Environmental Screening and Relevant Accelerated Tests for Products in an Outdoor Ground Environment

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SUMMARY AND CONCLUSIONS

Corrosion is the dominant failure mode of products in underground water pits. The failure mechanism was studied to determine the dominant variables. The major variables, which dictate galvanic and pitting corrosion, are pH, temperature and concentration of the various species in the solution.

A field screening procedure was used to determine the concentration of the anions, pH and temperature in different pits. These data show that there are wide ranges of pit severity as indicated by the pH and the total anion concentrations. The two variables of the pit solution viz. pH and the total anion concentration, could be used to characterize a pit environment and determine the material reliability.

The field data were used to design relevant accelerated test using the pit characteristics viz. anion concentration and temperature as the accelerating variables. The product application and its reliability requirements determined the time for the accelerated test.

In this study we have shown how to characterize a pit environment, design the relevant accelerated test for product reliability and use these data for the best selection of materials, based on low cost and high reliability. This, in turn, will lead to optimum and cost-effective materials used in product design.

1. INTRODUCTION

The long-term reliability of products in the outdoor ground environment strongly depends on the interaction of the material system, with the environment they are exposed to. This environment can change from place to place, as well as could change with time in a given location.

A large portion of water meters is located in underground pits. These pits are filled with water most of the time. The water in these pits also consists of various corrosive elements. These corrosive elements could be as a result of the migration of these compounds from the surrounding soil and also due to sweeping of other road salts into the pits.

The diverse changes in the surrounding environment, calls for design margin in products, designed for these applications. This usually leads to higher product cost. Most of the water metering products are designed to last a long time, as much as 20 years, in the field. The stringent life requirement calls for an in-depth study of the environment, these products are supposed to operate in, as well as, use of these data to have cost-optimum designs.

Salt spray tests (Ref. 1) have been used for many years as accelerated tests for determining the corrosive properties of ferrous as well as non-ferrous substrates and to determine the protection offered by various coatings. This is a very top-level test with a primary objective to compare relative performance of materials and coatings. However, this test does not have a correlation with the operating environment. The salt spray test could be used to evaluate different lots of the same product, once a standard level of performance has been established. It will be difficult to interpret the results from the salt spray test in the initial design stages and determine the product reliability, especially in a changing field environment.

The most commonly used and accepted salt spray test methods in the United States are the various methods outlined in ASTM standards B 117 and G 85 (Refs. 2,3). Many of the governmental agencies and automotive companies have written their own standards and procedures, but in the interest of national standardization, these standards have been revised to conform to most of the details of ASTM. However, these standards still have various statements, which are based on field data and correlations among laboratories (Ref. 4).

Other tests, which have been widely used in industry (Ref. 5), are the mixed gas test. This test is mainly used for determining the material compatibility of products in an outdoor environment, not necessarily in the ground. However, like the salt spray test, this test also could be used to determine the relative effectiveness of various materials but caution should be exercised when applying these data for products in the ground.

The long-term reliability of the product's material system depends on the materials as well as the environment; the product will be exposed to. In any product application, the failure mechanism due to the environment needs to be modeled and based on these data, appropriate materials and tests could be designed.

Itron has a program in place, where we have characterized the dominant properties of the water pit environment. The potential product failure mechanism has been studied in this environment, and using the data from environmental screening, relevant tests have been developed to simulate the field. The results from these laboratory tests are then used to

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estimate the product reliability in the field.

2. NOMENCLATURE

pH	Potential of hydrogen ion
aH^+	Activity of hydrogen ion
yH^+	Activity coefficient of hydrogen ion
mH^+	Molality of hydrogen ion
r	Corrosion rate
A	Rate constant
E	Activation energy, cals
R	Gas constant, cals/mole-deg
T	Absolute temp
c_i	Concentration of species i, mole/cm^3
z_i	charge number of species i

3. MECHANISM OF DOMINANT FAILURE MODE FOR PRODUCTS IN AN OUTDOOR PIT ENVIRONMENT

Aqueous corrosion is the dominant failure mode for products in the water pits. Depending on the materials present, there are various forms of corrosion, which could be present in the water pits as well as in the ground. The dominant forms are galvanic and pitting corrosion. In certain cases, the galvanic form might be the start of the corrosion which might lead to pitting. There are various environmental variables, which influence the corrosion rate, and some of the dominant ones are summarized below.

3.1 Effect of environmental variables on aqueous corrosion

Silverman and Puyear (Ref. 6) have given an exhaustive account of the dependence of the various environmental variables on aqueous corrosion. Some of these have been described below:

3.1.1. Effect of pH: The pH of a solution, whether acidic or basic has a profound effect on the corrosion. Some fundamentals relating to the pH are explained below.

The pH is defined as the negative of the base ten logarithm of the hydrogen ion activity. The latter quantity is related to the concentration or molality through the activity coefficient.

The pH is usually expressed as

$$pH = - \log aH^+ \quad (1)$$

$$= - \log (yH^+ \, mH^+) \quad (2)$$

where aH^+ is the activity of the hydrogen ion, yH^+ is the hydrogen activity coefficient and mH^+ is the molality of H^+ ions . The activity coefficient depends on the other ions and species in the solution.

The pH is usually measured with a pH meter, which is an electrometer. In this measurement, the voltage of a hydrogen ion specific electrode is measured in reference to a reference electrode. This voltage is compared is compared to a standard to yield the unknown pH.

The hydrogen ion concentration can be calculated from equation (2), once the pH is known. The importance of the hydrogen ion lies in its ability to interact with the surface of the alloy, causing it to dissolve. This usually involves the breakdown of the passivation film on the metallic surface. A rough rule of thumb states that lower the pH, the greater is the hydrogen ion concentration and hence greater will be the effect of the hydrogen ion on the metallic surface, thereby giving a greater corrosion rate. In general, the effect of corrosion is more severe in an acidic environment ($pH < 7$) than a basic environment ($pH > 7$). In this pH range also, we can define various others viz. Strongly acidic ($pH < 5$), Near-neutral ($5 < pH < 9$), strongly basic ($pH > 9$).

3.1.2 Temperature: Corrosion involves the dissolution of metal and being a rate reaction, temperature effect can be predicted using the Arrhenius model.

$$r = A \exp (-E/RT) \quad (3)$$

Where r is the corrosion rate, A is the constant, E is the activation energy, R is the gas constant and T is the absolute temperature.

The effect of temperature can be determined using equation (4):

$$\ln (r_1/r_2) = - (E/R) \, delT/(T_1 * T_2) \quad (4)$$

where the subscripts 1 and 2 refer to the two temperatures and del T is the difference in the two temperatures.

Apart from the chemical kinetics, temperature can also have other indirect effects on the other constituents present in the solution. An increase in temperature can increase the solubility of some species. For e.g. in the electrochemical reaction for corrosion, O_2 also plays a dominant part. An increase in temperature can cause to increase O_2 solubility in the solution. Moreover, temperature can also increase the initiation process. For example, chloride ions initiate pitting corrosion and its influence can drastically increase the metal degradation.

3.1.3 Velocity/fluid flow rate: The influence of fluid velocity is dependent on the alloy, fluid constituents, fluid physical properties, geometry and corrosion mechanism. The effect of velocity is very much dominant when the corrosion rate is controlled by the transport of species to the metallic surface. The effect of velocity is seen much more in localized corrosion like crevice and pitting. For example, type 316 stainless steel has been shown to pit in quiescent seawater and not in moving seawater (Ref. 7).

In most of water pits, the water is stagnant. However, in outdoor soil applications, the products might be exposed to flowing water streams.

3.1.4 Concentration: As explained above, the pH of the environment plays a dominant role in corrosion. In the environment, there will always be various other constituents. The effect of the concentration of these other species could be determined using the electro-neutrality equation for all species (i) in the solution:

$$c_i z_i = 0 \quad (5)$$

In other words, the environmental solution needs to be neutral and cannot have a charge. Hence, the concentration of the other species could influence the hydrogen ion concentration through equation (5), which in turn, could affect the pH (equation (2)) and hence the corrosion rate.

4. CHARACTERIZATION OF THE WATER PIT ENVIRONMENT

The water pits might or might not be filled with water. Also, the severity of the pits will depend on their location. Moreover, it should always be expected that the road salts and other chemicals from the surrounding areas might make their way in the pits.

Figure 1 shows the picture of a water pit. The water meter is inside the pit and the remote measuring device is hooked via cable to the meter. The pit and the pit lid are made of metal, concrete or plastic depending on the corrosiveness of the environment, cost and other factors.

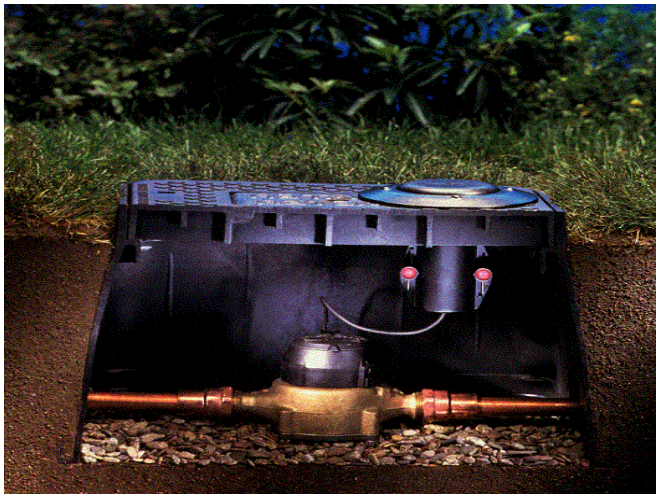

Figure 1: A water pit with the remote monitoring device

As explained above, the dominant variables, which characterize the pit environment, are as follows:

(a) pH of the pit solution

(b) Temperature inside the pit

(c) Concentration of the various elements in the pit solution

The solutions are quiescent in the pit and hence the velocity of the fluid in the pits is equal to 0 and was not measured.

4.1 Procedure to characterize the pit environment in the field

Itron has launched a program where we have characterized pits in various parts of the country. The pits were selected from the coastline to the interior depending on their severity to have a broad database. We are beginning to move this program internationally.

Table 1 shows the sampling data sheet, where various pit solution parameters and other typical parameters are seen and measured in the field. The actual data are proprietary and hence are not reported here.

Address	Pit Lid Shape Material	Pit Box Shape Material	Meter Depth	Location	Water in Pit (Y/N)	pH	Water Sample (Y/N)	°C	PIPE

Table 1: Representative field sampling data sheet for screening the pit environment.

In this field screening method, we also note the pit lid material, location and the type of pipe used. These data will enable us to determine the relative reliability of other materials used in this pit. Moreover, these data will enable us to design products with minimum design margins, thereby, having a cost-efficient design.

5. FIELD DATA FROM VARIOUS PITS

The pH and temperature were measured using a commercially available pH meter/thermocouple. Water samples are collected from some pits in polyethylene water bottles. The anion ionic constituents in the water samples were determined using Ion Chromatography (IC) in the laboratory. In this test only the anions were determined, as these are the dominant species contributing to the corrosion.

Data from pits from different locations in the US show that the pH varies from acidic to basic. Also, the anion concentration in the pit water samples varies as much as 2-3 orders of magnitude.

The field data also show that the pH and the total anion concentration could easily define the "severity" of the pits. Using the field data, the material reliability of a product could then be determined from the pH and total anion concentration in the pit solution.

6. ACCELERATED TESTS TO SIMULATE THE PIT ENVIRONMENT

6.1 Laboratory test

The following are observations from the pit solution data from the field:

(a) The anion concentration varies significantly (2-3 orders of magnitude).
(b) The pH values are from acidic to basic.
(c) The temperature in the pits is about 5-10 F greater than the ambient temperature.

The laboratory test should use the anion concentration and temperature as the accelerating variables. The acceleration factors could be determined for each of these variables as follows:

(a) The concentration dependence could be correlated to the field using data from pits of varying severity.

(b) Arrhenius model (Equation 4) could be used to correlate the temperature to the field.

The overall acceleration factor for the laboratory tests could then be determined from the above two correlations. If needed, pH could also be used as an accelerating variable.

Itron has developed a laboratory solution consisting of the dominant anions to accelerate the pit environment. The tests are conducted at a specified temperature with the pH of the solution adjusted, depending on the product application. These tests are conducted for a period of time determined, using the above acceleration factor and product reliability/life in the field. Good correlation is obtained between the field data for product performance and the accelerated laboratory data for the investigated failure mechanism.

6.2 Application to product design

In product design, there is an appreciable design margin left in material selection, as it is difficult to simulate the field environment based on conventional environmental tests. This leads to expensive materials being used leading to higher product cost or inappropriate materials being used, leading to field reliability problems.

The environmental screening will enable the designers to know the operating environment. This in turn will enable them to select the "best" material based on product reliability as well as cost, thereby reducing the design margin.

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