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Protection of Ductile Iron Water Mains against External Corrosion: Review of Methods and Case Histories

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Protection of Ductile Iron Water Mains against External Corrosion: Review of Methods and Case Histories

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Abstract: Ductile iron replaced grey cast iron as pipe material in the early 1970s. It has been estimated that almost half of all new water mains in North America are ductile iron. The main cause of the structural deterioration of all metallic mains is external corrosion, which is induced by environmental and operational conditions. Internal corrosion, on the other hand, can cause significant functional (hydraulic, water quality) deterioration within the distribution system. Methods for external corrosion protection include passive (coatings, wraps, etc.), active (cathodic protection) or a combination of both. Successes and failures have been reported on the usage of various methods under different conditions and circumstances. This paper provides the state of the practice in corrosion protection of ductile iron water mains, and describes case histories that have been reported from around the world. Some conclusions are drawn as to the suitability of methods to specific circumstances.

Key words: Ductile iron water mains, corrosion, cathodic protection, protective coatings.

INTRODUCTION

Corrosion of metallic water mains is a natural phenomenon dependent on a variety of environmental conditions, such as aggressive soil, use of dissimilar metals and stray electric currents. These conditions induce formation of electrochemical cells, which encourage external corrosion pits in ductile iron (DI) and graphitized zones in cast iron (CI). Pits and graphitisation can develop as early as 5 years or as late as 30 to 65 years after installation. Corrosion, an electrochemical process, usually occurs in two basic ways, galvanic and electrolytic corrosion. They differ in that galvanic corrosion involves direct electric current that is generated within the galvanic cell, whereas in electrolytic corrosion the direct current is from an external source. Appropriate background and detailed discussions on corrosion theory, galvanic corrosion, electrolytic or stray current corrosion and bacteriological corrosion can be found in published information such as Peabody (1967, 2001), NACE (1984) and AWWA (1987).

Ductile iron pipe is produced with low content of phosphorous and sulphur, while magnesium is added to the grey iron melt prior to casting. The addition of magnesium causes the carbon within the iron melt to precipitate, on solidification, in the form of nodules. The desired mechanical properties of strength and ductility are obtained by subjecting the spun cast DI to heat treatment, which eliminates the brittle micro-constituents produced during the casting process. The final microstructure of DI consists of a uniform distribution of graphite nodules within the ferritic iron matrix. In contrast, the graphite is in the form of flakes in grey cast iron pipes.

Since the 1970s, ductile iron all but replaced grey cast iron as pipe material. Kirmeyer et al. (1994) estimated that in 1992, in the United States about 19% of all water mains were ductile iron, and of the new pipes being installed about 48% were ductile iron. Rajani and McDonald (1995), in a survey encompassing 21 Canadian cities (about 11% of the population of Canada) reveal similar proportions.

Metallic water mains can be protected from corrosion by passive means that include external barriers such as coating or wrapping, or active means that include some form of cathodic protection. Often, active and passive techniques are combined to provide mains with a more complete protection system. Coatings act to electrically isolate the pipe material from its surroundings, thus cutting off the electric current flow and preventing the formation of corrosion cells. Cathodic protection acts to reverse the direction of the electric current so that protected pipes are not depleted due to corrosion cells. Both active and passive methods have been implemented in many cities in recent years, to reduce premature breaks and leaks in water mains.

The objectives of this paper are twofold:

1. Review available methods to protect new and *in situ* ductile iron pipes against external corrosion.
2. Describe and critique the performance (success / failures) of protected new and *in situ* ductile iron pipes, as reported in documented case histories, and draw some conclusions on the suitability of methods to specific circumstances

In the course of preparing this review many case histories were encountered that dealt specifically with grey cast iron and steel pipes. These were not included here to maintain focus on DI pipes, in line with the stated objectives above.

Corrosion failure modes

Although exact failure mechanisms are not well understood, three types of corrosion related failures have been observed in steel, ductile iron and grey cast iron pipes.

- Corrosion pitting, whereby localized corrosion creates a pit in the pipe wall. This pit can grow from either the inside or the outside surface until the pipe is fully penetrated, resulting in a water leak (Figure 1). Corrosion pitting is typical mainly in grey cast iron and steel pipes although some anecdotal evidence suggests that it may occur in DI pipes as well (Makar and Kleiner, 1999). Corrosion pits, when large and deep enough, can also cause weakening of the pipe structure by acting as stress risers. The pipe is likely to fail at the corrosion pit if it is subjected to excessive external stresses (e.g., soil pressure, bending moments, thermal induced stress, live loads, etc.) or internal pressure.

- Graphitisation, whereby the iron content of the pipe is leached away through corrosion, in a region resembling a corrosion pit, leaving behind a carbon flake matrix. This is typical of grey cast iron due to its material properties. Graphitisation is similar to corrosion pits in the way it weakens the pipe structure, however, it differs in the way it creates water leaks. Often, a graphitized water main will not leak even if the ferrous content was completely leached out, because the graphite forms a plug that can prevent water from leaking (Figure 2). However, any disturbance, such as water hammer, soil movement, etc., can dislodge this "plug" to create an instant leak.

Corrosion can start as a result of mishandling during transportation or installation. It can manifest itself in various shapes and forms that subsequently affect pipe strength. For instance, Makar (2000) reported on a cast iron main that received a long and deep scratch in its bituminous coating during installation. Corrosion developed along this scratch, and when it became deep enough, the pipe burst in a longitudinal failure that occurred along the corrosion line (Figure 3).

CORROSION PROTECTION

Coatings

Coatings act to electrically isolate the pipeline material from its surroundings, thus cutting off the return electron path and preventing the formation of a corrosion cell. An effective coating should be easy to apply and repair; adhere well; resist impact, and geomechanical stresses as well as soil that is chemically and bacteriologically aggressive. It should be flexible, with good dielectric strength (good insulation and good moisture barrier); be chemically and physically stable (maintain protective characteristics for a long time) and be resistant to cathodic disbondment.

Ideally, when applied correctly, coatings protect more than 99% of the pipe surface. Factors that may contribute to holidays in coatings include skips by the coating machine; rough handling; penetration by rocks or debris during backfill; cracking from excessive mechanical or thermal stresses; bacterial action in the soil and damage from subsequent construction activities.

The thickness of the coating varies with material types as shown in Table 1. Some examples of the more popular coating materials include bituminous coal tar enamels and asphalt mastics, thermoplastics including polyethylene and polypropylene, epoxies, phenolics and adhesive-backed tapes.

Under certain conditions a pipe with compromised coating could have a local failure sooner than a pipe with no coating at all. When the cathode in a corrosion cell is external to the water main, i.e., copper services and cast or DI mains, then a holiday in the coating will act to concentrate the electric current to a relatively small area on the anode. The result will be a high rate of corrosion at the unprotected surface of the main. This can be seen from equation (1) as follows (NACE, 1984):

$$mpy = \frac{K}{RA} \tag{1}$$

where mpy is the corrosion rate in units of length over time (NACE uses mils, or thousandths of an inch per year), K is an electrochemical constant depending on the metal and the conditions, R is the electric resistance of the metal-soil specimen to linear polarization (ohm), and A is the total area of the corroding specimen (NACE uses inch^2).

It can clearly be seen that all else being equal, the smaller the exposed area the higher the corrosion rate, resulting in a shorter time to total penetration. It is thus interesting to note that minimum Federal (USA) safety regulations for transportation of natural and other gas pipelines (Sub-Part I of the Office of Pipeline Safety Docket No. OPS-5, Part 192) require: "…all existing coated gas distribution mains must be cathodically protected…" and "…all existing uncoated gas mains must be cathodically protected in areas where active corrosion exists…" (Wagner, 1974). This means that the requirement to protect coated pipes is more stringent than uncoated pipes.

At the same time it is important to note that coating generally improves the effectiveness of cathodic protection (CP). CP needs to protect only exposed pipe, thus a good coating will reduce the amount of protective current, which will result in longer life of CP anodes (or power savings in case of impressed current CP).

Polyethylene (PE) wrap. In North America, loosely wrapped polyethylene sleeves (also sometimes referred to as PE wrap, PE loose wrap, PE sleeve, PE encasement; these terms are used here interchangeably) have been used to isolate metallic pipes from aggressive external environment since the late 1950s. The effectiveness of this practice, which is recommended by the pipe manufacturers, is somewhat controversial in that both good and poor performance have been reported (e.g., Garrity et al., 1989; Caproco, 1985; DIPRA, 1985; Malizio, 1986, among others).

Polyethylene wrap is different from conventional coatings in that it does not act to electrically isolate the pipe. It is postulated that the loose wrap, although it does not completely seal the pipe, in effect it isolates the pipe from the non-homogeneous soil medium, creating a uniform surroundings of passivated trapped water layer that prevents the formation of localized corrosion cells (Malizio, 1986). Initial rusting would thus occur, but oxygen in the trapped water will eventually be consumed by the cathodic reactions, thus inhibiting further corrosion.

This postulation has encountered some skepticism, especially among corrosion engineers. Many believe that the trapped moisture will, in the long-term, create local corrosion cells (e.g., Szeliga, 1991). Further, there is fear (as illustrated later in some of the case studies) that the loose PE wrap creates a moist air-gap between the pipe and the soil, which forms a shield that might diminish the effectiveness of cathodic protection, while still providing conditions for local corrosion cells (e.g., Jackson 2000). Furthermore, the oxygen depletion theory may not be true for all conditions. For instance, where the cathode is external to the water main, e.g., copper service pipe, there would be no oxygen depletion at the water main, which is anodic, rather the oxygen will be consumed by the copper tubing.

The polyethylene wrap method is inexpensive and because it is applied in the trench there is little risk in damage through pipe transport, storage and handling. However, the wrap can suffer cuts and tears due to stones in the trench. Although the method's proponents claim that it is relatively insensitive to small cuts and tears, care must be taken to ensure that large tears do not occur and that the pipe is free of clumps of clay prior to wrapping (Collins and Padley, 1983; Padley and Collins, 1987). Ellis et al. (1998) reported the results of a 10-year comparative study in Australia, where several wrapped and unwrapped DI pipe sections were buried in very corrosive soil. They observed that the wrapped segments generally corroded at a much lower rate than the exposed segments, however, on the wrapped segments there were relatively deep corrosion pits near cuts and tears in the wrapping. Melvin and McCollom (1993) reported similar observations. For this reason, some utilities choose to double (and in some cases triple) wrap their DI pipes (Jackson, 2000). In addition, there is evidence that cathodic protection can help mitigate corrosion at tears and cuts of the PE wrap (e.g., Schiff and McCollom, 1993).

Zinc galvanization. Zinc galvanization of cast iron (CI) water mains started in Europe in the early 1960s. Marchal (1981) reported high success rate in France, using zinc-based coating in both CI and DI pipes. He described experiments that demonstrated the "healing power" of the coating to mitigate corrosion cells occurring due to cuts and scrapes that expose the bare metal of the pipe. The bruised spot on the pipe becomes a small area cathode to the pipe's zinc coating, which is a large surface anode. The zinc coating thus cathodically protects the exposed metal.

In recent years galvanization has become a popular method to protect DI pipes in Europe and Japan. The zinc coating is applied to the pipe either by hot dipping or spraying (Nielsen et al., 1996) and is usually protected by a top layer of polyethylene wrapping, bituminous varnish, cold tar varnish or synthetic resin varnish, for extra protection. Zinc-coated pipes that have been exhumed after years in aggressive soils have been reported to be covered by a protective white layer of zinc corrosion products. This layer appears to protect the pipe even after all the zinc is consumed by corrosion (Marchal, 1981). There is no report on the durability of this protective layer and whether disturbances can compromise its integrity, exposing the pipe to renewed corrosion. Further, this protective layer cannot form in acidic soils.

Other types of metallic coatings are also available, and can be applied via immersion, electro-plating, cladding, flame-spraying, arc-spraying, chemical deposition, or vapor deposition. Some guidance about considerations of using one application technology over another can be found in Peabody (1967, 2001),

Thermoset coatings. Thermoset coatings including epoxy and polyurethane resins are applied as solvent-based, solvent-free liquid paints or as sintered powder (bonded epoxy). These high-quality coatings have been used extensively for steel pipes but rarely in DI pipes because these coatings can be applied at 300-500 microns thickness to smooth steel pipes, but the rough surfaces of DI pipes require a much thicker layer. This makes their usage for DI pipes prohibitively expensive (Collins and Padley, 1983). Maillard (1985) reported on successful usage of polyurethane-coated DI pipes for select sites with extremely corrosive conditions (e.g., areas frequently flooded by ocean tides). The thickness or the costs of these coatings were not reported.

Tape coating. The use of self-adhesive tape for pipe wraping started with steel pipes and was later adopted for DI pipes (Collins and Padley, 1983). Various materials and configurations are used, including PVC with bitumen-based mastic and low or high-density polyethylene combined with layers of butyl-rubber. Both hand (*in-situ*) or machine wrapping are available. The tapes are wrapped spirally with an overlap of about 50%. Applications vary from two to four layers with total thickness of 1 to 3 mm.

Noonan and Bradish (1995) reported successful use of PE tapes in steel pipes, but warn that when applying tapes to DI pipes, the practice should not be adapted blindly from steel pipes, rather special attention should be paid to the difference in the material properties and installation practices. For instance, steel pipes are usually back-filled with well-graded imported material, whereas DI pipes are often back-filled with native soil. The shear stress that DI will experience may thus be higher than is normally experienced by steel, requiring special considerations in the design of the protective tape coating. Noonan and Bradish (1995) also described the tape coating system as completely compatible with cathodic protection.

Thermoplastic coatings. This group includes polyethylene, coal-tar enamel, and bitumen sheathing, among others. Collins and Padley (1983) reported good results with bitumen sheathing, 6 to 8 mm thick, reinforced with asbestos fibers or glass cloth. Walker and Wood (1985) reported on the use of coal tar enamel mainly on steel pipes, since the

1920s. The advantages of this type of coating are listed as good adhesion to surfaces, water resistance, resistance to biological agents and to cathodic disbonding[1].

Collins and Padley (1983) reported the use of polyethylene cladding for DI pipes. There are several types of application process, extrusion for smaller diameter pipes and spiral wrapping for larger diameters. Other processes such as hot dipping and shrink-wrapping exist as well.

Cathodic protection

Cathodic protection can be defined as "…the reduction or elimination of corrosion by making the metal a cathode by means of an impressed direct current or attachment to a sacrificial anode (usually magnesium, aluminum or zinc)" (NACE, 1984). Cathodic protection can only protect the surface in contact with the electrolyte. For structures such as pipes and tanks, the internal surface of the pipe will not receive any protection. In general, pipes installed in clayey and silty soils or in a marshy environment will be more prone to corrosion than well-drained soils such as sand and gravel (however, gravel with sharp edged aggregates can heighten the risk for damage to existing coatings).

Ideally, a cathodic protection system should distribute protective current evenly over the entire pipe surface. However, this is rarely achieved because variations in distance between anode and points along the pipe (due to geometry), as well as variability in soil composition and presence of shielding structures, will result in variable attenuation of

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[1] Chemical reactions that take place between the pipe, severed coating and the surrounding soil lead to a very alkaline environment. This alkaline environment debilitates the adhesion of the organic coating to the pipe leading to a mechanism known as cathodic disbondment. Many other factors such as pipe surface preparation, cleanliness, pipe material quality, application temperature, its related physical-chemical properties, etc play a role in how fast this mechanism acts. Lesser mechanical properties in coatings can be augmented by the use of reinforcing fibres (asbestos or glass) or specialised fabrics, typically applied at thickness of 2 to 6 mm, either in the factory or in-situ.

current and uneven distribution. There are two types of cathodic protection anodes, galvanic and impressed current.

Galvanic (sacrificial) anodes. A galvanic anode is a metal that is higher than the protected structure (pipe) on the galvanic series. The presence of two dissimilar metals in an electrolyte (soil) gives rise to a galvanic corrosion cell if these two metals are electrically connected. Galvanic cathodic protection is thus a method in which a galvanic corrosion cell is induced so that the pipe is the cathode and the anode is the corroding (sacrificial) element. The anode is thus consumed and eventually replaced.

Anodes can come in many sizes and types to meet the requirements of the installation and the life expectancy of the system. Magnesium, zinc and aluminum are materials commonly used for anodes. They are usually packaged within a bag of chemical backfill, which is engineered to provide optimal working environment. Anode material can be characterized by *electric potential, current efficiency, actual current output, material consumption rate and polarization rate.* Table 2 lists typical characteristics of popular anodes. Details on typical configurations and design criteria can be found in Peabody (2001)

Impressed current. Impressed current methods use an external source of direct current (DC) to produce the electric current required for the cathodic protection. The positive terminal of the DC source is connected to the anode and the negative terminal to the pipe. Consequently the anode is forced to discharge current into the soil (anode bed). This current is eventually picked up by the pipe and returned to the source through the negative terminal, thus completing a corrosion cell. In this corrosion cell, the pipe is the protected cathode while the anode material is consumed by corrosion.

Impressed current anode materials are selected to achieve long life through low weight consumption rates. Several materials are commercially available, such as high silicone (14.5%) cast iron alloy, with a consumption rate of a few tenths of kilograms per ampere-year, or graphite with a consumption rate of under half a kilogram per ampere-year. Scrap metal can also be used (if cheap source is available) but these anodes will require frequent replacement. Table 3 compares the main aspects of galvanic and impressed current methods.

CP Protection criteria. There are several methods for determining whether a cathodic protection system is providing protection the way it was intended. These methods involve measuring potential changes of the protected pipe or measuring protective electric currents.

All chemical reactions typically start at a relatively high rate, and then, if conditions do not change, the reaction rate will slow down and tend to reach some equilibrium rate, which is lower than the initial rate. In corrosion, this phenomenon is called *polarization*. Polarization in buried pipes is typically predominant near the cathode, where hydrogen ions receive electrons and become hydrogen gas. The increasing presence of hydrogen gas interferes with the delivery of electrons from the cathode to the hydrogen ions. The net effect is that the cathode becomes increasingly more negative until its potential is almost as negative as the anode. This acts to retard the corrosion reaction because the difference in potential between the anode and the cathode is what drives the corrosion cell.

Figure 4 illustrates a typical pattern of potential values in a pipe to which cathodic protection is applied (Wendorf, 1988). It is an accepted practice to consider steel and iron structures completely protected if they are polarized to a potential of -850 mV to copper/copper sulphate ($Cu/CuSO_4$) reference electrode (CSE) (NACE, 1984). The reason for that value is that the most anodic steel found in practical situations has a potential of -800 mV. An additional -50 mV is a safety factor to allow for inaccuracies and extreme cases. Full polarization can typically take weeks or even months.

Monitoring the current produced by cathodic protection over time can give an indication as to the actual soil resistivity, actual pipe current demand, expected life of anodes and changes in environmental or operational conditions.

EXPERIENCE AND CASE HISTORIES WITH CORROSION PROTECTION IN DI PIPES

Galvanic CP

City of Prince Albert, Alberta, Canada. The City of Prince Albert has seen a significant decrease in breaks in DI mains (from about 3 to about 1 break/km/year.) after commencing a cathodic protection program in 1988 (Jansen, 1995). This observation, however, is based on only about 4 km of DI mains (the entire DI inventory) and the post CP breakage rate was observed for only 2-3 years.

The CP program included also CI mains, of which about 16 km (out of a total of about 38 km) have been protected. The mains selected for protection were the ones observed to have had the highest breakage frequency. No significant reduction in breakage rate was observed in these mains after CP implementation. This could be attributed (Yule, 2001) to the fact that many CI pipes in Prince Albert were in fact cathodically protected by the newer DI pipes[2]. Thus, the drop in breakage rate observed in CI was not as significant as in DI mains.

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[2] New ductile iron pipes are typically anodic to old grey cast iron pipes. Consequently, when both types of pipes are present in the same vicinity, and are electrically connected (e.g., a DI pipe segment replacing a deteriorated CI segment) the DI pipe will act as a sacrificial anode to the CI pipe.

Durham Region, Ontario, Canada. A cathodic protection program has been implemented in the Region of Durham since 1983 (Shymko, 1996). The program started as a reactive "hot-spot" implementation, wherein an anode was installed each time a water main was repaired. Gradually, the program evolved into a proactive, preventative-maintenance one, in which pipes were systematically retrofitted with anodes. The prime targets of the cathodic protection program were the DI mains, which suffered the highest breakage rates among all pipes in the region's inventory. By 1995 about 12% (approx. 80 km) of DI and 0.3% (approx. 1.4 km) of CI mains had been protected. Shymko, (1996) reported that the CP program resulted in a dramatic reduction in main breaks. This reduction appeared to be significant throughout the distribution system, but seemed to vary in magnitude along individual mains.

Winnipeg, Manitoba, Canada. Chambers (1994) reported on a positive experience with cathodic protection in Winnipeg. The city experienced relatively high water main breakage rates in its 1200 km of CI and DI mains, and as a consequence implemented in 1991 a "hot spot" cathodic protection program, in which a zinc anode was installed in conjunction with each CI and DI water main repair. A noticeable decrease in breakage rates ensued in the following years, although some of this decrease was attributed to favourable weather conditions in 1991 and 1993. Analysis using control charts led to the conclusion that at least 17% of the observed reduction in breaks could be attributed to the CP program. Chambers (2000) reported that a combination of measures, including CP retrofitting, CP hot spots and replacement of mains with the highest breakage frequency, has helped to reduce and stabilize the breakage rate (about 1000 breaks/year) between 1992 through 1998. Details were not publicly available to quantify the contribution of each measure to this reduction in breakage rate.

Scarborough (Toronto), Ontario, Canada. Scarborough started experiencing breaks in uncoated DI pipes in 1972, just seven years after DI was introduced (Doherty, 1990). A limited cathodic protection program was implemented in the early 1980s. This program retrofitted existing DI water mains with galvanic sacrificial anodes both in banks or individually. In addition, new specifications were implemented, whereby all new DI mains, copper services and appurtenances were installed with cathodic protection.

The CP retrofit appeared to have brought DI increasing breakage rates under control. At the time these activities were reported, only a few years after implementation, the breakage rate appeared to have leveled off. New distribution mains in Scarborough are all PVC.

Calgary, Alberta, Canada. In 1997, a three-year water main replacement study was undertaken (Brander, 2000) in Calgary. This study was aimed predominantly at quantifying corrosion rates in various environmental and operational conditions surrounding the Calgary water distribution system. It included extensive surveys of redox potentials, soil resistivities and corrosion pit measurements on exhumed pipes and pipe coupons. The study revealed, among other things, that along a given water main, the parts that corroded the most and the fastest were the parts closest to copper services. This observation is commensurate with basic corrosion theory regarding galvanic corrosion half-cell. The study further revealed that those water mains retrofitted in the mid 1980s with CP anodes displayed a significantly lower corrosion rate than the unprotected mains. This CP retrofit was originally intended to protect bare DI water mains with service saddles. Anodes were placed at these saddles approximately 15 m apart. These anodes appeared to have protected the entire length of the pipe. The corrosion pits on the protected pipes were significantly smaller than corrosion pits on the rest of the pipes.

Severn-Trent, UK. Green at al. (1992), Green (1993) and Green and De Rosa (1994) investigated the performance of retrofitted sacrificial anodes in protecting un-lined DI mains. Initially, they developed an approach, using micro-excavation and remote tapping to attach an anode to each 5.5 m pipe segment. After a trial study they decided on a configuration that included a magnesium anode placed near the bell of the pipe (0.5 m above its crown) and a potential measuring point in the middle of the pipe's barrel. Subsequently, two pilot studies were conducted in both urban and rural areas to investigate their influence, followed by two field studies. The results are summarized in Table 4. The field trials clearly showed that placement of sacrificial anodes were effective in reducing the pipe potential below the protection criterion of – 850 mV (CSE). In the first field trial, 75% of the pipe length received full protection. No explanation was offered as to why the cathodic protection measure was not effective in the other 25% of pipe length nor a comment on the performance of the cathodic protection in rural versus urban areas. Five thousand sacrificial anodes were installed on 22 km of DI pipe in nine different sites in the second field. Only 30 anodes were reported to fail in lowering pipe-to-anode-potential below - 850 mV (CSE). The accompanying break history showed that the breakage rates were reduced from 0.42 to 0.09 breaks/km/year for the two ensuing years. The authors expected even further reduction in subsequent years.

Milwaukee, Wisconsin, USA. A group comprising 3.6 km of DI mains 4" (100 mm) to 12" (300 mm) in diameter in the suburb of Milwaukee (Stetler, 1980) experienced a pronounced increase in main breaks six years after installation. This increase in breakage rate was attributed to corrosion resulting from un-insulated copper services as well as copper strap bonds that had been installed to make the pipes electrically continuous for the purpose of electrically melting freeze-ups. Magnesium sacrificial anodes were installed between November 1976 and July 1977 and no water main breaks were observed at the time the author reported the results, 27 months after the completion of the project. A study on the pattern of location of water main breaks indicated that 80% of them occurred within 1 m of copper water service pipe or copper bond strap.

Emo, Ontario, Canada. Gummow (1988) described two distribution water mains in Emo. One consisted of 6 km grey cast iron main installed around 1970 and the other 360 m of 6” (150 mm) DI main installed in the late 1960s[3]. These mains were protected on a trial basis in 1983 by installation of sacrificial zinc and magnesium anodes. The complete system was finally protected in 1985 using an impressed current system that was selected for economic reasons. The installation of the impressed current system dramatically reduced breakage rate in the mains (Figure 5).

Impressed Current CP

Savannah River plant, South Carolina, USA. Garrity et al. (1989) reported an impressed current cathodic protection system applied to 3.2 km of DI transmission mains 10” (250 mm) to 14” (350 mm) in diameter. At the design stage, it was identified that the main was designed to traverse an area with a high variability in soil type, including a swamp section. As well, the main’s route was in close proximity to several metallic structures such as a railway, underground cables and AC power lines. The designers, fearing significant corrosion, designed the main with coal-tar enamel coating and an impressed current cathodic protection system, which required that the main be made electrically continuous (using copper stranded bonding jumpers).

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[3] The authors commented that it was highly unlikely that ductile iron pipe which came into production in 1969-1972 had been installed earlier than cast iron mains. Sletmoan (2000), retired Water and Sewer Operator for Emo, confirmed that all water mains in Emo consist entirely of ductile iron mains.

The impressed current cathodic protection system was designed with current density of 21.5 mA/m^2 and an assumed coating efficiency of 97%. These design parameters were validated after the installation of the system was completed.

Initial potential measurements proved that the main was adequately protected, with pipe to anode potentials of equal or less than the required –850 mV. The report does not include any follow up on the performance of the system with respect to breakage rates.

The designers chose to stay away from polyethylene encasement because they believed that, when loosely wrapped, it did not provide all the normally expected characteristics of a protective coating (such as high dielectric strength, permanent bond to the pipe, resistance to deformation, resistance to disbondment, resistance to chemical attack, etc.). In essence, they did not believe in the theory about the formation of a passivated layer (described earlier) protecting the pipe from long-term corrosion.

Polywrap

Calgary, Alberta, Canada. Ductile iron pipes were introduced into Calgary in the early 1960s. By the end of 1980, 42% of all distribution mains were DI (Jacobs and Hewes, 1987). Soon after their introduction, a rapid increase in breakage rate was observed in the DI pipe, from 0.05 failures/km in 1970 to 0.29 failures/km in 1980. As a result, a study was commissioned to investigate the high rate of breakage, the results of which were published by Caproco (1985).

The study found that most of these breaks were attributed to corrosion, leading to complete perforation of the pipe walls. Although distributed randomly across the pipe, a higher frequency of corrosion pits was observed near service lines, that were typically copper tubes, connected (without electric insulation) to the DI main via bronze saddles or via DI saddles fastened with steel rods, through a brass main cock. In addition, corrosion pits appeared to be deeper in soils of lower electric resistivity. These observations appeared to be commensurate with basic corrosion theory of galvanic corrosion half-cell.

The study further found that the vast majority of failures occurred in the presence of corrosive clay and silty-clay soil, which is dominant in Calgary. Breakage rates were observed to peak in the cold winter months, especially during long cold spells or cold spells following long dry spells. Most of these breaks were attributed to mechanical failures and in many cases mechanical failure occurred in a location already weakened by corrosion.

In addition, the study found that until the late 1970s both cast and DI mains were installed with a thin bituminous coating (deemed by the report as ineffective), and in some cases loose polyethylene wrap was used. Caproco (1985) concluded with regard to the PE wraps that "…No evidence has been found that pipes protected in this way corroded at a lower rate than those which were placed in the soil without a wrap. It is possible that pipes and saddles coated in this way actually have failed at a higher rate."

The Caproco report (1985) raised an immediate response from DI pipe manufacturers (DIPRA, 1985). In their response, the Ductile Iron Pipe Research Association (DIPRA) accused the authors of the Caproco (1985) report of being biased and cast doubt on the validity of the tests carried out by Caproco. They argued that there was overwhelming evidence that corrosion rates in DI pipes were no worse than in CI pipes. They attributed the high corrosion rates in Calgary's DI pipes to "indiscriminate" joint bonding (a measure used to facilitate electric thawing of pipes and services) and to the practice of grounding the electrical services of houses to the copper service pipes. They argued that since new DI pipes were anodic to older CI pipes, electrically bonding these two types of pipes created bi-metal corrosion cells in which the DI pipes protected the CI pipes (which would have explained the observed high corrosion rates in the DI pipes). Similarly, the iron pipes (both CI and DI) protected copper services if these were electrically continuous with the iron mains. In addition, DIPRA claimed that a bonded system had a greater tendency to collect stray currents (including those from electric grounding), which increases corrosion rates. Furthermore, DIPRA claimed that in proposing solutions (e.g., CP and pipe replacement) Caproco neglected to consider costs versus benefits of these solutions. As to Caproco's assertion about the effectiveness of PE wrap, DIPRA said Caproco was conveniently ignoring many published reports as well as good results for millions of feet of pipe protected by loose PE sleeves. They claimed that the PE wrap likely failed in Calgary because of poor application that resulted in large cuts and tears in the sleeves.

It appears that while some of DIPRA's (1985) claims have merit (DI being anodic to CI, the effect of electric grounding, the effect of copper services un-insulated from the iron mains), discrediting Caproco did not change the fact that corrosion failure rates of DI pipes in Calgary went out of control.

Subsequently, Calgary completely switched over to PVC as the material of choice for water mains (Brander, 2000). In locations where there are concerns of hydrocarbon presence, the city uses DI pipe coated with an extruded PE coating (40 mil thickness with good bonding to the metal). These coated DI pipes are also protected by magnesium anodes, which are placed about 100 m apart. This large spacing is possible due to the completeness of the PE coating, and the fact that these pipes are electrically continuous. It should be mentioned that the DI pipe manufacturers developed a method for Calgary to coat the bonding straps as well.

Australia. Ellis et al. (1998) described an experimental case study where DI pipes were buried in five different trenches with different combinations of backfills and corrosion protection in the form of polyethylene sleeve encasement. Each trench contained three, 2 m long segments of DI pipe 100 mm in diameter (pipe wall thickness 6.1 mm), and each section had a dezincification resistant brass tapping ferrule to simulate service connections. The general site conditions consisted of low resistivity clayey soil with anaerobic sulphate reducing bacteria and a high ground water table.

A 2 m DI pipe section was exhumed from each of the 5 trenches at 2, 5 and 10-year intervals. Table 5 shows the description of each trench profile and the corresponding corrosion rates. These field tests suggested the following: (1) PE encasement can diminish external corrosion in DI buried in an aggressive environment but it is essential that PE encasement sleeves are free from slits or damage. (2) The use of angular (sharp) aggregate for backfill can damage the PE encasement sleeves permitting the ingress of moisture between the sleeve and pipe, which promotes external corrosion. (3) Well-draining backfill (sand) surrounding the unprotected DI pipe does not help reduce the external corrosion. (4) Protected DI pipe with well-draining backfill in contact with PE encasement appears to be more effective in reducing external corrosion than in cohesive soil (clay) backfill.

North America. Jackson (2000) reported on a study in which various US and Canadian utilities were surveyed by telephone on the performance of their DI pipes protected against corrosion. The responses were compiled into a qualitative assessment regarding the level of corrosion resistance of DI pipe with and without PE encasement. (Table 6).

The utilities surveyed reported varied experiences, although invariably, bare DI pipes resulted in high leakage rates in the presence of corrosive or even mildly corrosive soils. Of the utilities that used PE encasement, some had good success in reducing leakage rates, while others reported continuing problems. Several utilities decided to use “double bagging” (two PE encasement layers) to prevent local corrosion at cuts and tears in the wraps. One utility even went with triple bagging around valves and appurtenances. Several utilities, not having a positive experience, have altogether switched to PVC mains for new construction. Some continued to use DI pipes for large transmission mains and PVC for smaller distribution mains.

Some utilities used cathodic protection in conjunction with the PE encasement, while others were either advised (by consultants) against it or feared the shielding effect of the PE encasement. Some utilities used cathodic protection mostly for large (>12” (300 mm)) diameter mains presumably where they found it more economical to extend the life of a pipe than replace it.

This study seems to suggest that in large transmission mains PE encasement can be applied more effectively and can maintain its integrity longer because there are no disturbances such as service lines, tapping or appurtenances that tend to breach the continuity of the wrap. It should be reemphasized that all of these experiences were reported verbally. Most reporting utilities did not have thorough soil data and the exposure time of the pipes to their environments varied significantly.

Malizio (1986) reported on the performance of PE encasement of DI pipes in 12 US cities, from 7 to 20 years after installation. He noted that all protected DI pipe had no significant corrosion pitting despite the fact that all pipes buried in soils had a corrosion point score that exceeded 10 as defined by ANSI/AWWA C105/A21.5 (AWWA 1991)[4].

Ductile Iron Pipe Research Association (DIPRA). DIPRA has an on-going program to conduct "dig-ups" to inspect polyethylene encased DI mains. This program was initiated in 1963 and has records (Bonds, 2000) on the performance of cast iron (60 dig-ups) and DI (72 dig-ups) mains. The age of the DI mains (diameters 4" (100 mm) to 42" (1066 mm)) in these records ranges from 6 to 32 years. Of the 72 DI dig-ups, 58 were rated as either "excellent" or "very good", 9 were rated "good", and 5 had a rating of "excellent or good where properly wrapped." DIPRA concludes from these data that the performance of DI mains is acceptable when they are protected with polyethylene wraps.

North Dakota. Schiff and McCollom (1993) conducted field trials to evaluate the effectiveness of PE encasement on DI pipe before and after impressed current was applied. Corrosion rate measurements using steel probes were carried out regularly from 1982 to 1992 (the probes were not grounded to the pipe until 1989) and impressed current cathodic protection was installed in 1991. The principal observations of these measurements were: (1) Corrosion rates of DI pipe with undamaged polyethylene encasement were very low. (2) Corrosion rates of polyethylene encased DI pipe prior to grounding of the probes was very low but increased when the probes were grounded to the DI pipe (possibly because the probes were steel which is cathodic to DI). (3) Corrosion rates diminished somewhat after the application of impressed current cathodic protection on polyethylene encased DI pipe. Corrosion rates in exposed pipe diminished significantly upon the application of cathodic protection. (4) Electrical current

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[4] European countries use a similar procedure (Steinrath, 1966) intended to assess the soil corrosivity towards Fe-based material0s that accounts for several additional soil properties and site conditions such as

requirements for polyethylene encased DI pipe were more than an order of magnitude higher than for well-coated steel pipe but still lower than uncoated DI pipe. (5) Sandy backfill lowered the corrosion rates compared to the more corrosive native soils.

Additional experiences. Szeliga (1991) described a case history of a PE wrapped DI pipe in low resistivity soil (5,000 Ω-cm), where corrosion was detected 8 years after installation. The primary reason to which early failure was attributed was that moisture had penetrated the polyethylene sleeve creating an oxygen differential corrosion cell. This observation contradicts the theory (and observations) regarding the passivation of the trapped moisture, as described earlier.

Padley and Collins (1987) summarized the performance of 18, 2 and 6 PE encased DI pipes in England, Japan and the United States, respectively. Three of the six pipes examined in the United States were reported to have been laid in 1958 and 1960 when, in fact, ductile cast iron was not available in the United States. The pipes in Japan were 2.5 to 6 years old and generally displayed almost no corrosion. The pipes in the United States were 12 to 23 years old (although the 23 years is doubtful) and showed no corrosion. The pipes in England were examined between 2 and 13 years after installation. The incidence of corrosion pitting was found to be just as high on relatively young pipes (<6 years) as on old pipes (>6 years). In fact, 6 of 7 young pipes and 7 of the 10 pipes in England were found to have some form of corrosion pits. Most of these pits were attributed by Padley and Collins (1987) to damaged or improper installation of PE encasement.

Fuller (1978) reported the performance of PE encased and unprotected DI pipes installed in submerged marine clay, peat and clay with soil resistivities ranging from 110 Ω-cm to 900 Ω-cm. These pipes, examined 9 years after installation, indicated that the

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buffer capacity, neutral salts, sulphates, groundwater, horizontal and vertical homogeneity.

polyethylene sleeves reduced the maximum pit depth by a factor of six. Whenever, corrosion was detected on PE encasement-protected pipes, it was almost always due to tears or damage in the PE encasement sleeve.

Grau and Garcia-Peris (1996) made a passing remark that polyethylene sleeving used to protect DI pipes buried in aggressive soils had performed satisfactorily in Spain.

Other type of coatings

Japan. Miyamoto (1986) provided a general description of the Japanese experience using five different forms of corrosion protection in DI water mains. These included: (1) tar-epoxy coating, (2) zinc-rich paint coating + tar-epoxy coating, (3) tar-epoxy coating + PE encasement sleeve, (4) polyurethane coating, and (5) polyethylene coating. He indicated that tar-epoxy coating + PE encasement sleeves was the most widely used form of corrosion protection because of its low cost and easy handling. Morikawa et al. (1996) confirmed the practice of using PE encasement sleeves in conjunction with zinc-rich paint coatings (with a top synthetic resin coating) in 80% of all new pipe installations.

Sweden. Adamsson and Ljunggren (1987) reported on the requirement that all new DI mains in Gothenburg, Sweden, installed after 1986 had to have a factory installed 0.8 mm thick fluidized-bed powder coating, based on ethylene vinyl alcohol copolymer. This requirement stemmed from their experience with increased leaks/breaks on DI pipe. The bitumen and zinc combination of coatings was not considered because of the poor performance of hot-galvanized steel plates installed in the “muddy” clays of Gothenburg. Sacrificial anodes had been installed on existing systems to mitigate water main breaks but impressed current cathodic protection had to be used in most installations since the current load was unexpectedly high and life expectancy of the anodes was limited to 5 to 6 years.

Hedberg, (1996) reported that PE and PVC pipes were materials of choice for most new distribution systems in Sweden. However, when circumstances required DI pipe, it was coated with bitumen in non-aggressive soils, and with a combination of zinc and bitumen in aggressive soils.

France. Pedeutour (1985) reported on short-term (16 months to 4 years) laboratory and field tests on the performance of epoxy powder coatings applied on DI pipe and fittings. Although the duration of the observations was too short to draw any definite conclusions, two inferences were made: (1) High operating temperatures could damage the coatings fairly rapidly but no damage was observed when the temperatures were below 50°C. Operating temperatures were unlikely to rise above 15°C for most drinking water distribution systems. (2) Corrosion rates diminished with increased coating thickness even when the coatings were damaged to the same degree (exposing the same area of bare pipe). This inference may not be valid when the source of corrosion is either bi-metal galvanic cell or stray currents.

Japan. Since 1979, the Standards of Japan Waterworks Association (Morikawa et al., 1996) has required that all DI pipes of diameter 250 mm and under, be externally coated with a zinc-base primer. Morikawa et al. (1996) reaffirmed that this practice has proved positive in Japan because the zinc coating has a sacrificial anode effect and produced an insulating film even after the oxidation of zinc.

Europe. In a recent internal report on the prevention of internal and external corrosion (Nielsen, 1996), it was reported that DI pipe was coated with semi-permeable zinc paint in most European countries (Denmark, Luxembourg, France, Spain, Sweden, United Kingdom). This zinc coating had replaced bituminous and coal tar varnishes in most countries but several countries continued to use these thermoplastic materials as a protective coating on top of the zinc. Polyethylene sleeves were sometimes used as well.

France. Long-term (19 years) tests, carried out in France (Grandpierre, 1986; Hoffman, 1994) to compare the performance of DI mains protected by combined zinc and bituminous varnish with performance of pipes coated with bituminous paints only, showed that the former performed much better. This improved performance had been demonstrated (Grandpierre, 1986; Hoffman, 1994) by the reduced number of leaks in pipes with double (zinc + bituminous coat) protective systems. However, it was noted that the double protective system might not be as effective in aggressive soils, where the zinc coating is used in conjunction with polyethylene sleeves. (Leroy, 1996), reported on cases in France, where an organic polyurethane cover was used over the zinc coating in pipes installed in very aggressive environments such as coastal marine areas.

CONCLUDING COMMENTS

When DI pipes were introduced in North America in the late 1950s, producers, as well as users, focused mainly on their mechanical performance, which was superior to that of cast iron pipes. Initially, these pipes were laid with minimal or no corrosion protection. Within a few years it became apparent that unprotected DI pipes in aggressive soils tend to corrode at a rate which was at least equal to that observed in CI pipes. However, because DI pipes had smaller wall thickness than their equivalent-size CI pipes, perforation appeared in many cases relatively soon after installation.

Many methods to protect DI pipes from corrosion have been adopted or developed, including passive, active or combinations of both. Many of these methods performed well under some circumstances and poorly under others. It is often difficult, if not impossible, to tell whether a reported success or failure can be attributed to the quality of implementing a method or is inherent in the method's ability to perform under a given set of conditions.

The authors of this review can generally identify three schools of thought, which differ in their approach to the protection of DI water mains:

The first school, most notably represented by the Ductile Iron Pipe Research Association (DIPRA), advocates the exclusive use of PE loose wrap for most installations. They support their views by reiterating that millions of metres of DI pipes have been installed in this way, to the full satisfaction of their owners. They further advocate that DI pipes should not be joint-bonded, because a long, electrically continuous pipe would tend to collect large amounts of stray currents, which would result in corrosion at the point where these currents drain. Only in extreme cases, where a pipe must pass through an area that is prone to high stray currents is it advised to bond the relevant pipe section and make some arrangement of controlled current drainage. At any rate, PE wrap should always be used because it shields the pipe from collecting stray currents (Bond, 1998). It should be pointed out that this shielding effect will also work to shield the pipe from cathodic protection, except at tears and cuts.

The second school, most notably represented by corrosion engineers, does not put much faith in the loose PE wrap. As described earlier, they believe that in the long run, only a well-bonded coating, with the required characteristics can be effective. They often advocate cathodic protection, in addition to traditional bonded coating, for pipes in soils identified as corrosive. Consequently, they design these pipes with joint bonding, which allows for a more efficient cathodic protection system. They also, quite often, shy away from PE wrap because its shielding effect will hinder cathodic protection.

Water utilities in cold climates often use electrical thawing of frozen water services, which requires electrical continuity of water mains. This practice appears to make their networks unsuitable to polyethylene sleeves. Their method of choice would therefor be traditional coating, often combined with cathodic protection.

The third school, to which many European countries (and Japan) belong, advocates a combination of zinc coating, often protected by an additional synthetic polymer coating, such as coal-tar enamel, and a PE wrap (for good measure) as well. In extreme cases, traditional bonded coatings and cathodic protection is recommended.

It seems that a comprehensive study, comparing the three approaches (and one unprotected pipe to benchmark other approaches) under strictly controlled conditions is warranted. It seems further, that each approach may have merit under specific circumstances, and that such a study could alleviate some of the confusion as to when it is most economical to use a certain method rather than another. The measurements and data required to monitor the different approaches in the suggested study are too numerous to list here but would include items (Peabody, 2001) such as potential surveys, DC current and voltages, corrosion rates, coating resistance, etc.

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Figure 1. External corrosion of ductile iron pipe (source: PDL).

Figure 2. Pipe held water under pressure but found to be totally corroded (source: PDL).

Figure 3. Longitudinal split following corrosion initiated by scratch in coating (Ottawa, 1998).

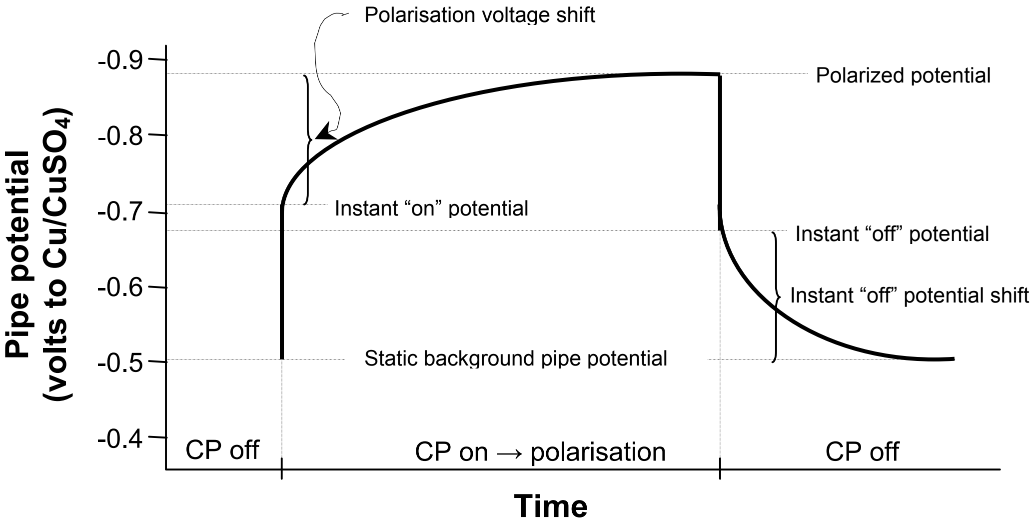
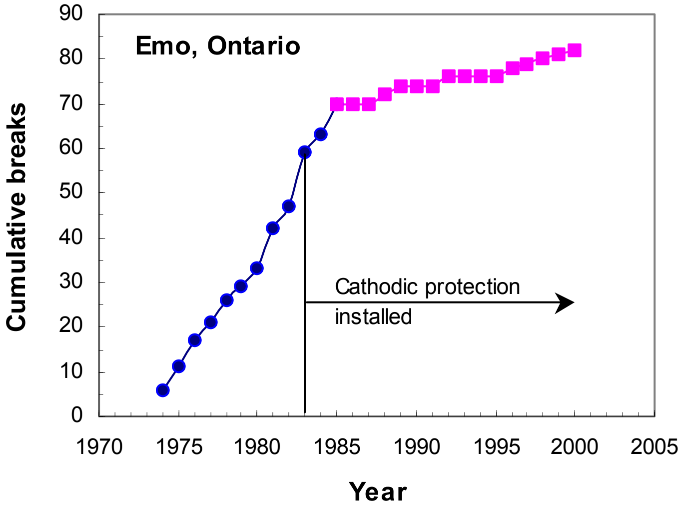


Figure 4. Polarization potential over time when cathodic protection is applied (after Wendorf, 1988).



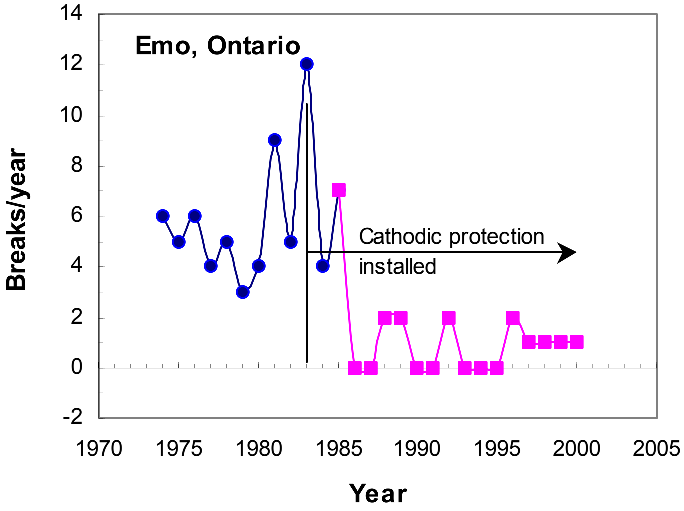


Figure 5. Ductile iron water main breakage history for Emo, Ontario.

Table 1. Coatings for ductile iron pipes in the water industry (Nielsen, 1996)).

		Minimum coating thickness	**Protection quality**
Organic coatings			
Thin	Bitumen, coal-tar	50 µm	Poor
	Bitumen + PE wrap	50 µm + 200 µm	Partly, reduced corrosion rate
Thick	Polyethylene	1.8 mm	Complete
	Epoxy	250 µm	Complete
	Coal-tar epoxy	250 µm	Complete
	Polyurethane	250 µm	Complete
Inorganic coatings			
Cement mortar lining		5 mm	Long-term durability (not at low pH)
Zinc + semi-impermeable surface layer		130 g/m^2 + 50 µm	Temporary/long-term (not at low pH)
Zinc + PE encasement (wrap)		130 g/m^2 + 200 µm	Temporary/long-term with reduced corrosion rates

Table 2. Typical characteristics of anodes.

Anode Material	**Potential**[1] **(mV)**	**Efficiency (%)**	**Actual output (amp-hr/lb.)**[2]	**Consumption rate (lb./amp-yr.)**[3]	**Polarisation (mV)**[4]
Zinc (high purity)	-1100	90	335	26.2	0
Magnesium (standard)	-1550	50	500	17.5	100
Magnesium (high potential)	-1800	50	500	17.5	100
Al-Zn-In	-1150	85	1150	7.6	-

[1] in reference to Cu/CuSO$_4$ electrode.
[2] No of hours /unit anode weight to sustain a production of one ampere before anode depletion.
[3] Anode weight required to produce one ampere over one year before anode depletion.
[4] Potential difference between anode and protected pipe.

Table 3. Comparison of galvanic and impressed current methods.

Issue	Galvanic	Impressed Current
Protective current and driving potential	Provides low current (up to 0.5 amperes for a single anode in very low resistivity soils), and low driving potential (up to a few hundred millivolts).	Can provide (theoretically) unlimited current and very high potential requirements.
Soil	Suitable for soils with relatively low resistivity (because of low current output), up to a few thousand ohm-cm.	Can be designed for low and high resistivity soils.
Power	No power source required	Power source required
Design	Anodes distributed along, and always close to protected structure, thus many are required.	Can be designed to protect large areas from a single or relatively few installations.
Interference	Not likely to be a problem because of close proximity to protected structure.	Can be a problem in systems where protection is provided from a distance.
Maintenance	Require only replacement when anodes are consumed, frequencies typically vary from a few years to 25-30 years, depending on conditions.	Rectifier requires maintenance and can be subject to vandalism. If power source is AC then subject to power failure, if batteries or fuel cell then regular replacement required.
Over protection	Not likely due to low potential and current output.	If not designed properly, or if conditions change, over protection can cause hydrogen embrittlement and disbondment of coating.
Stray currents	Not very likely to be a problem because of close proximity and low potential and output currents.	Proper design is required to ensure that other structures are not damaged by stray currents.
Cost	Low cost per unit installed, low cost for maintenance. High cost per ampere produced.	High cost per unit installed, high maintenance cost. Low cost per ampere produced.
Other considerations	Suitable for pipes in relatively low resistivity soils. If protecting an existing pipe (retrofit) which is not electrically continuous then every pipe segment has to be connected to an anode (or adjacent segments have to be electrically bonded). Suitable for “hot spot” protection. Suitable for areas where other metal structures exist, which may be damaged by stray currents. Good records are required because often buried anodes are forgotten and abandoned.	Suitable for pipes in high resistivity soils. Suitable for large structures that require high current output (e.g., large, uncoated pipes). Not suitable for pipes that are not electrically continuous. Rectifier is a substantial piece of equipment, not very likely to be forgotten or abandoned.

Table 4. Performance of CP in DI pipes in Swindon and Severn-Trent (Green et al. (1992), Green (1993), Green and De Rosa (1994)).

Case study	Pipe description	Soil type/ resistivity	Anode description	Copper sulphate electrode potential	Breaks/km/year	
					Before	After
Evaluation study	10 m long 150 mm DI pipe	clay / 1200 to 1600 Ω-cm	7.7 kg Mg anode at pipe end 0.5 to 1.0 m from crown of pipe	-850 mV after 2 days	-	-
Pilot study – rural zone	200 m long 200 mm unwrapped DI pipe	3000 to 12000 Ω-cm	Mg anode at spigot end	-620 mV (prior) -850 mV after 15 days	27	4.5
Pilot study – urban zone	160 m long 200 mm unwrapped DI pipe	5000 to 11000 Ω-cm	Mg anode at midpoint	-550 mV (prior) -850 mV after 45 days	10	1.5
Full-scale trial – urban and rural zones	1.4 km long 227 mm unwrapped DI pipe	industrial waste and native soils / 1300 to 9000 Ω-cm	260 Mg anodes, one on each pipe length of 5.5 m	-850 mV in 75 % of mains (totally protected); -750 mV in 25% of mains (partially protected)	1.3	0.5
Area trial – urban and industrial zones	22 km long unwrapped DI pipe	-	5000 Mg anodes, one on each pipe length of 5.5 m	-850 mV in 99.4 % of mains (totally protected); > -850 mV in 0.6% of mains partially protected	0.42	0.09

Table 5. Performance of ductile iron pipes in Australia (Ellis et al. (1998)).

Trench		**1**	**2**	**3**	**4**	**5**
Backfill profile	Backfill below ground level	Clay	Clay	Clay	Clay	Clay
	Backfill above DI pipe	Sand (200 Ω-cm, pH 8)	Sand (200 Ω-cm pH 8)	Quarry rubble	Clay (100 Ω-cm pH 8)	Clay (100 Ω-cm pH 9)
	In contact with PE encasement /DI pipe	Sand (300 Ω-cm pH 8)	Sand (200 Ω-cm pH 8)	Quarry rubble	Clay (100 Ω-cm pH 9)	Clay (100 Ω-cm pH 8)
	Soil from side of trench	Silty clay (200 Ω-cm pH 8)	Silty clay with gravel (200 Ω-cm pH 9)	Clay	Clay	clay
Corrosion protection		PE encasement	No	PE encasement	PE encasement	No
PE encasement damaged?		Yes	n/a	Yes on underside	Yes	n/a
Corrosion rate (mm/year)	5 years	0.2	0.6	0.3	0.38	0.64
	10 years	0.2	0.52	0.25	0.43	>0.61
Maximum pit depth (mm)	5 years	1	3	1.5	1.9	3.2
	10 years	2	5.2	2.5	4.3	6.1
Galvanic corrosion near tapping ferrule		No	No	Yes	No	Yes

Table 6. Performance of ductile iron pipes in US (Jackson (2000)).

Utility	**Installed**	**Pipe Type**	**Pipe size/class**	**PE encase**	**CP**	**Bonded Coating**	**Soil type**	**Experience**	**Now use PVC**
1	-	DI	Class 56	Yes		-	Corrosive	Good	-
2	1986	DI	14”	Yes		-	-	Good	Yes
3		DI	24”	Yes		-	Corrosive	Poor	Dist
4	-	DI	>12”	Double	Yes	-	Corrosive	Good	<=12”-
5		DI	-	-	-	-	-	-	Yes
6	1965	DI		Double	No	-	Corrosive	Good	-
7	1979	DI	-	Yes	No-	-	Corrosive	Good	-
8	-	DI	Class 51	Yes	No	-	-	Good	Dist
9a	-	DI	Class 52	Double	Yes	-	-	Good	-
9b	1960	DI	-	No	-	-	Corrosive	Poor	-
9c	-	Steel	-	-	Yes	-	Corrosive	Good	-
10a	-	DI	-	No	-	-	Corrosive	Poor	Yes
10b	1942	Steel	-	No	Yes	-	Corrosive	Yes	
11a	-	AC	-	-	-	-	-	Good	No
11b	-	Steel	>16”	-	No	No	-	Good	-
12	-	DI	-	Yes	HS	-	Corrosive	Good	-
13a	1967	DI	24”	Yes	-	-	Corrosive	Very Poor	-
13b	>1980	Steel	-	No	Yes	Yes	Corrosive	Good	-
14	1976 -	DI	8”, 12”	Yes	-	-	Corrosive	Very Poor	-
1	1991	DI	16”	Yes	Yes	-	Corrosive	Good	Yes
2a	< 1985	DI	-	No	No	-	Corrosive	Poor	-
2b	> 1985	DI	-	Double	Yes	-	Corrosive	Good	-
3	1982	DI	-	Yes	Yes	-	Corrosive	Good	-
4	-	DI	-	Yes	-	-	Mildly	Good	-
5a	-	DI	Small	Yes	No	-	Mildly	Good	
5b	-	DI	Large	No	Yes	Yes	Mildly	Good	-
6a	1947-	CI	Small	Yes	No	No	Limestone	Good	Yes
6b	-	Steel	Large	-	Yes	Yes	Limestone	Good	-
7	-	DI	-	Yes	Yes	Yes	-	Good	-
9	-	DI	Small	No	Yes	-	Corrosive	Good	Yes
10	1960-	DI	-	No	-	-	Corrosive	Poor	Yes
11	-	DI	-	No	-	-	Very	Mixed	Yes