are estimates of the actual cost to the End-User (i.e. Building Owner). These estimates only include fittings. These estimates do not include labor for the installation.

**Total Building Piping capacity refers to the entire amount of sprinkler piping within the building (i.e. the combined capacity of all Dry or Pre-Action Systems). Our figures also reflect that the largest single Dry or Pre-Action System will be no larger than 1,750 gallons (equating to about 52,000 sq ft.).*

CONCLUSIONS

Preliminary results of long-term, comparative testing of galvanized and black steel under compressed air and 98% nitrogen supervision show:

- A uniform wall thinning mechanism on black steel.
- A localized pitting mechanism on galvanized steel.

- Average black steel penetration rate of 8.4 mils/yr under compressed air supervision.
- Average galvanized steel penetration rate of 17.97 mils/yr under compressed air supervision.
- Average black steel penetration rate of 2.5 mils/yr under 98% nitrogen supervision.
- Average galvanized steel penetration rate of 1.57 mils/yr under 98% nitrogen supervision.
- Potential extension of black steel pipe service life from 14 to 48 years as a result of nitrogen supervision instead of compressed air supervision.
- Potential extension of galvanized steel service life from 7 to 79 years as a result of nitrogen supervision instead of compressed air supervision.
- Depending on the diameter and wall thickness of pipe used, significant cost savings can be realized by using black steel pipe in combination with nitrogen supervision instead of galvanized steel pipe.