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Control of External Corrosion On Iron and Steel Watermains

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INTRODUCTION

External corrosion of iron watermains has been a problem for municipalities for over 100 years. The three main causes of corrosion, in a historical context are:

- stray currents from electrified transit systems
- dissimilar soils
- galvanic corrosion

All of these causes remain with us today, although to varying degrees.

STRAY CURRENT CORROSION

Corrosion of cast iron water piping became a considerable problem in many North American cities in the early 1900's following the electrification of public transportation systems during the late 1800's. Stray current from these DC powered transit systems were found to be causing so-called 'electrolysis' of iron water mains. A 1906 study in Toronto[1] reported that damage to water and gas mains was due "to railway currents' as a result of the deterioration of rail joint bonds and the practice of bonding the watermains to rails at certain locations. Figure 1 illustrates the general arrangement between a watermain and a DC transit system which results in stray current corrosion on the watermain.

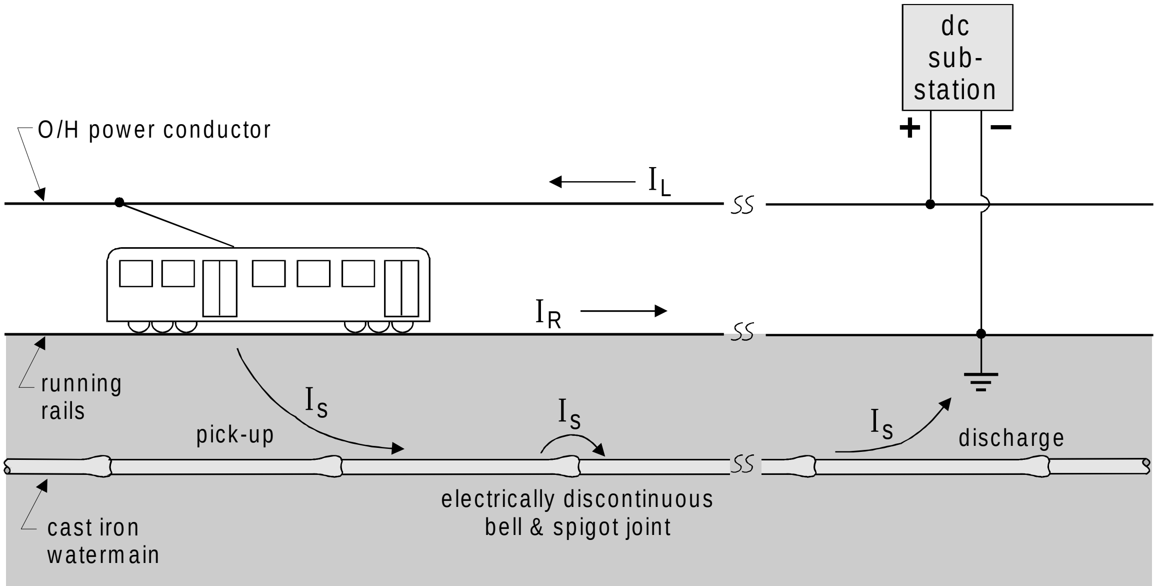

Figure 1 – Typical Stray Current Paths Around a DC Transit System

Because metallic water piping provides an alternative current path compared to the rails, current leakage (I_s) from rails is picked-up near the locomotive and returns to the source along the watermain before discharging to the substation ground. When the current discharges to earth, corrosion occurs at a theoretical rate of about 10kg per ampere-year of current. The amount of stray current is directly proportional to the resistance of the running rails and inversely proportional to the running rail resistance to earth, the earth resistivity, the resistance of the watermain, the proximity of the water-main to the running rails and substation ground. Although significant corrosion damage occurs near the DC substation, attack will also occur at any electrically discontinuous joints, as current jumps around these discontinuities through the soil. Figure 2 shows corrosion attack at an electrically discontinuous bell and spigot joint.

Figure 2 – Stray Current Corrosion at a Bell & Spigot Joint

The presence of stray currents cause electrical potential fluctuations on the piping system as illustrated in Figure 3. Note that the quiescent period between 2AM and 6AM is typical of a transit system operation.

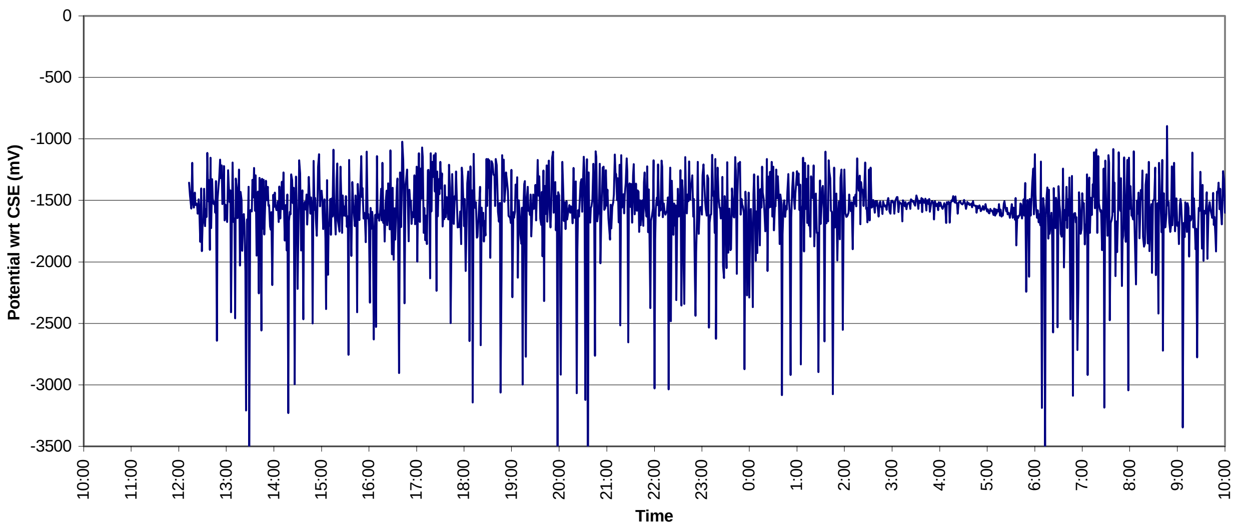

Figure 3 – Typical Structure-to-Soil Potential Recording with Time Caused by Interference from a DC Transit System

Such was the magnitude of the problem in North America, that the National Bureau of Standards (NBS) was commissioned by the US Congress in 1910 to investigate and recommend remedial solutions.[2]

As a result of these studies and other efforts by individual water utilities, the general approach to controlling stray current corrosion involved the establishment of electrolysis departments staffed by engineers who conducted extensive testing to identify problem areas and who installed and monitored drainage bonds between the watermains and the electrical railway (Figure 4).

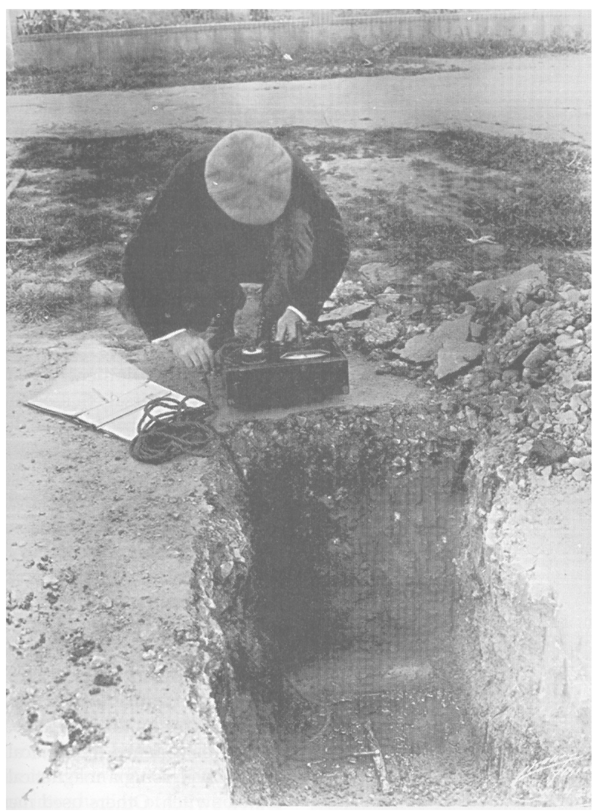

Figure 4 – Early Testing for Stray Current Activity
(courtesy of East Bay Municipal Utility District, Oakland, CA)

This activity was often coordinated through newly formed electrolysis committees. Cathodic protection, which was relatively unknown at the time, was dismissed by the NBS as having any merit in the remediation of railway stray currents. Unfortunately much of this early expertise, gained from combating stray current corrosion, was lost and never replaced after the electrical transit systems where converted to buses and rapid transit systems.

Today, stray current corrosion is mitigated by one or a combination of the following methods:

- electrical isolation of rails and substation (Figure 5)
- electrical bonding the watermain to the substation negative bus through a shunt or unidirectional device (Figure 6)
- forced drainage bond between the watermain and substation ground (Figure 7)
- cathodic protection

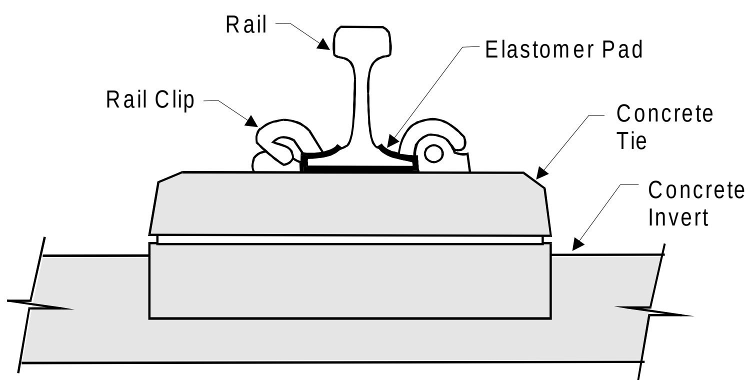

Figure 5 – Typical Direct-Fixation Isolating Fastener[3]

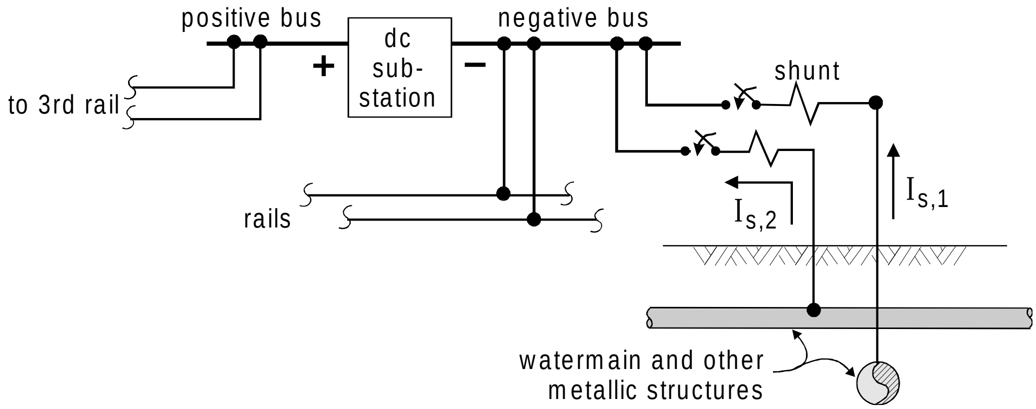

Figure 6 – Typical Structure-to-Soil Potential Recording with Time

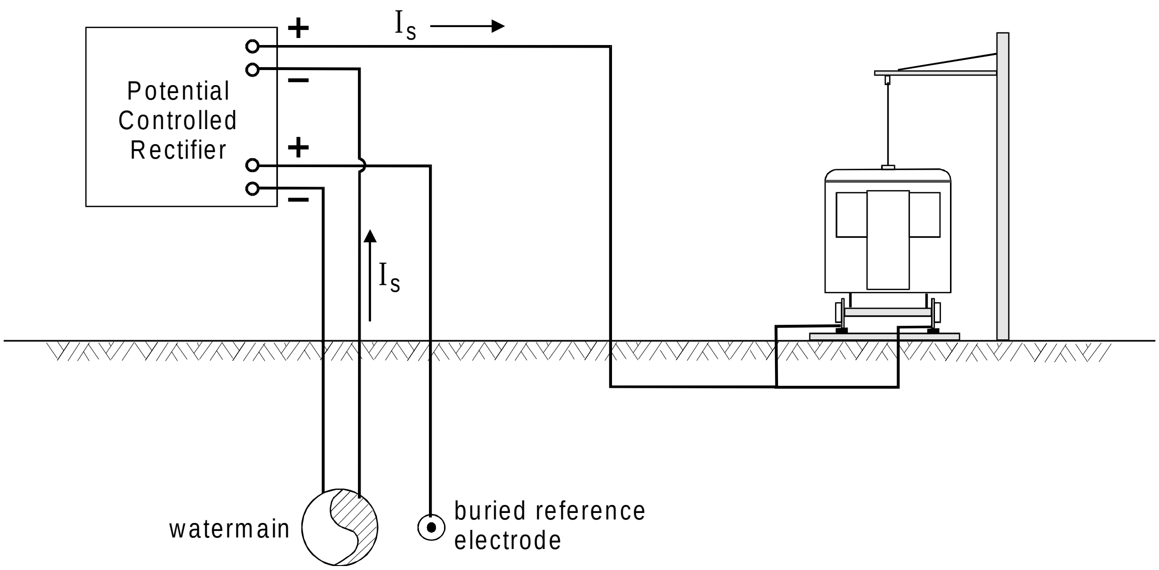

Figure 7 – Forced Drainage Bond Using a Potential Controlled Rectifier

SOIL CORROSION OF CAST IRON

Although corrosion failure of cast iron pipe by electrolysis was generally recognized in the water works industry, soil side corrosion was not. Grey cast iron main failures were, and still are, called ‘breaks’ which denotes the brittleness of this material but obscures its susceptibility to soil corrosion. This is understandable since many of these failures appear as beam breaks without the visual appearance of a corrosion pit (Figure 8) that one would normally observe on steel. It wasn’t until the 1960’s that the fundamental cause of grey cast iron watermain breaks was identified as soil corrosion. Remus[4] analyzed 40 years of break data from the city of Detroit and showed that the rise in break rates did not correlate with the length of the water system but rather increased logarithmically with age as illustrated in Figure 9.

Figure 8 – Typical Beam Break on Grey Cast Iron

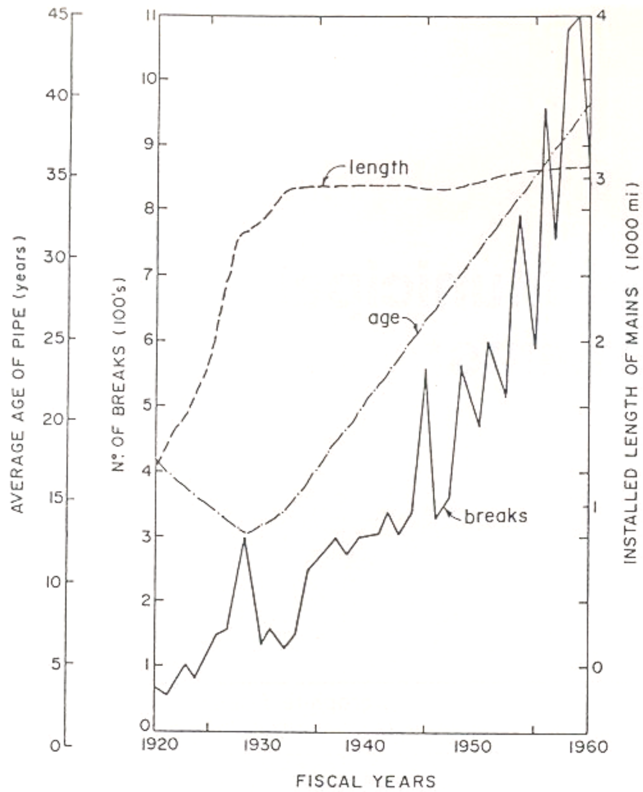

Figure 9 – Cast Iron Main Break Record in Detroit

This relationship was typical of the pattern of corrosion caused leaks in steel piping systems. In addition, Fitzgerald[5], in 1968, demonstrated that breaks on grey cast iron were principally due to the weakening of the pipes with time by graphitic corrosion. He recommended that pipe breaks be examined for signs of graphitization and that cathodic protection be considered for cast iron watermains exposed to soil having a resistivity of 5000 ohm-cm or less (Figure 10).

Figure 10 – Cast Iron Break in Figure 4 After Pipe Sample was Sandblasted to Remove the Graphite Corrosion Product

The water works industry however remained relatively unaware of the fundamental contribution of corrosion, partially because of the widely held belief that the corrosion rate of grey cast iron was less than steel. This view was sustained despite the fact that Speller[6], in 1951, had shown that the corrosion rates for steel, cast iron, and wrought iron, in 20 different soils were essentially the same (Figure 11). Speller's results along with Romanoff's[7] work at the NBS did however indicate that the corrosion rates for cast iron were relatively modest, and therefore of little concern, especially when the wall thickness of the cast piping was taken into account. Unfortunately, these tests were conducted on isolated pipe samples and not on a piping network. Therefore the accelerated effect of anode/cathode surface area ratio on the corrosion rates when piping is interconnected in a water distribution system was not considered.

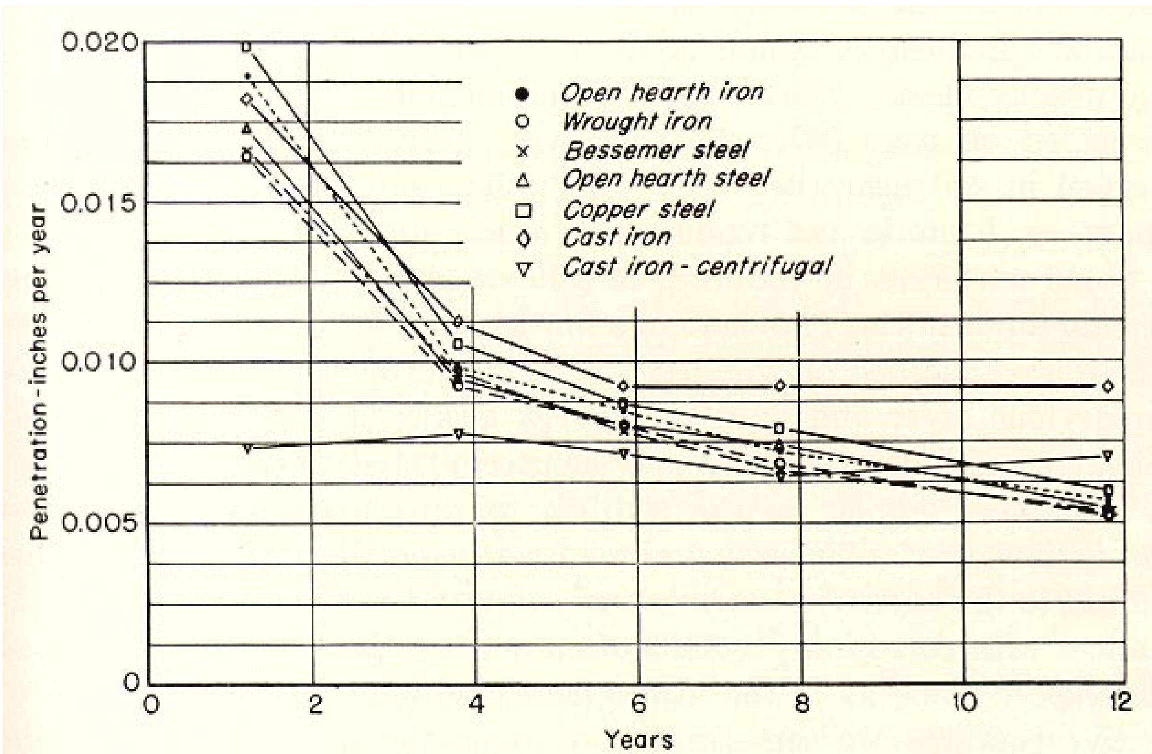

Figure 11 – Average depth of maximum pits for each of the ferrous pipe metals vs. age in the 26 soils in which all metals were buried for each period

GALVANIC (DISSIMILAR METAL) CORROSION

In Canada, it wasn't until the 1970's that the true significance of corrosion of cast iron piping became painfully apparent to some water utilities. In the mid 1960's the water industry began to use ductile cast iron piping in order to avoid the break problem experienced on grey cast iron. Failure of some of the early ductile iron installations occurred in as little as 3 years, and was recognized immediately as corrosion because the failure morphology was similar to that for steel piping corrosion and these failures were soon termed 'leaks' rather than breaks (Figure 12) The accelerated rate of corrosion was due to a thinner wall thickness than for similar sized grey cast iron, a small anode/cathode surface area ratio created (ironically) by a cosmetic coating applied to the surface to prevent rusting, the use of copper water services which introduced a galvanic corrosion cell as depicted in Figure 13), and the gradual decrease in soil resistivity with time caused by the increased use of de-icing salts.

Figure 12 – Typical Corrosion Pit in Ductile Cast Iron

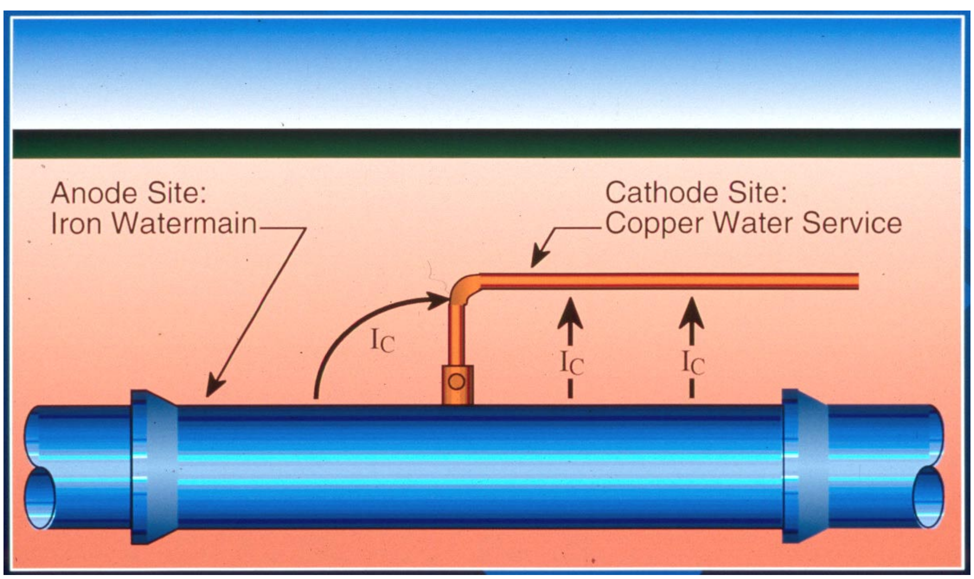

Figure 13 – Dissimilar Metal Corrosion Cell between Cast Iron and Copper Services

Wakelin[8] has quantified the accelerating effects of both soil resistivity and the presence of copper services, as shown in Figure 14. The corrosion rate of cast iron with copper services increases logarithmically as the soil resistivity decreases and is 4-10 times greater for cast iron with copper services than with lead or steel services.

In many Canadian cities chlorides, arising from many years of de-icing salt application, have percolated through the soil to pipe depth, producing chloride concentrations greater than 1000ppm, which has resulted in soil resistivities much less than 1000 ohm-cm and correspondingly higher corrosion rates.

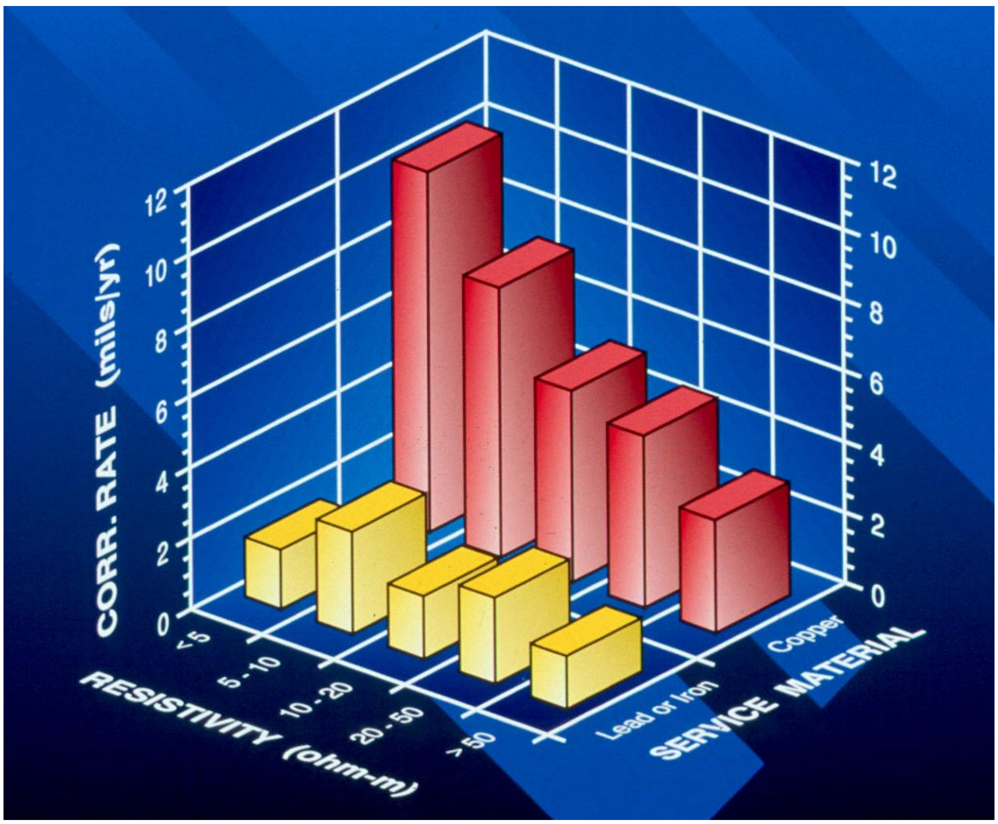

Figure 14 – Watermain Corrosion Rates vs. Soil Resistivity & Service Material

CATHODIC PROTECTION AS A CORROSION CONTROL TECHNIQUE

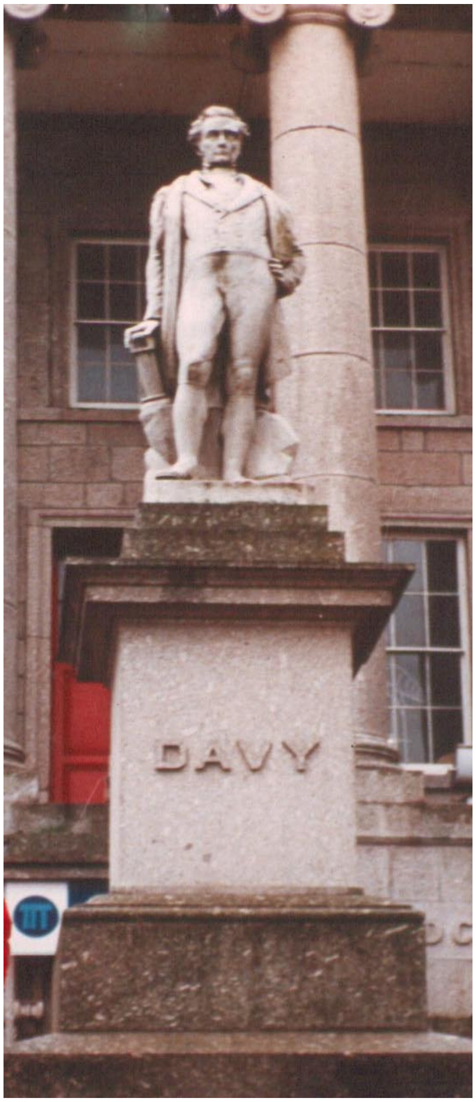

Figure 15 – Sir Humphry Davy Statue in Penzance, Cornwall

General

The first application of cathodic protection dates back to the 1820's when Sir Humphry Davy[9] of the Royal Institution in London prevented corrosion of the copper sheathing on wooden war ships by attaching zinc or iron blocks to the copper. Although a technical success in preventing copper corrosion, it was a practical failure since the ship hulls bio-fouled because there was insufficient copper ion present at the surface to kill the marine organisms.

After this aborted attempt, it was about 100 years before cathodic protection was applied again. R.J. Kuhn, considered the father of cathodic protection,[10] applied cathodic protection to cast iron water mains in New Orleans in the 1920's to prevent electrolysis.[11] Apparently he was unaware of Sir Humphrey Davies' work since he had reasoned that if a DC current leaving a structure resulted in corrosion then an equal and opposite current would prevent corrosion. His early success on iron water systems was shortened when he took the technology and its development to the oil and gas industry to prevent corrosion on steel pipelines.

Figure 16 – Medal Struck in Germany in Honour of Robert J. Kuhn

Interestingly, the oldest existing cathodic protection system on a water line is on steel not cast iron. A 95" diameter, 90-mile long, riveted steel aqueduct, installed near Oakland, California in the early 1920's, experienced corrosion failures in the early 1930's and received protection from an impressed current cathodic protection system in 1934-35. Figure 17 shows the above ground portion of this pipeline.

Figure 17 – View of the Mokelumne Aqueducts. Middle pipe is the original aqueduct installed in the early 1920's
(photo courtesy of East Bay Municipal Utility District, Oakland, CA)

The cumulative corrosion leaks vs. time curve in Figure 18 illustrates the importance of cathodic protection in preventing corrosion as the subsequent addition of two aqueducts resulted in a sudden surge in leaks each time until the cathodic protection system was upgraded to deal with the added pipe. This curve exhibits almost 70 years of cathodic protection operating performance and clearly illustrates the extraordinary benefit of cathodic protection in extending the service life of this water transmission line.

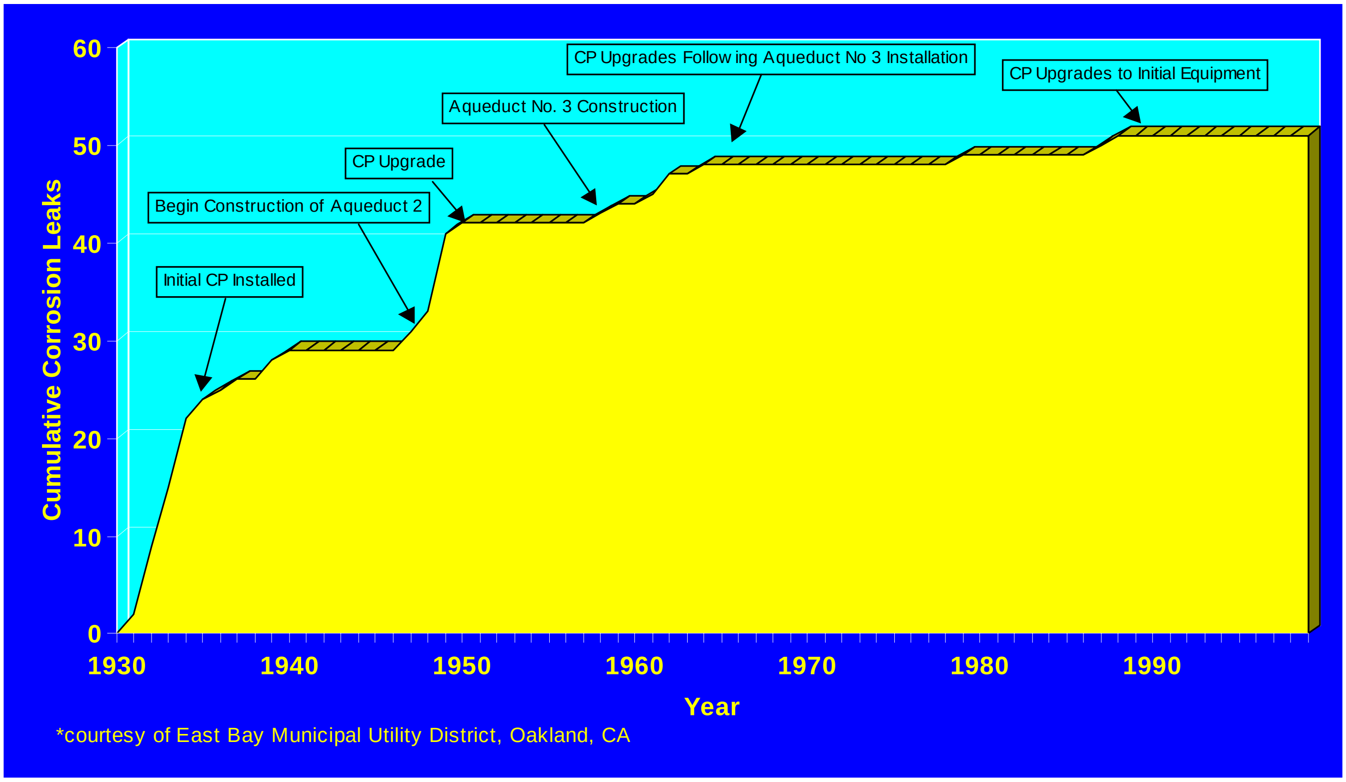

Figure 18 – Leak and CP History on Aqueduct No. 1

CP OF IRON WATERMAINS IN CANADA

Historically, the water works industry has been reluctant to apply cathodic protection to cast iron water mains, partly because they didn't accept that the break failures on grey cast iron were caused by corrosion and, partly because they were suspicious of the effectiveness of this technique. The latter viewpoint is curious in light of the fact that iron water mains have been inadvertently, but successfully, cathodically protecting copper service piping for many years. Copper service corrosion was never a problem until PVC began to replace cast iron as the material of choice for the mains.

Sacrificial Cathodic Protection

The first retrofit application of cathodic protection to a ductile iron watermain was in the city of North York in 1978 on about 500m of 150 mm diameter distribution main that had experienced 22 corrosion failures following its installation in the mid-1960's. For about 10% of the estimated replacement cost of this section of pipe, magnesium anodes were installed at regular intervals along the pipe route. This galvanic system, labeled an 'auginode' system, as illustrated in Figure 19, was developed by Corrosion Service.[12]

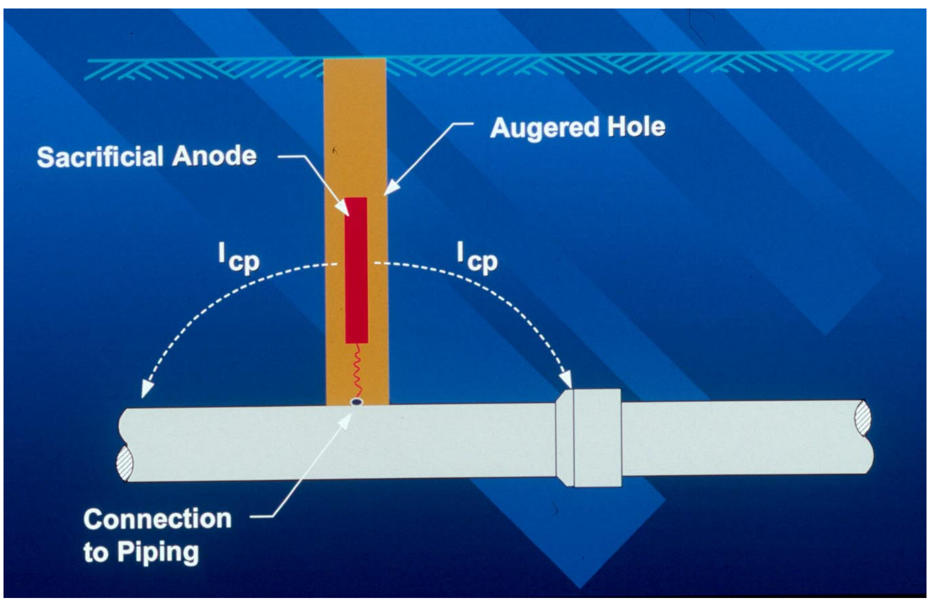

Figure 19 – Illustration of the 'Auginode' CP Technique

This method involves augering a minimum 450mm diameter hole above the pipe until the pipe is exposed. After cleaning the pipe surface the anode lead wire of a 9kg packaged magnesium anode is attached to the cast iron pipe by stud welding and the anode is lowered into the augered hole as shown in Figures 20 and 21.

Figure 20 – Augering Hole Above the Watermain

Figure 21 – Lowering Magnesium Anode into the Augered Hole

Cathodic protection substantially reduced the leak rate on the 500m length of pipe as shown on the cumulative leaks versus time curve of Figure 22. Ten years after the initial installation the leak rate began to rise again which prompted a second galvanic

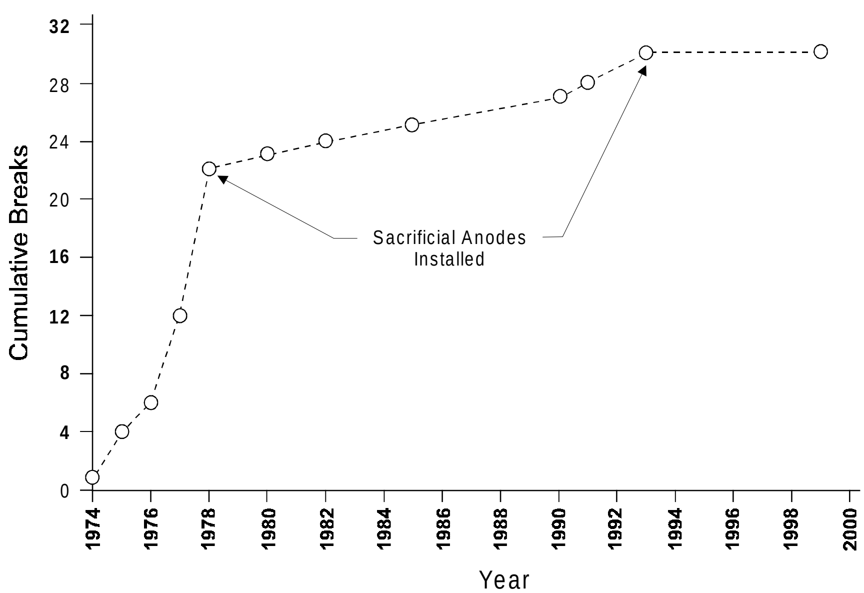

Figure 22 – Failure History on a 500mm Length of Ductile Iron Piping
(Before & After the Application of Cathodic Protection)

anode installation in 1993. As a result of the initial success of the auginode system, the city of North York embarked on a program to protect other sections of ductile iron distribution piping that had been installed between 1967 and 1970. Compilation of the leaks before and after the application of galvanic cathodic protection on 37 of these projects indicated a dramatic decrease in failures as shown in Figure 23.

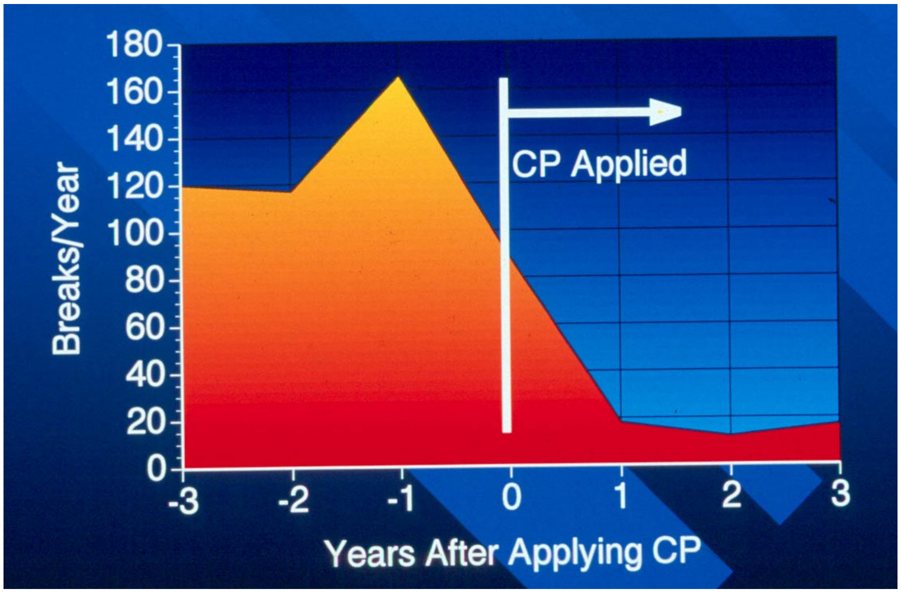

Figure 23 – City of North York
37 Residential Ductile Iron Watermains

Auginode cathodic protection is presently being installed on about 300km of iron watermains in Canada annually.

Impressed Current Cathodic Protection

Impressed current cathodic protection of cast iron water piping was once considered impractical owing to the electrical discontinuity of the bell and spigot joints, and the consequent corrosion caused by the discharge of cathodic protection return current around these joints. Whereas this a valid concern for water transmission piping it is less of a problem for distribution piping, since copper services are either directly or indirectly connected to the electrical grounding system at each residence. The local electrical power distribution neutral therefore serves to make the distribution system electrically continuous, at least for the pipe lengths that have at least one service. Furthermore, it is these pipe lengths that will experience accelerated corrosion because of the iron/copper galvanic couple and where cathodic protection is needed most.

In 1985 a distributed impressed current cathodic protection system (DICCAP) was installed in Emo, Ontario on 5700m of Class 22 grey cast iron distribution piping.[13] This piping system, that was installed in 1967-1970, had experienced 38 breaks by the end of 1981. The DICCAP system relies on the electrical neutral to return the cathodic protection current to each of 42 small power supplies distributed around the town. Each impressed current system, as illustrated in Figure 24, consists of a 20V/1A constant current rectifier whose positive terminal is connected to a platinum-clad niobium anode wire that is surrounded by calcined petroleum coke inside a 64 mm diameter steel tube. The negative terminal of the DC power supply is connected to the overhead AC Neutral rather than the water main.

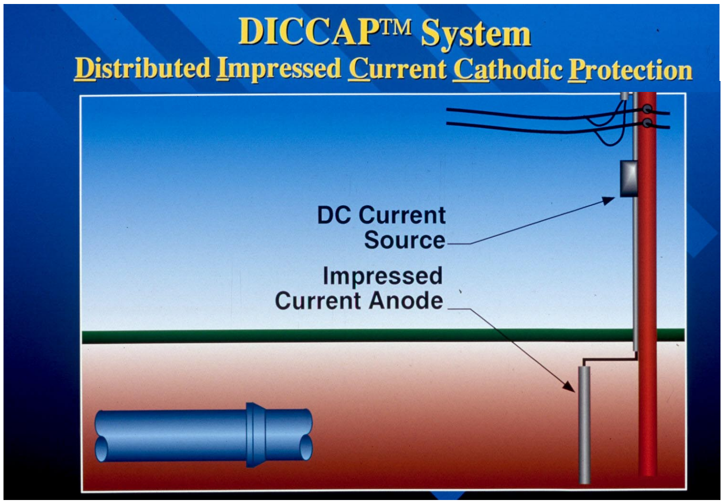

Figure 24 - Illustration of a Distributed Impressed Current Cathodic Protection System

This system has the following features:

i. minimal excavation required since watermain does not need to be exposed,
ii. low power costs - typically $50/km per year,
iii. anode life of 40 years,
iv. constant current rectifier accommodates variable soil resistivity conditions,

The effectiveness of the DICCAP in reducing the break rate in Emo is shown in Figure 25.

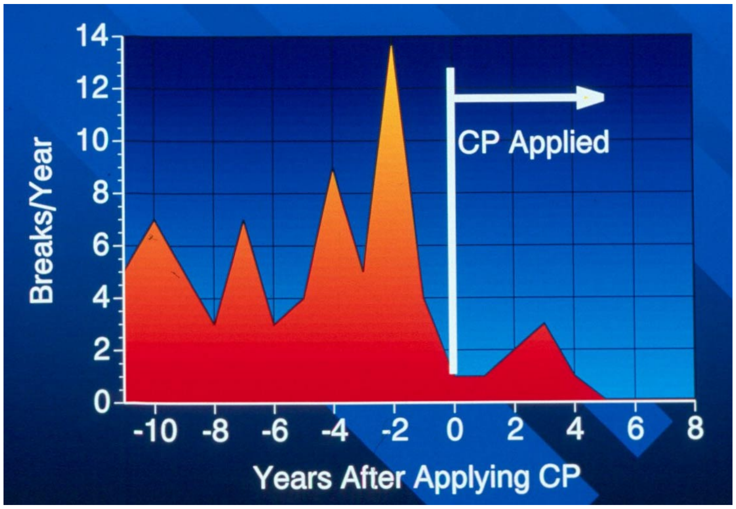

Figure 25 – Township of Emo - 6 km of Grey Cast Iron Watermains
Installed 1970 … Cathodically Protected 1985

PRESTRESSED CONCRETE CYLINDER PIPE (PCCP)

Prestressed concrete cylinder pipe, used for water and sewer transmission service, is composed of a thin wall steel cylinder, lined on the interior and exterior with cement mortar, and reinforced by prestressing wire either wrapped around the steel cylinder or embedded in the exterior mortar (Figures 26a & 26b). These large diameter composite pipes are often considered immune from corrosion because the steel cylinder and prestressing wire is covered by concrete whose alkalinity promotes the formation of a protective passive film on the steel surfaces. As with many passive films however, the protective film is subject to breakdown by chlorides and there have been an increasing number of failures on PCCP piping due to chloride attack. Once the film is penetrated and corrosion is initiated on the prestressing wires, that are typically under about 200 ksi tension, stress corrosion cracking occurs, often resulting in catastrophic failure of a major water transmission main.

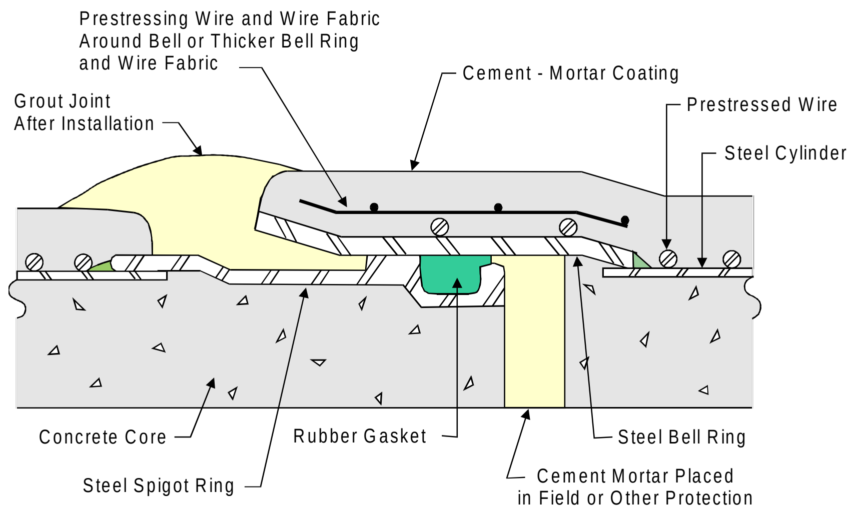

Figure 26a – Prestressed Concrete Cylinder Pipe with the Prestressing Wire Wrapped around the Steel Cylinder

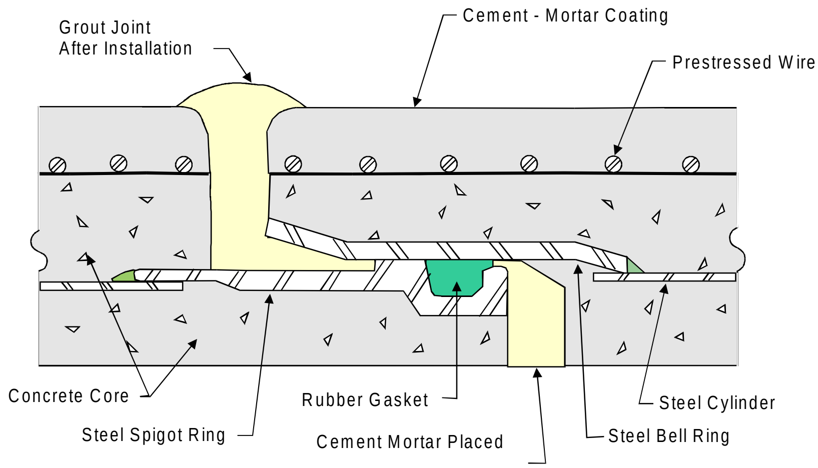

Figure 26b – Prestressed Concrete Cylinder Pipe with the Prestressing Wire Embedded in the Exterior Cement Mortar

A high soil concentration of chlorides is normally not required for chloride attack to occur. If the pipe is subjected to a variable water table that produces wet/dry cycles, whereby the pipe surface is wetted and dries by evaporation, then chlorides left behind on the concrete surface result in a concentration of chlorides sufficient to migrate through the mortar cover and attack the underlying steel. This has been the cause of numerous failures like that shown in Figure 27.

Figure 27 - Typical Corrosion Failure of a Prestressed Concrete Cylinder Pipe

Cathodic protection has been used to prevent this problem[14] on the Pockwock 42" diameter water transmission line, the main water feed for the city of Halifax. In 1985, within 10 years of its installation, this pipeline had its first failure, which was closely followed by 5 more failures. Galvanic cathodic protection was first applied in 1991 to the section of piping where the failures had occurred. The cathodic protection system consisted of 80 inch long zinc anodes weighing 8 lb. surrounded by a sulphate/bentonite backfill inside a cardboard tube. Every other pipe joint was excavated so that the joint could be electrically bonded and 2 of the zinc packaged anodes were installed at each location. Zinc was chosen in order to limit the polarized potential on the pipe to less negative than $-975mV_{cse}$ to minimize the risk of causing hydrogen embrittlement (HE) of the prestressing wire. The current requirements turned out to be so low ($< 200\mu A/m^2$), that many of the originally installed zinc anodes were subsequently disconnected.

Prestressing wire is particularly susceptible to HE because of its alloy and hard drawn manufacturing process. A HE susceptibility test (ASTM 227) has been developed which has resulted in improved performance. Lewis[15] has demonstrated, from the results of this test, that many existing PCCP piping systems contain prestressing wire that is vulnerable to HE. As a result a number of HE failures have occurred where the PCCP piping has been in close proximity to a cathodic protection groundbed.

CORROSION CONTROL USING POLYETHYLENE ENCASEMENT

The use of polyethylene to encase ductile iron pipe has been recommended by the Ductile Iron Pipe Research Association (DIPRA) when the AWWA soil test produces a result of 10 points or greater. This 10 point scheme bears little relationship to the important corrosion factors, as identified by Wakelin,[16] such as soil resistivity and whether or not the piping is connected to copper water services. In addition, Spickelmire[17] has proposed a more comprehensive procedure to address the obvious deficiencies in the AWWA test and to accommodate a risk assessment feature.

The intent of the polyethylene is to prevent corrosive soil from contacting the iron, similar to what is expected from a bonded protective coating. However, there is a maxim in the corrosion control industry that says 'a pipeline should not be coated unless it is to be cathodically protected'. This is because a coating is never perfect and accelerated corrosion can occur at holidays in the coating and cause a perforation quicker than if the pipe remained bare. To have accelerated corrosion requires active cathode sites, which are readily available on distribution systems having copper services, as depicted in Figure 28. This was the mode of premature failure on polyethylene encased ductile iron pipe in the city of Calgary, reported by Hewes and Jacob.[18] On transmission lines such cathodes are less likely, which tends to explain why many of the successful applications of polyethylene encasement claimed by DIPRA, are on transmission lines.

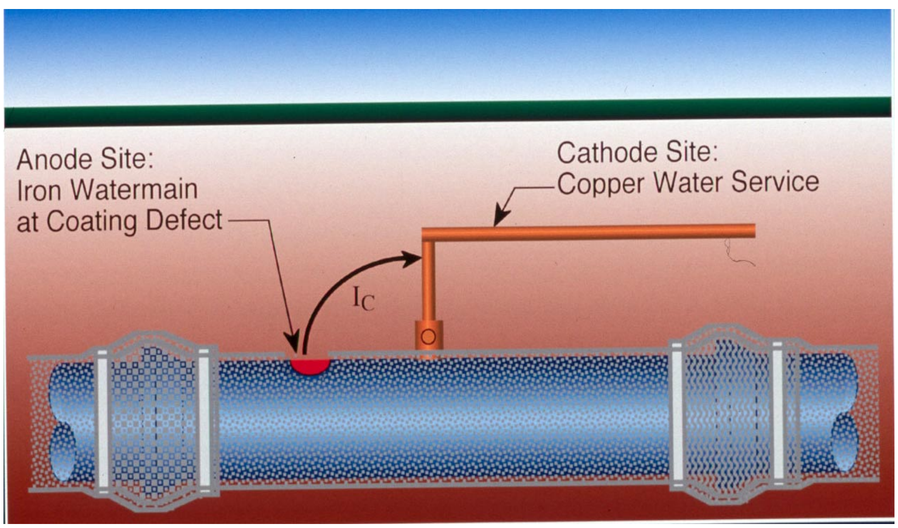

Figure 28 – Corrosion Attack at a Break in Polyethylene Encasement due to Galvanic Couple

Some of the corrosion control success, attributed to polyethylene encasement, could in fact be due to the internal mortar lining, now applied routinely to ductile iron piping by the suppliers. This lining prevents small corrosion perforations from showing up as leaks until such time as the corrosion at the base of the pit is so large that the lining can no longer resist the water pressure. At that point it may be too late to salvage the serviceability of the pipe with cathodic protection, since there may exist numerous other pits where the lining is on the verge of failure. Hence cathodic protection should be installed on any distribution piping that is polyethylene encased at the same time that the pipe is being installed.

CONCLUSIONS

Cathodic protection can play an important role in controlling corrosion on iron, steel, and PCCP water mains. It is an economical means of extending the service life of ferrous water piping indefinitely as long as there is a commitment to maintain the performance of the cathodic protection system and to upgrade it on a timely basis. Lary[19] has estimated that there are an average of 700 water main breaks per day in North America which serves to illustrate that, as powerful and effective as cathodic protection is in reducing corrosion rates, it is clearly under-utilized by the water works industry

ACKNOWLEDGEMENTS

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