The Corrosion of Municipal Iron Watermains*

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Introduction

THE COST OF REPAIRING OR REPLACING watermain piping perforated by corrosion is becoming a major item in many municipal budgets, and correspondingly in most individuals' municipal taxes. In metropolitan Toronto, for instance, it is estimated that over $5 million will be spent in 1983 for repair, replacement, or renewal of domestic water piping systems. Winnipeg, which has, perhaps, the highest failure rate of any Canadian city,[1] had approximately 2200 failures in 1982, requiring a $7.7 million program just to limit annual leaks to the 2200 level, which is a leak frequency of 1.1/km/y. Many cities such as Scarborough (North York), Edmonton, Calgary, and Saskatoon, have system leak frequencies of 0.5/km/y. In most of these cases, the water piping system is comprised principally of a mixture of grey cast iron and ductile iron. Although it is understandable that cast iron failures occur both from a mechanical and age point of view, one alarming experience is that ductile iron which was installed in the late 1960s and 1970s is also exhibiting a significant failure rate. Recent investigations, supported by previous studies, have indicated that corrosion is a primary cause of failures on both grey cast and ductile iron piping. As this fact has become recognized more widely by the waterworks industry, so has the need for corrosion prevention solutions.

Historical

It is ironic that much of the corrosion prevention technology which can be used to combat this problem owes its development to the waterworks industry. Near the turn of the century, prior to the growth of the oil and gas pipeline industry, corrosion prevention methods were being developed primarily on water piping systems. The watermains in some urban areas at the time were being ravaged by the deleterious effects of stray currents arising from DC electric transit systems. Out of these early challenges came numerous guidelines, standards, and recommendations regarding the mitigation of corrosion and the application of cathodic protection. Investigators such as Kuhn were instrumental in developing the −850 mV cathodic protection criterion which now enjoys universal usage.[2] Despite this early work, almost 50 years later the waterworks industry is facing ever-increasing expenditures occasioned by watermain corrosion which in some municipalities is reaching enormous proportions.

How is it that the industry which was the cradle of early corrosion prevention technology could be in such need of this same technology developed nearly a half century ago? The answer probably rests in the general lack of understanding as to the corrosion behavior of grey cast iron.

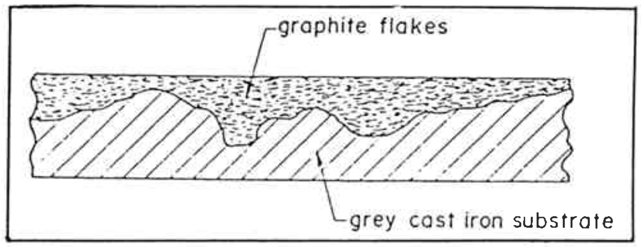

FIGURE 1 — Graphitization of cast iron.

Corrosion Behavior of Grey Cast Iron

Grey cast iron, an iron-graphite material, corrodes at about the same rate as wrought iron when exposed to similar environments.[3] A unique characteristic of the corrosion of grey cast iron is the resultant graphitization of the material. When corrosion occurs, the iron goes into solution, leaving behind the graphite flakes. Over a period of time, the cast iron structure becomes a composite of grey cast iron and a graphite matrix, as shown in Figure 1.

The graphite flakes left behind not only retain the shape of the original casting, but also camouflage the roughened substrate, and thus the true extent of corrosion is not readily apparent. Because of the relative obscurity of the corrosion damage to the naked eye, the magnitude of corrosion, and hence an appreciation for grey cast iron's corrosion vulnerability, has gone relatively unnoticed despite efforts to arouse the industry by Fitzgerald in the late 1960s.[4]

The notoriously brittle nature of cast iron has worked against the increased awareness of its corrosion susceptibility. In fact, failures on cast iron piping systems are called "breaks." This term, used throughout the waterworks industry, by definition ignores the contribution of corrosion to most pipeline failures and implies that all failures are caused by the brittle nature of cast iron. Work by Remus,[5] based on data covering a 40 year period in Detroit clearly dispelled this erroneous yet generally held belief. He was able to demonstrate, as illustrated in Figure 2, that the break curve was increasing with

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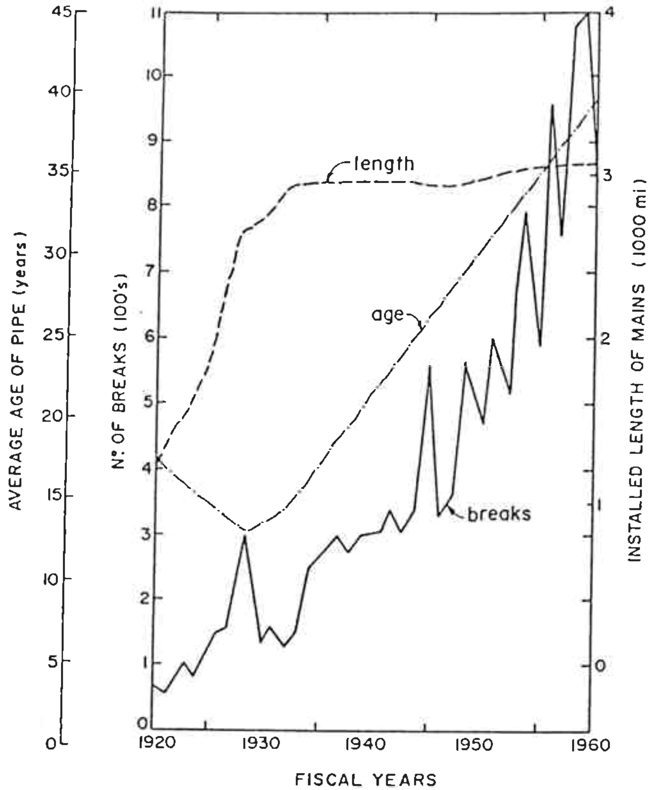

FIGURE 2 — Cast iron main break record in Detroit.

time despite the fact that the total length of piping was relatively constant. Increasing breaks with increasing time is typical of a piping system experiencing corrosion failures. Had the breaks been caused by brittleness only, the break curve would have paralleled the length curve.

Oddly enough, the true contribution of corrosion to grey cast iron failure is only being recognized on an industry-wide scale because of the seemingly premature corrosion failures experienced on ductile iron piping installed during the 1960s and 1970s. Had grey cast iron corrosion been recognized earlier, there is no doubt that the ductile iron corrosion problem could have been avoided.

The corrosion penetration of buried iron is not particularly dependent on soil composition, but varies more dramatically with the physical and chemical properties of the soil. The depth of penetration is a function of time given by the following general equation:

$$P = kT^n \quad (1)$$

where P = depth of the deepest pit in time (T) and k and n are constants.

For normally encountered soils, the value of n is less than one, which produces a depth vs time curve typified in Figure 3.

Corrosion Behavior of Ductile Iron

This relationship shown in Figure 3 has serious implications concerning the time to failure of grey cast iron vs ductile iron. The wall thickness of ductile iron piping is as much as 50% thinner for equivalent nominal pipe diameter; consequently it will perforate in a much shorter time. Furthermore, since the curve is nonlinear, the time to perforation on ductile iron piping (t_{DI}) is a small fraction of the time to penetration on grey cast iron (t_{CI}). This partially explains the appearance of corrosion failures on ductile iron piping after only a few years of service.

Galvanic Corrosion of Water Piping

The corrosion rate of buried iron piping is also affected by factors other than differences in soil composition. A water

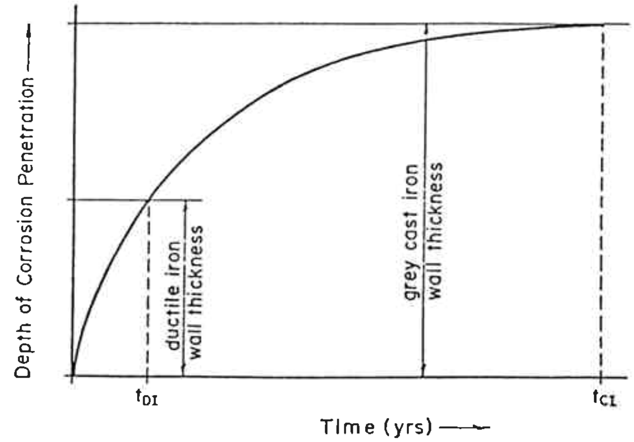

FIGURE 3 — Depth of corrosion penetration vs time.

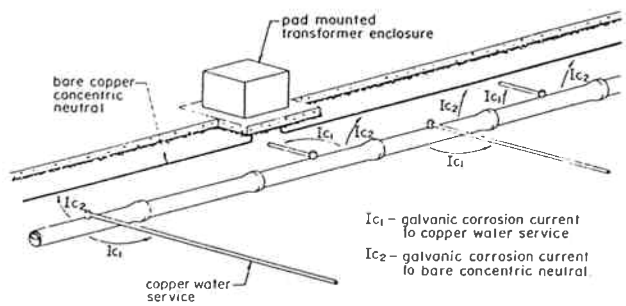

FIGURE 4 — Typical galvanic corrosion activity on iron watermains.

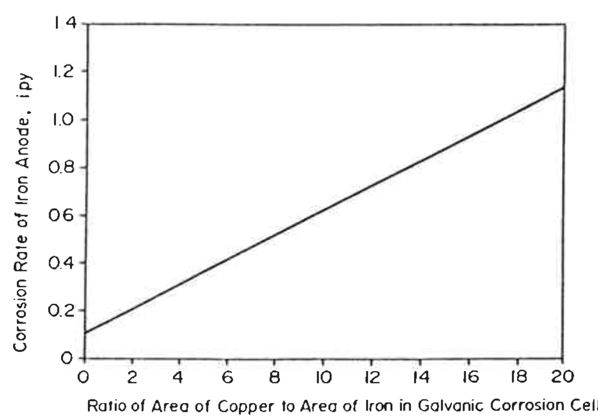

FIGURE 5 — Effect of copper:iron surface area ratio on corrosion rate of iron in seawater.[6]

distribution system is not a homogeneous metallic system because copper piping is used universally for customer services. This mixed metal system (Figure 4) accelerates corrosion of the iron piping which participates as the anode of a galvanic corrosion cell in which the copper acts as the cathode. The copper service receives current produced by the corroding iron, essentially reducing the corrosion rate of copper and giving it an unearned reputation for excellent corrosion resistance in soil environments. Underground bare copper concentric neutral cables installed by electrical utilities can accelerate the corrosion of iron piping more because the copper neutral, having been interconnected to the water piping at each residence, also participates as a cathode.

Influence of Copper:Iron Surface Area Ratio

As the copper iron surface area ratio increases, so does the rate of corrosion of iron (Figure 5).

Protective coatings applied to cast or ductile iron, although reducing the overall weight loss of iron caused by corrosion, generally accelerates the localized corrosion rate at breaks in the coating. The net result of the protective coating is to reduce the area of the iron anode which increases the copper:iron surface area ratio, and greatly increases the penetration rate. Paradoxically, as the coating quality and integrity is increased, so too is the penetration rate at the fewer and smaller anode sites. Accordingly, an applied protective coating accelerates the penetration rate instead of reducing it.

Road Salt Pollution Increases Galvanic Corrosion

A galvanic corrosion cell causes corrosion current to flow through the soil. The current magnitude and, hence, the corrosion weight loss depends partly on the electrical resistance of the soil current paths. Accordingly, the corrosion rate increases as the soil resistivity decreases. In most urban areas, the soil electrical resistivity has been steadily decreasing over the years because of soil contamination, principally by road deicing salts. It is not unusual to discover chloride concentrations of 1000 ppm or greater in the vicinity of water distribution piping. The increasing concentration of the chloride ion in soils has reduced the soil resistivity, causing an increase in the iron corrosion rate.

Corrosion Prevention by Cathodic Protection

Recognition of the extent of corrosion damage to the watermains has come late to some municipalities which are now facing a financial struggle to simply keep the failure rate from growing. The remedial options are few. Renewal is the last resort and the most expensive method, and most utilities can afford to replace only a small fraction of their total piping system on an annual basis. One powerful and less expensive remedial method is the use of cathodic protection. This electrochemical technique, widely used on oil and gas transmission and distribution piping, can, with a few modifications, be used to either slow the overall corrosion rate or in fact to stop the corrosion. Two basic cathodic protection systems—namely, sacrificial and impressed current—are traditionally used, but only the sacrificial system is appropriate for corrosion prevention on cast or ductile iron piping systems since the piping is seldom electrically continuous and therefore susceptible, as are adjacent structures, to stray current corrosion if an impressed current system is installed.

Sacrificial protection uses galvanic anodes of zinc or magnesium, packaged in a low resistivity backfill which has a chemical composition that inhibits anode polarization. Zinc has a lower corrosion potential than magnesium and a lower protective current output so that it is practical only in low resistivity soils (generally less than 2000 ohm•cm) or where only a small cathodic protection current is required. Magnesium anodes have a larger current output and are applicable over a wider range of soil resistivities and watermain sizes.

In either case, the packaged galvanic anode is connected directly to the watermain at predetermined intervals, depending on the length of piping to be protected, on pipe diameter, on pipe coating quality, and on the soil resistivity. To decrease the corrosion rate to a negligible level, the water piping must be polarized to -850 mV with respect to a copper/copper sulfate electrode.

The galvanic anodes can be incorporated in a variety of maintenance programs which have varying degrees of effectiveness. Protection applied in a hot spot program involves attaching one or more sactificial anodes to the watermain at the time of leak repair prior to backfilling the excavation. This program will not completely eliminate corrosion, but will slow it down dramatically in the vicinity of the leak. A more comprehensive program consists of installing anodes at close intervals along a length of existing watermain which has exhibited a high leak density. Figure 6 illustrates the dramatic

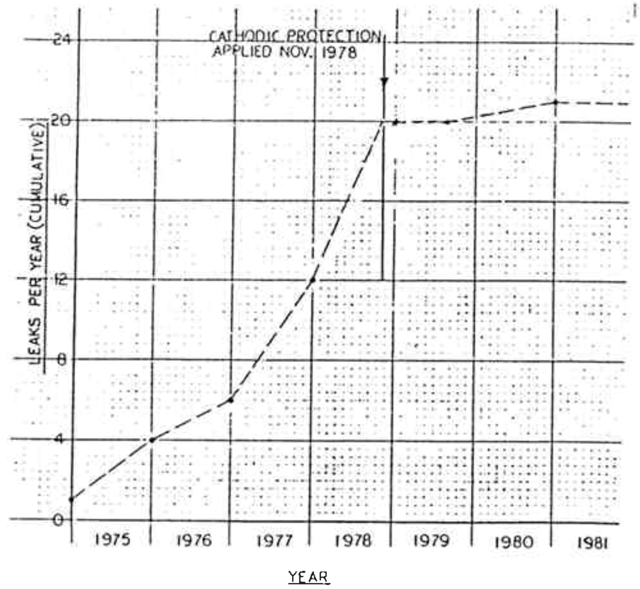

FIGURE 6 — Effect of leak frequency of ductile iron piping after applying cathodic protection using magnesium anodes.

success of this approach on a ductile iron residential watermain.

Although cathodic protection of ductile iron piping can stop the corrosion failure successfully, this technique does not necessarily apply to extensively corroded grey cast iron. Corroded grey cast iron is much more sensitive to physical disturbance and will therefore continue to break in proportion to the mechanical force applied, regardless as to whether corrosion has been halted. On severely graphitized cast iron, it is questionable as to whether or not cathodic protection can stop corrosion at the interface between the graphite and iron. Accordingly, cathodic protection cannot be routinely applied to grey cast iron systems, and any proposed use of cathodic protection for this purpose must be researched carefully to demonstrate the relative benefit.

In areas where the watermain failure frequency is significant, consideration must be given to the piping material for new or replacement programs. Clearly, where ductile iron is to be used, it should be cathodically protected and, under certain economic circumstances, coated and electrically isolated as well, although the latter two requirements are optional and not absolutely necessary to achieve effective protection. If nonmetallic piping materials such as asbestos cement, polyvinyl chloride, polyethylene, etc., are chosen, then the metallic fittings such as iron tees, elbows, valves, hydrant assemblies, and copper services should be cathodically protected. Zinc anodes, having a low current output and a long life, are ideal for this purpose (Figure 7).

The cathodic protection of copper services not connected to iron mains is important because the copper will be susceptible to soil corrosion. Furthermore, as the nonmetallic watermains are no longer electrically continuous, copper services are more apt to transfer AC current to the soil, thus causing AC corrosion. Cathodic protection of the copper will ameliorate AC corrosion attack as well as the natural soil corrosion.

Summary

In summary, the corrosion problem which waterworks utilities are facing on a national basis is the result of many years of questionable practice and standards. Both grey cast iron and ductile iron have a similar, natural tendency to corrode in soil. An accelerating factor is contact with copper in the soil.

The rate of corrosion failures has been accelerated in recent years by an increased amount of copper as a result of the higher density of residential services and the presence of

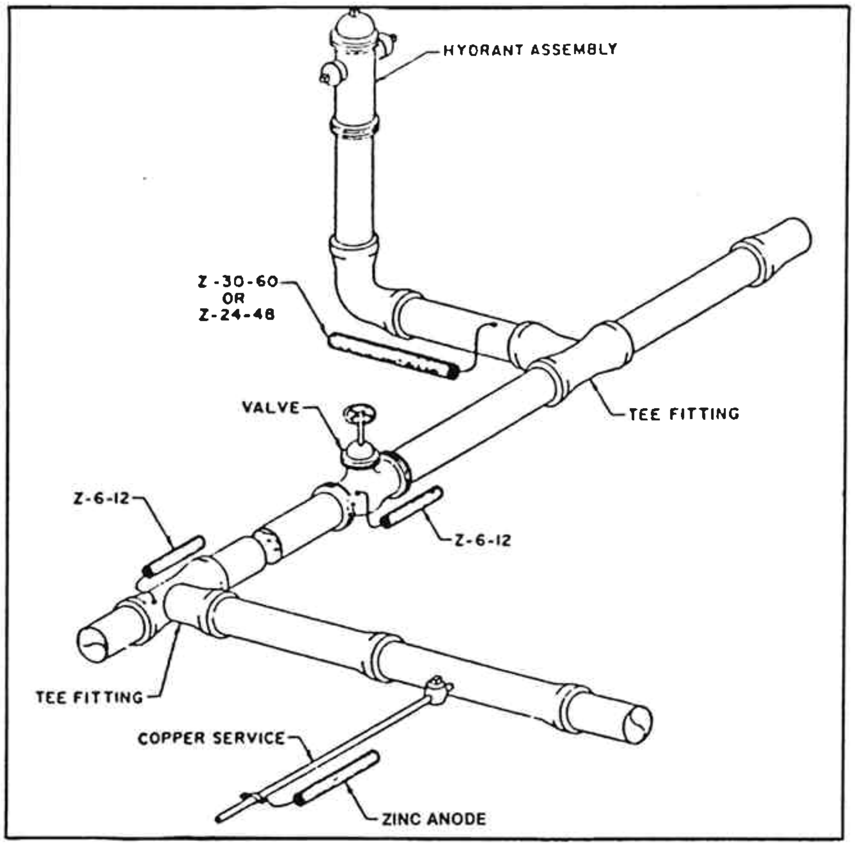

FIGURE 7 — Cathodic protection of iron fittings and copper services on nonmetallic piping.

underground concentric neutral cables, by the application of protective coatings to water distribution piping, and by increased soil corrosivity occasioned by greater soil contamination originating principally from road deicing salts. The early and seemingly premature failure of ductile iron is partially caused by the foregoing factors, but is primarily the result of its much thinner wall thickness. There is no doubt that, had it been realized that corrosion was a primary cause of grey cast iron break failures, thin wall ductile iron would not have gained general acceptance throughout the industry. On the other hand, the corrosion of ductile iron has awakened the waterworks industry, after half a century, to an appreciation for the potential severity of corrosion.

Looking ahead, the waterworks departments in many Canadian cities will be encountering increased failure rates on both grey cast and ductile iron piping, reminiscent of the extensive failures in the early 1900s caused by stray current corrosion from electric transit systems. Aside from piping renewal, cathodic protection (especially on ductile iron piping systems) is an effective and economic remedial method. To combat the corrosion effectively, waterworks personnel will have to reacquaint themselves with this technique, which owes much of its early development to the efforts of waterworks personnel over 50 years ago.

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