THE EFFECT OF COPPER

ON THE CORROSION OF IRON WATERMAINS

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ABSTRACT

The data obtained from several municipal watermain corrosion studies in the Province of Ontario is presented. This data corroborates the findings of a previous study indicating that the galvanic couple formed by the connection of copper service piping to iron watermains is a principal factor controlling the watermain corrosion rates.[1] Soil electrical resistivity is found to be of major importance only where this galvanic couple exists. A simple means of estimating the integrity of a watermain based on soil resistivity and service type is also presented.

Keywords: copper, corrosion rates, galvanic effects, graphitization, lead, resistivity, water pipelines

INTRODUCTION

Although early studies had shown corrosion to be the principal cause of failures on iron watermains,[2,3] this fact was not widely recognized by the waterworks industry until recently. The major reason is that in the case of grey cast iron piping, the iron corrodes leaving behind a hard but weak matrix of graphite flakes which retain the shape and appearance of the original pipe casting, thereby concealing the true extent of the corrosion damage. Figure 1 shows a failure on a 6" diameter cast iron pipe that was described in the repair records as being simply a circumferential break (ie. brittle fracture). After sandblasting the pipe to remove the graphitic corrosion product, the cause of this break is actually seen to be a corrosion perforation, from which the crack subsequently propagated (Figure 2).

Corrosion resulting from the connection of dissimilar metals was recognized as early as 1824, when Sir Humphrey Davy discovered that zinc corroded at a higher rate when it was connected to copper. Since that time it has become generally well known that the more electronegative metal in a galvanic couple (the anode) will corrode at a rate roughly proportional to the cathode to anode surface area ratio, the potential difference between the two metals, and the conductivity of the electrolyte.

In spite of this, the use of copper water service piping on iron watermains has gained universal acceptance, perhaps due to the general lack of concern that the waterworks industry had for corrosion. Lead service piping, which was widely used before copper piping, has a galvanic potential similar to that of un-graphitized cast iron, whereas copper is approximately 300 mV more electropositive than iron (see Figure 3).[4] To make matters worse, copper services are installed in the ground uncoated, whereas iron watermains are almost always supplied with a thin, bituminous coating for asthetic reasons. This serves only to increase the cathode to anode surface area ratio, resulting in accelerated corrosion rates at coating defects (see Figure 4). Coating damage, perhaps caused by a chain or a sling during construction, resulted in the row of concentrated pits shown in Figure 5, leading to the premature failure of this cast iron pipe. The common practice among electrical utilites of interconnecting the electrical neutral system with the water distribution system futher increases the copper to iron surface area ratio, particularly where bare AC power copper concentric neutral cables have been installed, as shown in Figure 6.

Beginning in 1987, municipalities in the Province of Ontario were able to apply for financial assistance from the provincial government to assess the condition of their infrastructures and to determine their needs for rehabilitation. An important component of every *needs* study is the investigation of the corrosion problems experienced on the water distribution system. This typically involves a review of the municipality's construction and repair methods and watermain failure history, as well as a sampling program in which the corrosion characteristics of several pipe samples are correlated with soil corrosivity and other factors. The objectives of such a study are to identify the most important factors contributing to watermain corrosion failures, to provide a general assessment of the integrity of this system, and to prioritize the implementation of remedial measures based upon these findings.

WATERMAIN CORROSION INVESTIGATION PROCEDURE

Sample locations were selectively chosen to provide a representative cross-section of the conditions to which a watermain could be exposed. This included choosing some ductile iron samples as well as some grey cast iron samples, some samples from copper service areas as well as from lead service areas, and areas having high failure rates as well as low. Samples were also taken on a random basis whenever waterworks personnel had a watermain exposed for a repair or modification.

A pipe sample two to three feet in length was obtained from each location, as was a corresponding soil sample. Each soil sample was taken at the edge of the excavation from the undisturbed soil which was still in contact with the pipe.

All soil samples were analyzed for electrical resisitivity, pH, chloride ion concentration, and the presence of sulphide ions. Soil moisture content and soil composition were observed qualitatively. The pipe samples were inspected and photographed in the *as-found* condition and were sandblasted to remove all earth, coating, and corrosion product adhering to the metal. The samples were then rephotographed, and evaluated in terms of maximum pit depth, average pit depth, and percent surface area pitted.

RESULTS

The data for sixty pipe and soil samples, representing six municipal watermain corrosion studies, has been tabulated. Although these studies covered internal corrosion as well as external corrosion, only the results from the external studies will be presented here.

Of the various corrosion characteristics which were measured, the maximum external pit depth is considered to be the most important indicator, since the extent of corrosion penetration ultimately determines the time to watermain failure. Exceptions to this are where pits have not fully penetrated the pipe wall but have resulted in a brittle fracture failure as shown in Figure 5, or where a pit has penetrated the pipe wall but the failure has been deferred by a layer of graphitic corrosion product (Figure 1) or an internal lining. As these exceptions should balance out somewhat, the maximum external pit depth remains the single most important indicator of corrosion severity.

The *maximum pit penetration rate* (MPPR) was calculated for each sample as being the maximum pit depth divided by the pipe age, which implies that the pit growth rate is constant. Typically, the depth of pit penetration decreases exponentially with time, but there is insufficient information available in this study to characterize this exponential relationship. The MPPRs were graphically correlated with each of the measured and observed soil characteristics, as well as with the materials used for the watermains and water services. The only factors which were found to have an effect on the MPPRs for this study group were service piping type and soil electrical resistivity. The MPPRs are plotted against soil resistivity for both lead and copper services in Figure 7. A portion of the samples had either been connected to a mixture of copper and lead services, or were originally connected to lead services which in recent years were changed over to copper. The MPPRs for these samples are shown as a third category.

Of the 60 pipe samples analyzed, those which were connected to copper services had an average MPPR of 6.4 mils/year, compared to 2.4 mils/year for those connected to lead services. Both of these sample groups corresponded to an average soil resistivity of 2400 Ω-cm. The samples taken from mains having a mixture of copper and lead services had an average MPPR of 2.7 mils/year, which is slightly higher than that for the lead group, although the average resistivity associated with this sample group is higher at 4200 Ω-cm.

The data in Figure 7 also shows that while a high soil resistivity results in a low corrosion rate, low resistivity does not necessarily result in a high corrosion rate. This is particularly true of the data for the iron-copper couple, which form the majority of the upper boundary of this plot. The data for the lead-copper couple, however, seems to be less dependent upon resistivity. Although this may in part be due to a lack of sufficient data, it is nevertheless consistent with the concept that resistivity is of major importance only where corrosion occurs as the result of the formation of a macrocell, such as a galvanic couple.

CASE HISTORY

A needs study was conducted for the Regional Municipality of Ottawa-Carleton (RMOC) in 1988 and 1989.[5] The RMOC's water distribution system is 2,000 km in length, portions of which are over 100 years old, and has a replacement value of $800,000,000.

A database was prepared for all available information regarding the existing watermains (age, class, lining, bedding, types of joints and services, etc.) and their failure histories (date of break and description of failure). While the analysis of this information yielded several interesting observations, perhaps the most significant is that illustrated by Figure 8. This plot shows that with the exception of the very old watermains (pre-1913), only the mains installed in the 1950's and later exhibit a significant failure rate. The time chart at the top of the figure indicates three changes in construction methods coincident with the increased failure rate: sand bedding replaced native bedding, mechanical joints replaced leaded joints, and copper services were used rather than lead services.

A watermain corrosion investigation was conducted in which twenty pipe and soil samples were analyzed. The ten pipe samples exhibiting the highest MPPRs (7 mils/year to 24 mils/year) had all been connected to copper service piping, while the five lowest MPPRs (1.5 mils/year to 2.6 mils/year) were associated with lead services. The average MPPR for the copper service group was found to be 12.4 mils/year, four times higher than the average MPPR for the lead service group (the associated average soil resistivities were 1500 Ω-cm and 1100 Ω-cm respectively). This confirmed what the analysis of the failure history records suggested; the coupling of copper service piping to the iron watermains is principally responsible for the majority of watermain failures. Furthermore, while only three of the twenty pipe samples were from neighbourhoods where bare copper concentric neutral cables were used, one of these samples had the highest overall MPPR, another had the third highest, thereby lending some support to the importance of the copper to iron surface area ratio.

PREPARATION OF A CORROSION INDEX

It is proposed that the relationship observed between the MPPR, the soil resistivity, and the type of service piping can be used to formulate a corrosion index by which watermain integrity can be estimated, and which would form the basis for the prioritized implementation of cathodic protection to watermains which had not yet begun to exhibit a significant failure frequency.

To serve as an illustration, the data given in Figure 7 will be considered to represent a single municipality. The first approximation for the index is simply based upon the average MPPRs associated with both lead and copper services.

$$\text{Average MPPR} = 2.4 \text{ (mils/year)} \cdot K_s \qquad (1)$$

where K_s is the service piping factor, equalling 2.7 where copper services are used (ie. 6.4/2.4), or 1 where lead services are used. The rate of 2.4 mils/year may be thought of as the background corrosion rate, or the average rate at which a pit will penetrate the pipe wall in the absence of strong galvanic coupling.

The relationship between MPPR and soil resistivity must also be accounted for. As shown in Figure 7, all data is found to fit beneath the line having the equation

$$\text{MPPR (high upper limit)} = 25 - (\rho / 600) \qquad (2)$$

although the majority of the data (95%) fits beneath a second line defined by

$$\text{MPPR (low upper limit)} = 20 - (\rho / 600) \qquad (3)$$

where ρ is the soil resistivity in Ω-cm.

Combining Equation (1) with Equation (3), the upper limit on the MPPR for a particular soil resistivity and water service type would be

$$K_c = [20 - (\rho / 600)] \cdot (K_s/2.7) \tag{4}$$

where K_c is the watermain corrosion index in mils/year. As previously noted, a clear relationship does not exist between the MPPR and soil resistivity for the lead/iron couple, and hence there is little justification for applying the slope in Equation 3 for use with this case. However, when plotted on Figure 7, it is seen that equation (4) does indeed account for the upper limit on the MPPRs for the lead/iron couples in 80% of the cases, and so it shall be considered empirically valid.

Finally, on the basis of the assumptions that the rate of pit penetration is constant and that 100% pit penetration of the pipe wall is equivalent to a failure, then the mean time to a watermain's first failure can be estimated as

$$\text{Mean Time to First Failure (years)} = \frac{\text{Wall Thickness (mils)}}{K_c} - \text{Pipe Age (years)} \tag{5}$$

A graphical alternative to Equation 5 is shown in Figure 9. By associating a watermain of a known age and wall thickness with its K_c value, the integrity of the pipe can be estimated on the chart by observing its proximity to the failure zone. The upper curve is simply a plot of $1/K_c$, which gives the age at which a pipe of a specific wall thickness will fail given its K_c value. The lower curve is a vertical translation of the upper curve by 5 units, corresponding to the difference between Equations 2 and 3.

This graph should also be used as a means for prioritizing the application of corrosion control measures such as cathodic protection. Presumably, a watermain sitting to the left of the failure zone would not be a priority for protection, whereas a watermain sitting on the edge of the failure zone should receive a high priority. Watermains well inside the failure zone are overdue to receive cathodic protection, and would possibly be candidates for replacement.

SUMMARY

An analysis of pipe and soil data obtained from several municipal watermain studies has shown that corrosion rates on iron pipes coupled to copper water services are significantly higher than on those connected to lead services, in this particular case by a factor of 2.7 times. It was also found that watermains in high resistivity soils experienced a low corrosion rate, but that in low resistivity soils, the rate could be either low or high. For the study group involving the copper-iron couples, the maximum pit penetrations varied from 1 to 24 mils/year in soils having a resistivity of less than 1000 Ω-cm. The data did not conclusively indicate a relationship between corrosion rates and resistivity for the lead-iron couples.

For one municipality in particular, the copper-iron galvanic couple was proven to be the single most important cause of watermain corrosion, and consequently, the principal reason for watermain failures.

A method for producing a corrosion index to assess watermain integrity was developed using pipe and soil sample data. The data available at the time of this study showed this index to be a function of soil resistivity and galvanic coupling only. It is proposed that if a municipality were to routinely take pipe and soil samples during the course of watermain repair work, enough data would soon be available to account for secondary corrosive effects, cathode to anode surface area ratios, and to generally refine the accuracy of this prediction technique.

ACKNOWLEDGEMENTS

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Figure 1 - Grey Cast Iron
Watermain Failure (Before Sandblasting)

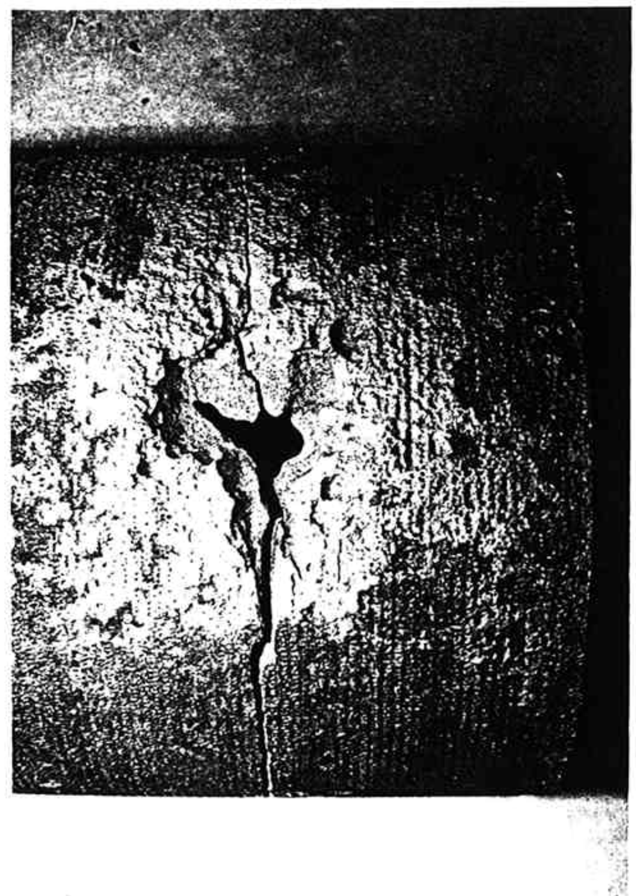

Figure 2 - Grey Cast Iron
Watermain Failure (After Sandblasting)

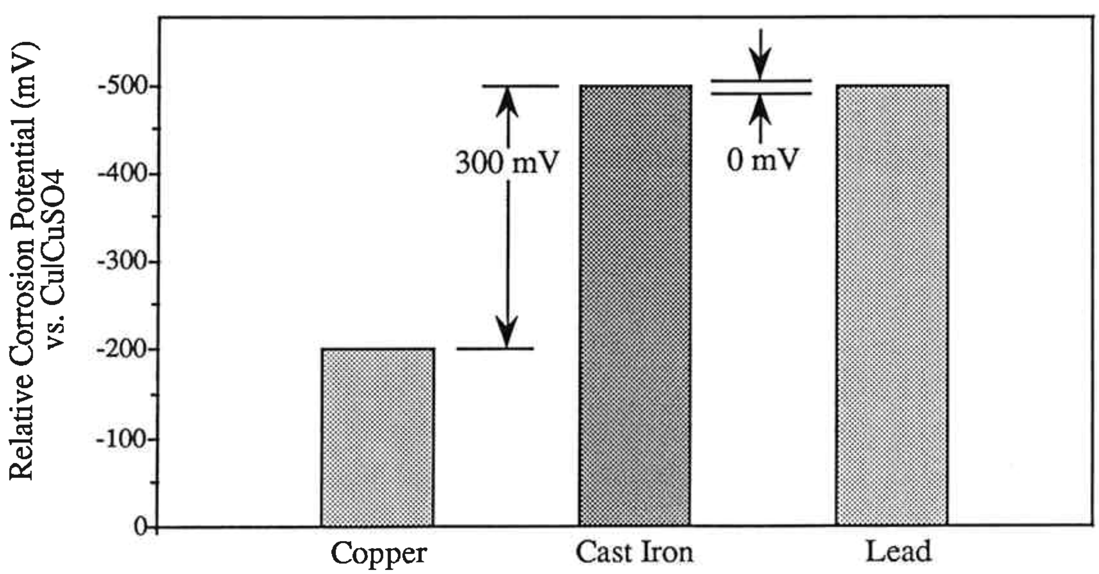

Figure 3 - Potential Differences Between Common Water Piping Materials

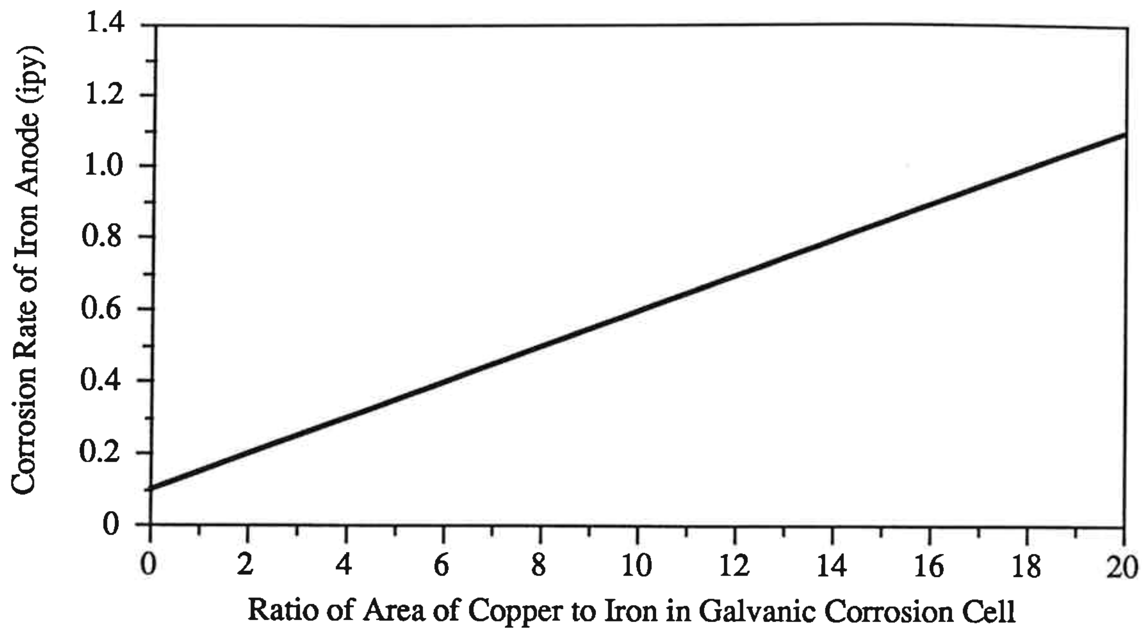

Figure 4 - Effect of Copper to Iron Surface Area Ratio on the Corrosion Rate of Iron in Seawater [6]

Figure 5 - Grey Cast Iron Watermain Break at Row of Concentrated Pits

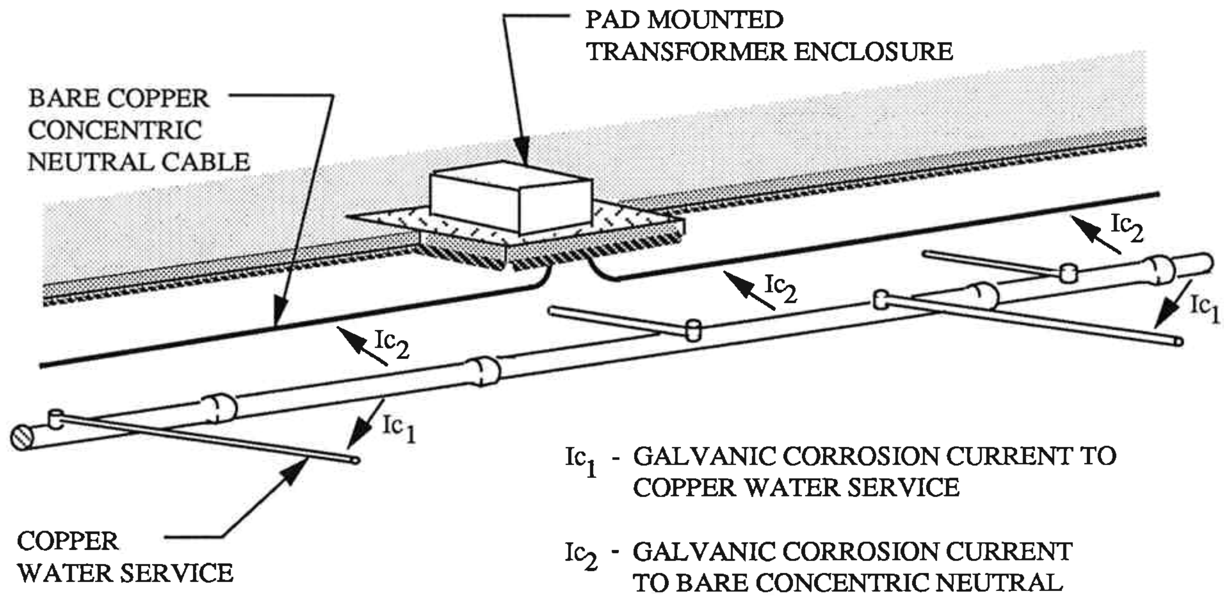

Figure 6 - Copper-Iron Galvanic Couples on Water Distribution Systems

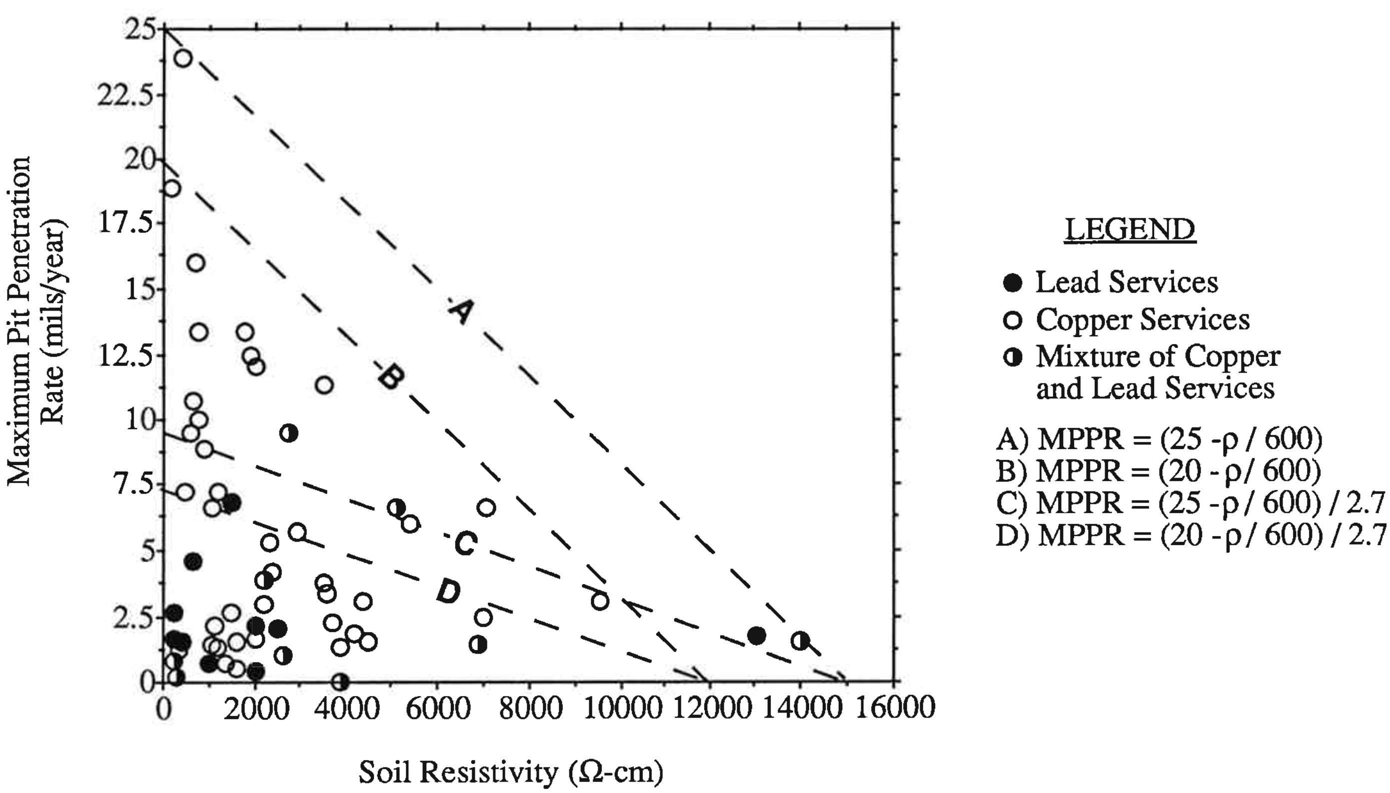

Figure 7 - Rate of Maximum Pit Penetration vs. Soil Resistivity

<table>
<tr><td>Lining</td><td colspan="3">Unlined</td><td colspan="2">Cement Lined</td></tr>
<tr><td>Pipe Material</td><td colspan="4">Grey Cast</td><td>Ductile</td></tr>
<tr><td>Services</td><td colspan="2">Lead</td><td colspan="3">Copper</td></tr>
<tr><td>Joints</td><td colspan="2">Leaded</td><td colspan="2">Mechanical</td><td>Tyton</td></tr>
<tr><td>Bedding</td><td>Native</td><td colspan="3">Sand</td><td>Granular</td></tr>
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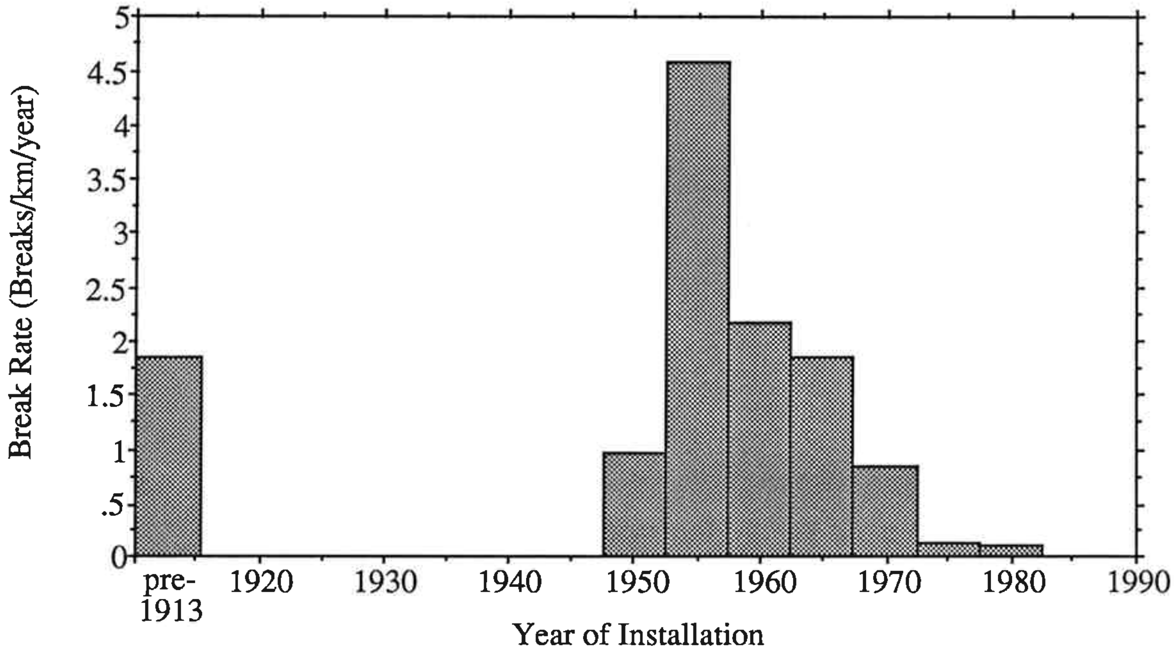

Figure 8 - Watermain Break Rate vs. Year of Installation for the Regional Municipality of Ottawa-Carleton

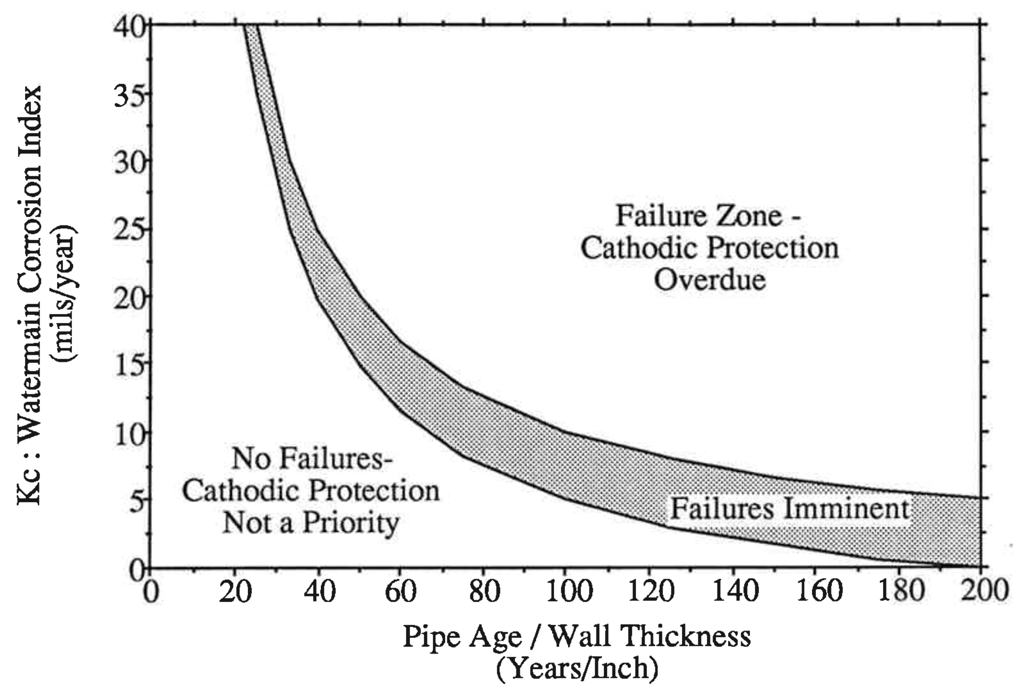

Figure 9 - Graphical Method of Prioritizing Cathodic Protection for Watermains