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CORROSION CONTROL CONSIDERATIONS FOR DUCTILE IRON PIPE – A CONSULTANT'S PERSPECTIVE

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ABSTRACT

This presentation will discuss various corrosion considerations and controversies surrounding ductile iron pipe. Case histories of documented corrosion failures of cast and ductile iron pipe will be presented. The effectiveness of polyethylene encasement as a corrosion control method for cast and ductile iron pipe will be covered. Factors to consider during a corrosion risk assessment evaluation will be discussed, along with a 25-point corrosivity evaluation risk assessment methodology for ductile iron pipe. This proposed risk assessment methodology combines an evaluation of the corrosivity of the route, the pipe location, size, function and desired design life. Various recommended levels of corrosion control methods for different pipe materials, and details to consider during selection of the external corrosion protection methods, along with life-cycle analysis factors, will be summarized.

Keywords: ductile iron corrosion, graphitization, polyethylene encasement, tight-bonded coatings, surface preparation, cathodic protection, electrical shielding, electrical continuity, MIC corrosion, protection levels, corrosion risk assessment, life-cycle costs.

INTRODUCTION

As a flexible pipe, ductile iron has several advantages to consider during water and wastewater pipeline designs. Some of these are its thicker wall, availability, and utility and contractor familiarity – provided the correct corrosion control methods are used. As with all metallic pipes, however, failures will occur if corrosion is not adequately addressed. It is just a matter of time.

A wide range of opinions surrounds the need for and methods of corrosion control for ductile iron. The need for tight-bonded coatings, cathodic protection, and the effectiveness of polyethylene encasement is a controversial subject with many differing opinions and numerous references in the corrosion industry. As an industry, we basically have agreed that we don't agree. The purpose of this paper is to present one method of evaluating the need for corrosion protection based on experience and a structured risk assessment approach.

Some proponents argue that polyethylene encasement alone provides adequate protection if installed correctly and that other corrosion control methods are too costly and complex. [1] They state that "*The number of documented failures of polyethylene encased pipelines – the vast majority of which are the result of improper installation – is insignificant compared to the miles of Cast and Ductile Iron pipe that are afforded excellent protection with this method of corrosion prevention.*"

Others maintain that polyethylene encasement alone is ineffective because it cannot be constructed in an intact condition. Some are concerned that corrosion may be concentrated at defects in the polyethylene encasement. Others believe polyethylene encasement may hamper the effective use of cathodic protection because of electrical shielding. There is concern that microbiological-influenced corrosion (MIC) may be a major corrosion mechanism underneath loose-bonded polyethylene encasement. Reports from different utilities and corrosion consultants indicate corrosion problems and failures under both damaged and undamaged polyethylene encasement. Some do not allow polyethylene encasement alone or with cathodic protection. Other utilities and consultants allow the use of polyethylene only in certain conditions, and in the most corrosive conditions require tight-bonded coatings and cathodic protection for ductile iron. There is no clear-cut approach that is accepted throughout the industry. [2]

An article in the American Water Works Association (AWWA) Journal on ductile iron corrosion discusses these wide variations in corrosion control approaches and utilities' experiences. [3] The authors summarize three general schools of thought with markedly different corrosion control approaches currently being utilized in the industry. The first, represented mainly by the ductile iron pipe manufacturers and the Ductile Iron Pipe Research Association (DIPRA), promotes the use of a passive protection system only (polyethylene encasement), and advocates against the use of joint bonds except in interference areas. The second school of thought, as the AWWA article states, "*does not put much faith in loose PE wrap,*" and is represented by the corrosion engineers. They point out that the corrosion engineer's approach depends on more traditional corrosion control methods of cathodic protection: tight-bonded coatings and joint bonding, and often avoids polyethylene encasement *"because its shielding effect will hinder CP"* (cathodic protection). The third school of thought, represented more by the Europeans and Japanese, utilizes a combination of zinc-rich coatings with *"an additional synthetic polymer coating, such as coal tar enamel, and a PE wrap (for extra protection)."* The AWWA article reports that this last group uses tight-bonded coatings and cathodic protection in some situations.

The fundamental task of a design engineer and corrosion consultant is to provide a constructible project that meets the owner's requirements at the lowest total cost and in compliance with applicable laws and codes. Bid specifications also include supplemental requirements for materials. These requirements include provisions deemed necessary by the design engineer and owner to make alternative products as equivalent as possible and still achieve the desired results of the project. Such supplemental requirements (including corrosion control) are common for projects in which large quantities of pipe materials are used. It is common for pipe manufacturers to lobby for and argue against various supplemental requirements that may affect sales of their particular products.

The major issue in the pipeline market is the selection of pipe materials and choice of corrosion control protection methods. Corrosion control costs may be the market difference among different pipe types. As water is becoming a more precious and expensive resource and leak repair costs escalate, the pipeline useful life and reliability is becoming more critical to utilities faced with major rehabilitation of their infrastructure. Therefore the need for and the type of corrosion control selected are becoming more critical.

The problem in corrosion control is that there is no single reference book or technical source available to determine what does and does not work. The National Association of Corrosion Engineers -

International (NACE) generally agrees on corrosion control procedures for steel and concrete structures and pipelines but there is a full spectrum of opinions on ductile iron and the use of polyethylene encasement. Claims by pipe manufacturers, coating suppliers, and cathodic protection firms are often slanted by their vested interests in selling their products.

Since corrosion is time dependent it may take a number of years for corrosion problems to become apparent and correct methods to prove themselves. Corrosion control is therefore part an art, part scientific, and part individual experience. No non-biased independent study has been completed that shows one position is more correct than the other. We must, therefore, draw on our experience in similar environments, not only with ductile iron pipe but also with other buried metallic pipe materials. One of the major challenges in the pipeline market is choosing appropriate corrosion control methods for the different metallic pipe materials that provide equal levels of long-term protection. Since corrosion control costs may represent the market difference between different pipe types, the need for it is widely debated by the different pipe manufacturers for their own and their competitors' pipe type.

The risk assessment approach outlined here presents corrosion control recommendations for different pipe materials that attempt to provide equal life for each. In other words, as corrosion professionals, we must try to make the playing field level by providing the necessary corrosion control measures for each of the pipe materials to meet the same design life based on scientific evidence, not rhetoric or market positioning. This allows the true pipe material costs to be compared on the basis of actual life-cycle cost rather than initial cost alone.

RISK ASSESSMENT FACTORS

Need For Corrosion Control

Utilities are currently facing a large problem maintaining their infrastructure, partly because pipe manufacturers, owners, and engineers historically have failed to recognize and provide adequate corrosion control methods to protect buried cast iron and ductile iron piping and fittings. Despite warnings from corrosion experts in the late 1960s and again in the 1980s about possible iron pipe corrosion problems, water and wastewater utilities continued the practice of installing metallic pipe without sufficient protection. Corrosion is now generally considered to be the major reason for below-ground pipe failures. The cost of repairing or replacing ferrous metal pipes is one of the largest expenditures in some utility budgets. [4]

In an October 1989 AWWA Journal article, Kelly O'Day wrote: *"Research in Philadelphia and Boston and observation of corrosion and main failure in Calgary, Denver, EBMUD, Los Angeles, and other utilities show that external corrosion is a major contributor to water main deterioration."* [5] He further notes that many utilities do not appreciate or recognize that corrosion has led to conditions that eventually caused the leak or break. Corrosion control programs if well-designed and properly managed can help a water district control corrosion both by prolonging life on existing structures and maximizing corrosion protection on new pipelines. One of the major problems that face the water industry is "*… that there is no well-established method for utilities to follow in assessing their corrosion control options."* Mr. O'Day says that one of the greatest needs is for the water industry to develop procedures that accurately assess the trade-offs in the benefits and costs of alternative levels of corrosion control.

In his report, "Analysis of Winnipeg's Watermain Failure Problem," G. Chambers indicated that because of the corrosive soils in Winnipeg, iron pipe only had a useful life of between 10 to 90 years. [6] The number of leaks per kilometer per year were double that of other Canadian cities. He summarized that the increase in the number of leaks required that Winnipeg expend more than $7.7 million in 1982 for their pipe replacement program. *"Approximately 60 percent of Winnipeg failures in cast iron and ductile iron pipe were found to be attributable directly or indirectly to corrosion…. This compares closely to experience with cast iron watermains in Texas. Three cities, Dallas, Fort Worth, and Corpus Christi, all with soils similar to Winnipeg, reported that 30-60 percent of their cast iron watermain failures were caused by corrosion."*

In an article entitled "Corrosion, Not Age, is to Blame for Most Water Breaks" the author estimated that an average of 700 water main breaks will occur each day in North America. [7] These breaks, more than 250,000 annually, will cost approximately $1 billion per year. The author states that most people believe that old age is the major contributor to iron water pipe main breaks, but it is actually corrosion damage, as older pipes can continue to operate as long as corrosion is controlled. *"The majority of water piping installed in the 20th century was cast or ductile iron, which was expected to provide water utilities with 50 to 100 years of trouble-free services. Unfortunately, these pipes are susceptible to corrosion and subsequent breakage. …Ductile iron pipe, introduced to the water systems in the 1950's and still in use today, was intended to offer better quality than cast iron. However, the pipe's matrix and thinner wall make it vulnerable to pitting and corrosion attack."*

Bob Gummow attributes the increases in the rate of premature corrosion failures primarily to the thinner-wall ductile iron pipe, but also to galvanic corrosion from copper services and increased corrosivity from use of road salts. [8] *"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 gray cast iron and ductile iron have a similar, natural tendency to corrode in soil. ...On the other hand, the corrosion of ductile iron pipe has awakened the waterworks industry, after half a century, to an appreciation for the potential severity of corrosion."*

The need for corrosion control and the historical failure of the water and wastewater community to adequately address corrosion is best summarized in the report "Corrosion Cost and Preventive Strategies in the United States." [9] This comprehensive three-year study was completed in 2001. The Federal Highway Association (FHWA) and National Association of Corrosion Engineers International (NACE) jointly supported the study, mandated by the U.S. Congress. The study points out that the total cost of corrosion per year in the U.S. is $276 billion, or approximately 3 percent of the nation's gross domestic product. A disturbing finding is the revelation that the largest single component of this annual corrosion cost is the water and wastewater sector, at $36 billion. According to the study, a major reason for this corrosion problem is the lack of awareness and understanding of corrosion and the lack of corrosion control. It states that many utilities have contributed to their own problems by their approach where *"often an attitude is taken of burying the water pipe and forgetting about it until it fails."* The authors maintain that corrosion-related costs may add up to *"approximately 50 percent of the total budget of the water departments."* The coatings and cathodic protection can effectively mitigate external corrosion: *"Although these systems have problems of their own, the initial cost for installing coatings and cathodic protection on new systems is almost always warranted because large maintenance-cost savings can be achieved over the life of the piping system."* Two of the most important preventive strategies recommended in this report to minimize the future cost of corrosion were *"to increase the awareness of the large corrosion costs and potential savings"* and *"to change the misconception that nothing can be done about corrosion."*

The $36 billion water and wastewater cost of corrosion is partly the owner's fault because the utilities historically did not want to acknowledge and spend the additional money necessary for adequate corrosion control. But it is also partly the fault of the corrosion industry as a whole in not resolving the differences in corrosion control on ductile iron. We have just continued to agree that we don't agree, instead of doing the necessary research to find the correct technical answers. This paper and the 25-point risk assessment design matrix is one attempt to provide a preliminary decision making process (risk assessment) to evaluate the need and type of corrosion protection required for ductile iron.

Corrosion Rate

Initially, ductile iron was advertised as exceeding the corrosion resistance of gray cast iron. [10] This idea gained acceptance in the marketplace and allowed the thinner-wall ductile iron pipe to replace cast iron pipe. However, research by Melvin Romanoff of the National Bureau of Standards (now the National Institute of Standards and Technology) as reported in 1964 and 1967 articles indicated ductile iron, cast iron, and steel corrode at similar rates in low-resistivity soils. [11] [12] Additional National Bureau of Standards testing concluded in a 1976 article that ductile iron and steel *"buried in the same soils…corrode at nearly the same rates when encased in some soils. Different soils, however, alter the corrosion rates for both materials"*. [13] DIPRA in their 75 year paper acknowledges that for practical purposes ductile iron and cast iron can be considered to corrode at the same rate. [14]

Failure to Recognize Different Forms of Cast Iron or Ductile Iron Corrosion Damage

One of the problems that have contributed to the increasing cost of repairing water or wastewater pipelines is the inability or reluctance of utilities to recognize and even acknowledge that corrosion is a major factor in their pipe failures. This is partially understandable because iron pipe failures are often not visibly recognized as corrosion related. Cast iron and ductile iron differ from steel in that they are alloys composed primarily of iron, carbon (graphite), and silicon. In gray (cast) irons, much of the carbon separates into very small flat-shaped flakes of graphite that are uniformly distributed through the metal. In ductile iron, the carbon is in the form of spheres.

Graphitic corrosion commonly called graphitization in the water and waste water industry is corrosion of cast or ductile iron. This graphitic corrosion occurs as selective dissolution of the iron matrix in the alloy. This corrosive action leaves behind only the graphite flakes or nodules and corrosion products. This process is known as graphitic corrosion or graphitization and is a common form of corrosion on buried cast iron pipe and to a lesser degree on ductile iron. [15]

Graphitic corrosion (graphitization) in cast iron results in the carbon flakes being overlapped in a flat matrix pattern that still provides some strength because of the interconnected flat flakes. Graphitization in ductile iron, however, may not have the same strength as cast iron since the graphite flakes are in a nodular, or plug, shape, which do not overlap or interlock each other. There is no consensus on the amount of difference. This graphitization layer increases in thickness as corrosion continues, but the pipeline still retains some structural strength. We have seen examples of both plug (slap) and flake types of ductile iron corrosion graphitization similar to cast iron, but typically ductile iron corrodes more like steel, in a pitting type of corrosion with the graphitization layer still able to bridge the pit to some degree.

Graphitized cast or ductile iron has low structural strength but may have sufficient strength to allow a severely corroded pipe to remain in service if low or moderate water pressures are maintained and no mechanical disturbances affect the pipe. Stresses are often created by heavy vehicles, nonflexible pipe joints, soil condition or movement (frost, swelling clays, settlement), and beam action. As the graphite shell retains little strength, it may crack, either circumferentially or longitudinally. Because the pipe appears sound, such failures are not often recognized as corrosion, but are usually referred to merely as "beam breaks, point loading, or main breaks, etc." However, the chance of catastrophic failure (splits, beam breaks, blowouts, etc.) increases with both time and the amount of corrosion. Graphitized cast iron has larger, more catastrophic breaks than graphitized ductile iron, which, though less than prestressed concrete cylinder pipe failures, is usually much larger than for steel pipe pinhole-type leaks.

The failure of pipe that appears to be in good condition was noted in the article "Analysis of Failures In Water Mains:" "*Graphitic corrosion is deteriorated gray cast iron in which the metallic constituents are selectively removed or converted to corrosion products, leaving the graphite intact. When this occurs, the pipe wall appears to be sound, but the remaining uncorroded metal may be extremely thin and brittle, and it might fracture completely from excessive loads.*" [16] In a 1979 presentation to the AWWA, Ontario Section, Gummow noted that, based on his experience "*the failure of municipal authorities to recognize that corrosion was the primary cause of most cast iron waterman "breaks" is at the root of the rapid failure of ductile iron piping. Yet it is understandable that the corrosion was not recognized since with cast iron the corrosion pattern is well camouflaged.*" [17]

Graphitized iron pipe responds with a dull sound when struck with a metal object, is soft like pencil lead and can be gouged or dug into with a knife or screwdriver. To fully evaluate the damage, the graphitization must be removed by abrasive blasting (sand blasting) or tested by other non-destructive evaluation methods (e.g., ultrasonic, remote eddy field current). Recent papers summarizing pipe material assessments utilized by both the City of Ottawa and the City of Calgary [18] [19] confirmed that the pipe needs to be abrasive blasted to remove surface debris in order to visually accurately identify actual metal loss as shown in Figure 1. This is because the smooth surface appearance of graphitized cast iron, and in some cases ductile iron, may lead one to believe that the pipe has no corrosion damage and still has sound structural integrity.

Figure 1
Exterior Surface of Pipe Appears To Be In Good Condition

But when viewed from the side, the graphitization appears black at the carbon-rich areas where the iron has been selectively consumed, as shown in Figure 2. The surface of corroded cast or ductile iron pipe will show corrosion damage similar to steel pipe when the graphitization, which is soft like pencil lead, is removed.

Figure 2
Soft Black Graphitization Pockets Visible on Pipe Edge When Cut

Figure 3
Sandblasted 10-Inch 40-Year-Old Cast Iron Pipe With Crack At Failure Location

It is critical that the pipe be abrasive blasted, as shown in Figure 3, in order to accurately assess the amount of corrosion damage. The depth and cracking of the graphitized cast iron is readily apparent only after the overlaying graphitization layer is removed by abrasive blasting.

As discussed earlier, the surface of a corroded ductile iron pipe may appear in many different corrosion forms, depending on the microstructure/microchemistry of the pipe and the corrosion products formed. Some of the reasons for the wide variations seen in the ductile iron corrosion patterns and corrosion products may be the consistency of the pour, the graphite shape, and influences of scrap iron metal. According to some of the pipe manufacturers' technical representatives, although technology has improved and ductile iron pipe pours are much more uniform now, early ductile iron pipe may have had pockets of graphitization layers similar to cast iron if the pour was not consistent. The types of ductile iron corrosion can range from graphitization layers similar to cast iron pipe, plug or pitting graphitization, longitudinal or circumferential corrosion caused cracking, or, as shown in Figures 4, 5, 6, and 7, bright metal corrosion with no graphitization, similar to steel-type corrosion.

Figure 4
Sandblasted 24-Inch 33-Year-Old Ductile Iron Corrosion With 3/16-Inch Surface Graphitization Layer

Figure 5
24-inch 33-Year-Old Ductile Iron Pipe with 2-inch by 3-inch Sized 0.310-mils Deep (75 Percent of Pipe Wall) Plug-Type Corrosion With Some Surface Graphitization

Figure 6
Sheridan Deep Graphitization Corrosion Along Crack on Ductile Iron Pipe in Less Than 15 Years

Figure 7
Sheridan 35-Year-Old Ductile Iron Corrosion Similar to Steel with No Graphitization Visible and Bright Metal At Bottom Of Corrosion Pit When Initially Exposed; Unprotected 60-Year-Old Coated Steel Line in Same Area With Minimum External Corrosion Problems

Figure 8
Laramie Plug Graphitization and Leak from 35-Year-Old Cast Iron and Ductile Iron Pipe Lines; Replacement Less Than 5 Years After First Leak and Major Graphitization Discovered

As shown on Figure 8, even though the pipe has major corrosion damage, the graphitization and cement mortar lining can hold water or sewage pressures for a period of time if not disturbed. Melvin Romanoff of the National Bureau of Standards demonstrated that graphitized cast iron pipe could withstand pressures up to 500 pounds per square inch for 1.5-inch (3.8-cm) Class 150 pipe even if completely penetrated. [20] Thinner 0.125-inch (0.3175-cm) steel pipe failed at pressures of 150 pounds per square inch. Thicker 0.250-inch (0.635-cm) steel pipe failed at 400 pounds per square inch. He concluded: "*These results on both cast iron and steel indicate that serious corrosion and even complete perforation by corrosion products does not always destroy the ability of the pipe to transport liquids.*" And: "*These short-term failures presumably reflect a difference in the type and coherence of the corrosion products formed on cast iron and steel in the same soil.*"

Although cast or ductile iron pipe corrode at the same rate as steel, they do not usually fail as rapidly as steel pipe. [21] This is partly a result of the wall thickness, but also because of the ability of the iron pipe graphitization to withstand some pressure if undisturbed and not subjected to external or internal stresses until the corrosion damage becomes too large. But the cost and damage caused by these types of graphitized iron pipe failures may be more severe when they do occur, as shown in Figures 9, 10, and 11. As mentioned earlier cast iron is more brittle than ductile iron, which results in more catastrophic-type failures than for ductile iron, as shown by this failure in a major road intersection in Hawaii.

Figure 9
Catastrophic-Type Break Hawaii 34-Year-Old Cast Iron Main Break (14.5 Points)

Figure 10
Major Leak on 24-Inch Polyethylene-encased Ductile Iron Line in Colorado

Figure 11
Colorado Corrosion Damage Repair Required Removal of Five-Foot Section of Polyethylene-encased Ductile Iron and Replacement with New Pipe with Galvanic Anodes

Ductile Iron Metallurgical Differences

According to the Mike Woodcock, a metallurgist from Washington Suburban Sanitation District, the seventh largest water and wastewater utility in the United States, the difference in the corrosion-resistant properties of ductile iron may be because of the different metallurgical properties[22]. Figure 12 shows some of the flake structure he has observed. In some cases, such as on the 1982 ductile iron sample, he observed a mixed spheroids and graphite flake structure. He felt that the difference in metallurgical properties may help explain why in some cases some ductile iron corrodes very quickly while in the same soil some ductile iron appears to be very corrosion resistant. He believes that the metallurgical properties of the ductile iron are also just as important as the corrosivity of soil conditions in the influence on the corrosion rate. [23]

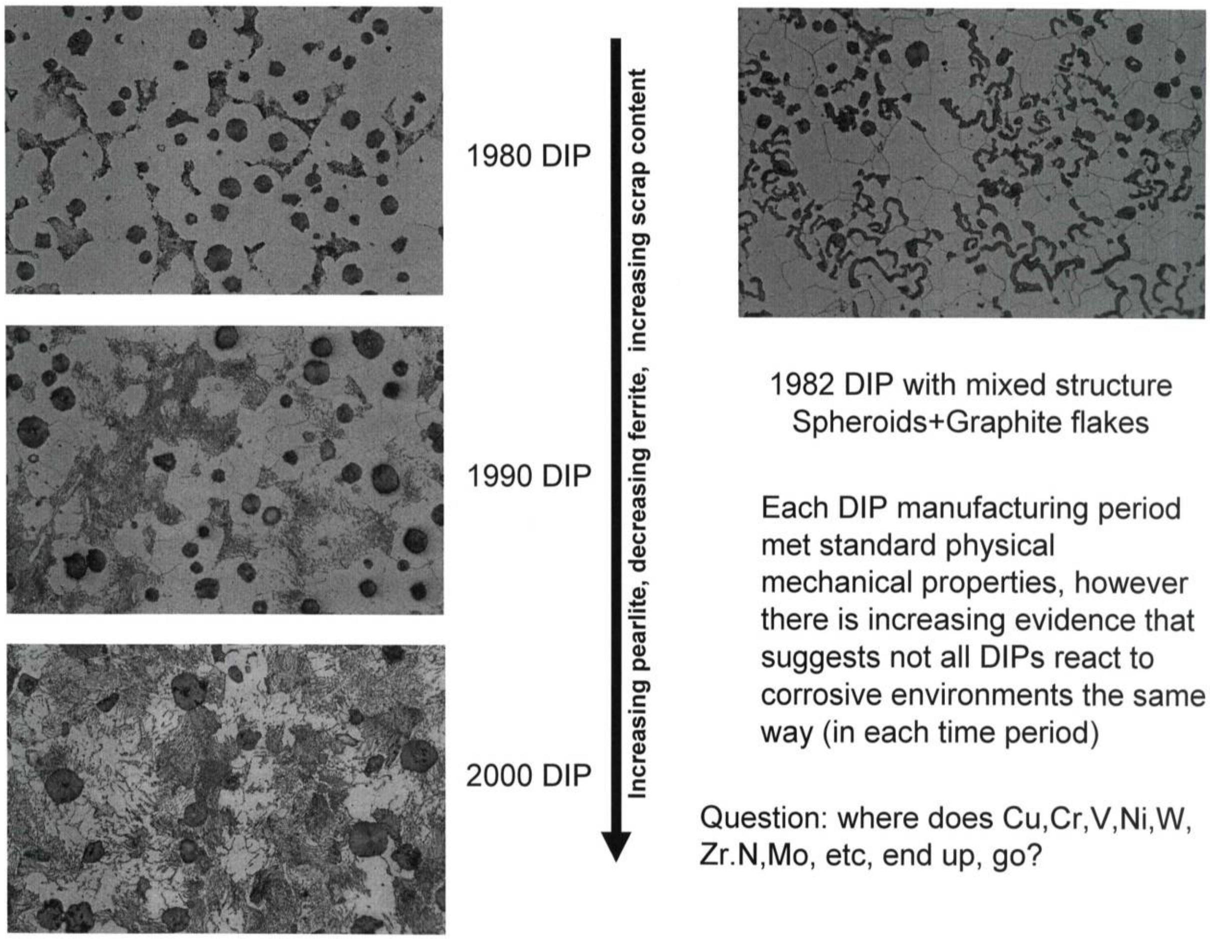

Figure 12
Variations in Ductile Iron Metallurgical Flake Structure, Courtesy of Washington Suburban

Reduction in Iron Pipe Wall Thickness

The thinner wall of ductile iron pipe is one of the factors that contribute to its shorter useful life compared to cast iron. Historically, the extra thickness of the cast iron pipe provided more metal for corrosion to attack (corrosion allowance). As shown in Figure 13, the historical wall thickness difference in some cases can be as much as 75 percent thinner for a similar pressure and diameter pipe. If the wall thickness of ductile iron is only one fifth of the cast iron wall thickness and the corrosion rate is the same, then the expected life of ductile iron will be substantially less than for cast iron in similar corrosive environments. The difference in wall thickness is one consideration that must be taken into account during corrosion evaluations and selection of appropriate corrosion control methods. Some utilities are specifying increased ductile iron pressure classes for additional wall thickness in an attempt to provide a larger corrosion allowance.

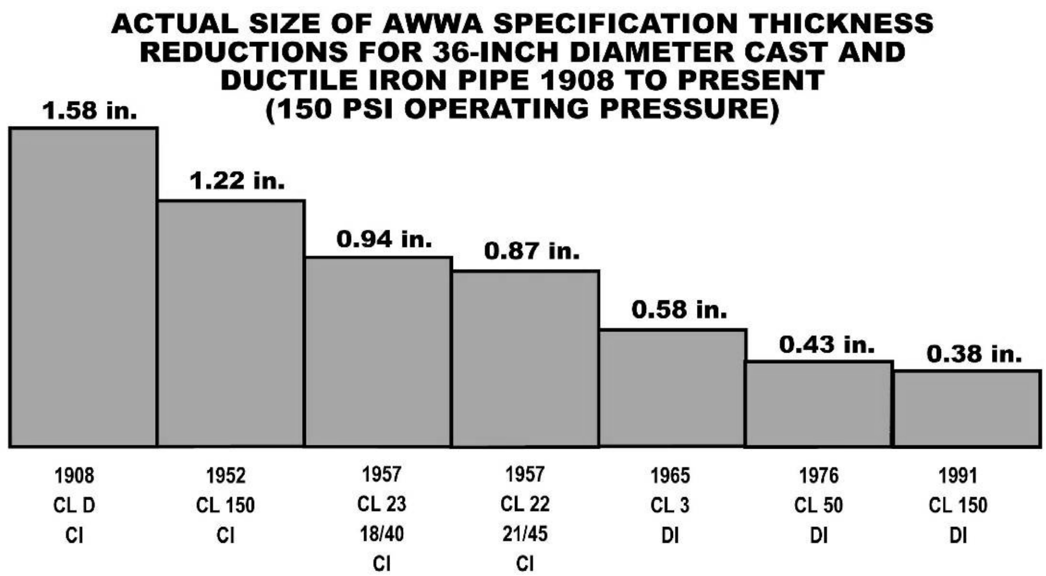

Figure 13
Historical Iron Pipe Wall Thickness Reductions

Many utilities and agencies have been faced with an unexpected crisis and had to come up with ways to extend the life of their buried pipelines. One method that has found success on graphitized iron mains is the use of cathodic protection. Gummow claims that some of the problems on water distribution piping are a result of copper water services when combined with damage to the thin cosmetic pipe coating, which allows small-anode to large-cathode corrosion cells to develop. This results in faster penetrations of the thinner-wall ductile iron pipe. [24] If the soils are contaminated by the use of road salts (chlorides), the corrosion rate can be accelerated even further. Gummow's article describes a method of retrofitting leaking ductile iron and cast iron mains with a galvanic anode cathodic protection technique called "auginode." Anodes are placed in augured holes at evenly spaced intervals along the selected main to be protected. One of the first of this type was installed in the late 1970s and successfully halted the number of corrosion leaks on a section of ductile iron main that had previously suffered 22 corrosion leaks in less than 10 years' burial. This cathodic protection method was reported to be very economical at only 5 to 10 percent cost of replacement and has since been adopted by many of the major cities in Canada. Gummow maintains that this type of cathodic protection system should be able to halt the cumulative number of corrosion leaks and extend the life of the mains almost indefinitely, as long as the anodes are replaced as needed. Although different cathodic protection methods can help prolong ductile iron life, it points out the need for corrosion control on thinner-walled ductile iron pipe even more than for the previous heavy-walled cast iron pipe and in a shorter time. The influence of wall thickness of present-day pipe and previous performance of similar pipe types in the same environment should be considered in the risk assessment and evaluation process for selecting which corrosion control measures are required for each specific pipeline.

Corrosion Risk Assessment Evaluation Procedures

Although there is no universally accepted corrosion risk assessment methodology for ductile iron, we have summarized a number of different procedures for evaluating the corrosive conditions and their influence on the pipelines. Soil resistivity is one method of gauging how corrosive a soil may be to any given type of metallic pipe. A July 2003 Materials Performance article, "Evaluating Ductile Iron Pipe Corrosion," relates soil resistivity with a corrosivity rating tied to the amount of time until failures have been reported on ductile iron. [25] Table 1 shows the authors' evaluation of soil resistivity and how it may correlate to the time period when ductile iron corrosion failures have been observed.

Table 1
Resistivity Versus Corrosivity

Resistivity	Corrosivity	Failures Have Been Reported in
Less than 1,000 ohm-cm	Extremely Corrosive	5 Years or Less
1,000 to 5,000	Very Corrosive	15 Years or Less
5,001 to 10,000	Corrosive	20 Years or Less
10,001 to 25,000	Moderately Corrosive	25 Years or Less
Over 25,000	Mildly Corrosive	Over 25 Years
July 2003 NACE Materials Performance		

Some authorities report that soil resistivity is the most important factor, along with pipe type and wall thickness and the presence of copper services, in their analysis of corrosion rates on water distribution iron piping. They found that soil resistivities below 2,000 ohm-cm range are the most corrosive to iron pipe. [26] In this study, Calgary attempted to correlate corrosion rates on pipe joints that had been removed, sandblasted, and closely investigated between 1993 and 1997 with soil samples. Their evaluation of the data indicated that the major influence factors are only soil resistivity, pipe material and non-isolated copper services lines. They found that with soil resistivity, the best correlations were obtained using the 2,000 ohm-cm level as the break in distinguishing soils according to their corrosiveness. Other soil chemical tests (chlorides, sulfates, and pH) had minimum correlation with observed corrosion rates and were deemed to be uneconomical and impractical. Work by R. G. Wakelin and R.G. Gummow in Ontario indicated that for distribution piping, the major influences of low resistivity soils and copper services or grounds are so overwhelming that secondary effects of other soil characteristics (redox potential, pH) were negligible.[27]

A US Bureau of Reclamation document from July 2004 outlines their recommended overall corrosion prevention strategy and corrosion control methods that are based, in part, on a ten percent probability of encountering soils with a given resistivity. [28] Soils with soil resistivity values below certain levels require more stringent corrosion protection methods; higher soil resistivity soils require less. For ductile iron, a bonded dielectric coating, corrosion monitoring, and cathodic protection are required for soil resistivity below 2,000 ohm-cm. Corrosion monitoring includes joint bonding, insulators, and test stations. The minimum corrosion control requirement for soil resistivity between 2,000 and 3,000 ohm-cm range is an unbonded coating (polyethylene encasement) for ductile iron with corrosion monitoring and cathodic protection. For soil resistivity above 3,000 ohm-cm, the minimum corrosion control requirements are polyethylene encasement with corrosion monitoring for ductile iron pipe. Where soil resistivities are already low (below 2,000 ohm-cm soil), they do not require additional soil chemistry tests, as the most conservative corrosion control measures are already required.

Table 2

Bureau of Reclamation's Corrosion Prevention Criteria and Minimum Requirements[1] July 2004

Pipe Alternative	Soil Resistivity – 10 % Probability Value (ohm-cm)	Minimum External Protection (Primary / Supplemental)	Corrosion Monitoring	Cathodic Protection[2]
Ductile Iron	≤2,000 ohm-cm	Bonded dielectric[3]	YES	YES
	>2,000 ohm-cm <3,000 ohm-cm	Polyethylene encasement	YES	YES
	≥3,000 ohm-cm	Polyethylene encasement	YES	NO
Pretensioned Concrete	<3,000 ohm-cm	Mortar / coal-tar epoxy	YES	YES
	≥3,000 ohm-cm	Mortar	YES	NO
Reinforced Concrete	<3,000 ohm-cm	Concrete / coal-tar epoxy	YES	YES
	≥3,000 ohm-cm	Concrete	YES[4]	NO
Steel	≤2,000 ohm-cm	Bonded dielectric[3]	YES	YES
	>2,000 ohm-cm <3,000 ohm-cm	Mortar / coal-tar epoxy	YES	YES
	≥3,000 ohm-cm	Mortar	YES	NO

[1] This table should be considered the minimum corrosion prevention requirements for a pipeline corrosion design. Additional soil conditions and risk assessment factors should be considered on a case-by-case basis for each specific project.

[2] OMR&E costs for cathodic protection for each pipe type should be evaluated.

[3] Bonded directly to the metal to be protected.

[4] Corrosion monitoring is required for concrete pipe with steel joint rings, but not for concrete pipe with concrete joints.

From the Bureau of Reclamation Technical Memorandum No. 8140-CC-2004-1, Corrosion Considerations for Buried Metallic Water Pipe, July 2004, Page 5, Table 2, "Corrosion Prevention Criteria and Minimum Requirements."

Rather than basing the corrosivity of a soil solely on its resistivity, others have devised tables for rating the soil's overall corrosivity. These include the Ductile Iron 10-point System, summarized in Appendix A of the ANSI/AWWA Standard C105. [29] While this Appendix is not a part of the ANSI/AWWA

Standard, it provides a 10-point rating system for corrosivity relative to ductile iron. The Ductile Iron 10-point System rates five soil factors and assigns point values for each of the soil characteristics. These are soil resistivity, pH, redox potential, presence of sulfides, and moisture. If the total of these values is 10 points or more, the soil is considered to be corrosive to ductile iron and additional protection in the form of polyethylene encasement is recommended. In “uniquely severe” conditions, other corrosion protection measures may be justified, according to the ANSI/AWWA C105 standard.

Other soil assessment methods include those presented by C.P. Dillon in his book *Corrosion Control in the Chemical Process Industries* [30] and one developed in Australia called the ORSTAD Chart (Observation and Resistivity, Sulfide, and Total Acidity Determination). [31] Normally, bare pipe or polyethylene encasement is the only corrosion control methods that are included in the 10-point system and the ORSTAD evaluation results. Others have expanded these two corrosivity evaluation results to include additional corrosion control methods, and use the anticipated level of corrosivity to determine if polyethylene encasement with or without cathodic protection or tight-bonded coatings with cathodic protection, are justified.

Some utilities contend that, in addition to soil corrosivity, other factors need to be given more consideration in pipe route corrosivity evaluations and feel that corrosion control options other than just polyethylene encasement should also be considered. Washington Suburban Sanitation District employs the point values from the Dillon assessment table, along with a decision tree that notes water in the borehole and the size of the pipeline. [32] They utilize a decision tree that not only uses polyethylene encasement as a corrosion control method but also requires tight-bonded coatings and cathodic protection based on their evaluation of the anticipated level of risk and size and function of the pipeline.

Another corrosion risk assessment method that we have proposed and was summarized in NACE Materials Performance, July 2002, is called the Ductile Iron 25-Point Risk Assessment Analysis, which modified and expanded the Washington Suburban risk assessment method and decision tree. [33] This procedure incorporates the soil corrosivity factors from the Dillon assessment method, factors from the AWWA C105 10-point procedure, other soil corrosivity factors, and additional pipe design/function factors and requires different corrosion control methods for the different zones in a similar fashion as the Bureau of Reclamation procedure. Other soil corrosivity evaluation factors include possible influence of sulfates as a MIC food source, changing groundwater conditions, wetting and drying cycles, and possible soil contamination. The additional pipe design and function evaluation factors include pipe location, size, pressure, design life, leak repair difficulty, presence of potential interference sources, previous corrosion leaks, as well as the specific pipeline function. Values have been added or increased to account for these items. Corrosion control methods vary from bare pipe with standard asphaltic shop coating (do-nothing), to polyethylene encasement alone or with cathodic protection, to use of tight-bonded coatings with cathodic protection.

Though the 25-point risk assessment values are somewhat arbitrarily assigned for the corrosivity evaluation design factors, they are based on my and other corrosion consultants’ personal experience and can be modified to reflect others’ observations. The primary purpose of this proposed risk assessment methodology is to demonstrate a thought process that evaluates not only risk of failure but also the consequences of failure. This methodology allows various corrosion control possibilities to be evaluated and selected based on the perceived degree of risk. The 25-point risk assessment approach is more applicable for larger transmission pipe than for small distribution piping. The premise is that since corrosion failure and leak repair costs are minor on a 6-inch (15.24 cm) line but catastrophic on a 60-inch (152.4 cm) line, transmission and distribution piping may require different levels of corrosion control. An example of the 25-point risk assessment procedure is shown in Table 3.

Table 3 Ductile Iron 25-Point Risk Assessment Analysis with Project-Specific Assigned Point Values*			
Analyze Type	**Analysis Range**	**Point Ranges**	**Specific Project Points****
1. pH (AWWA C105 and Dillon)			
	0 – 2 pH	5	**0 pH 7.2**
	2 – 4 pH	3	
	4 – 6.5 pH	0	
Add 3 points if sulfides present & low/negative redox	6.5 – 7.5 pH	0	
	7.5 – 8.5 pH	0	
	> 8.5 pH	3	
2. Chloride Content (Dillon)			
	> 1,000 ppm	10	**2 156 ppm**
	500 – 1,000 ppm	6	
	200 – 500 ppm	4	
	50 – 200 ppm	2	
	0 – 50 ppm	0	
3. Sulfate Content (To account for MIC and possible food source for sulfate reducing bacteria in anaerobic conditions under loose-bonded coatings)			
Very Severe	> 200 ppm	5	**5 3,060 ppm**
Severe	150 ppm to 200 ppm	4	
Minimal	100 ppm to 150 ppm	2	
Little	50 to 100 ppm	1	
None	< 50 ppm	0	
4. Redox Potential (Conduct at site to evaluate anaerobic conditions [C105 and Dillon])			
Anaerobic Conditions	Negative	5	**3.5 +72mv**
Possible Chance Anaerobic	+0 to +50 mV	4	
Minimal Chance Anaerobic	+50 to +100 mV	3.5	
Aerated Soil	> +100 mV	0	
5. Soil Type Description (Dillon with additional soil types where corrosion observed)			
	Coal Seams or Cinders	15	**5 Fat Swelling Clays/Clay Stone**
	Ocean Tidal Zones	15	
	Highly Organic Soil, Mucks	10	
	Clay (blue-gray or swelling)	10	
	Alkaline Salt Flats	10	
	Clay/Stone	5	
	Clay	3	
	Silt	2	
	Dry Loamy Soil	1	
	Clean Sand	0	
6. Soil Resistivity (Dillon modified 5 points, based on problems in 2,000 to 3,000 ohm-cm soil)			
Based on 10% or more of route having soil corrosivity values in that range, either lowest average, layer, or saturated distilled water, according to U.S. Bureau of Reclamation probability procedures.	< 1,000 ohm-cm	15	**15 300 to 400 ohm-cm range**
	1,000 – 1,500 ohm-cm	13	
	1,500 – 2,500 ohm-cm	11	
	2,500 – 5,000 ohm-cm	9	
	5,000 – 10,000 ohm-cm	7	
	> 10,000 ohm-cm	0	
7. Sulfides (To account for presence of sulfide reducing bacteria, sodium azide test C105)			
	Positive	3.5	**0 Negative**
	Trace	2	
	Negative	0	
8. Moisture (To account for problems encountered with water tables that fluctuate in pipe zone and wetting/drying cycles influence on salt concentrations and oxygen levels)			

Table 3 Ductile Iron 25-Point Risk Assessment Analysis with Project-Specific Assigned Point Values*			
Analyze Type	**Analysis Range**	**Point Ranges**	**Specific Project Points****
Numerous Changes Soil Resistivity, Aeration, or Dry to Wet		6	**5 Assumed Moist with Changing Groundwater**
Changing Water Table Over Pipe - Intermittently Wet/Dry		5	
Bottom ½ Pipe Under Water Table With Top Dry – Stable		4	
Above Water Table – But Soils Generally Moist		3	
Always Below Water Table - Continuously Wet		2	
Minimal Seasonal Changes - Normally Dry		1	
Well Drained Always Above Water Table – Always Dry		0	
9. Pipe Size Factor (Minimum inside pipe diameter) (To account for consequence of leak)			
	Equal to or > 64-inch	8	**2 24-inch**
	50-inch to 63-inch	6	
	40-inch to 49-inch	4	
	30-inch to 39-inch	3	
	24-inch to 29-inch	2	
	< 23-inch	0	
10. Maximum Design Surge Pressure Factor (To account for influence of increased pressure)			
	Equal to or > 300 psi	6	**2 Assumed 250 Surge**
	251 psi to 299 psi	4	
	201 psi to 250 psi	2	
	151 psi to 200 psi	1	
	< 150 psi	0	
11. Pipe Minimum Design Life Factor (To account for reliability/service life)			
	300 years	8	**2 Assumed 50 to 100 years**
	201 years to 299 years	6	
	101 years to 200 years	4	
	50 years to 100 years	2	
	< 50 years	0	
12. Pipe Location & Leak Repair Difficulty Factors (To account for consequence of leak)			
High risk, environmental sensitive, steep slopes, water crossings		12	**2 Assumed Next to Road**
	Congested Downtown Area	10	
	Four Lane Road	8	
	Industrial Area	6	
	Two Lane Concrete Road	4	
	Two Lane Asphalt Road	2	
	Remote Poor Access	1	
	Cross-Country Good Access	0	
13. Potential Interference Sources (To account for possible influences from interference)			
A. Potential Interference Sources within 1,000 Feet of New Pipeline	Impressed Current > 20 amp	10	**0 None Observed**
	Impressed Current 11- 20 amp	8	
	Impressed Current < 11 amp	6	
	Light Rail Station	20	
B. Potential Interference Sources within 2,500 Feet of New Pipeline	Impressed Current > 20 amp	8	
	Impressed Current 11- 20 amp	6	
	Impressed Current < 10 amp	4	
	Refinery, Tank Farm, Rail Station	10	
C. Light Rail Tracks or Foreign Pipe Crossings	Long Light Rail or Pipe Parallel	10	
	Light Rail or Pipe Crossing	5	
D. Oil or Gas Well Field w/ Impressed Current Systems	Through Well Field	15	
	Multiple Track/Pipeline Crossings	15	

Table 3 Ductile Iron 25-Point Risk Assessment Analysis with Project-Specific Assigned Point Values*			
Analyze Type	**Analysis Range**	**Point Ranges**	**Specific Project Points****
14. Pipe Zone Backfill Materials (To account for influence of different pipe bedding types)			
To account for use of native soil backfill or backfill with sharp points. Assumed that select backfill will provide more uniform, homogenous-type environment than native backfill, while sharp backfill will cause more coating or polyethylene encasement damage	**Native Soil (<3,000 ohm-cm) or Select/Native Backfill with Angular or Sharp Rock Points**	4	**0 Assumed Select Backfill**
	Native Soil (<5,000 ohm-cm)	3	
	Native Soil (<10,000 ohm-cm)	2	
	Rounded Select Backfill (<10,000 ohm-cm)	1	
	Rounded Select Backfill (>10,000 ohm-cm)	0	
15. Future or Additional Factors To Consider (To account for other miscellaneous factors)			
A. Possible Soil Changes from Chemical Additives or Contaminates	Heavily Salted Roads with Pipe in Drainage Area (Borrow Ditch)	10	**0**
	Heavily Fertilized Irrigated Field	8	
	Dairies, Feed Lots, Barn Yards	6	
B. Previous Corrosion Leaks on Bare or Polyethylene-Encased Ductile Iron or Cast Iron Pipe or Fittings in Same General Area	Polywrap DIP or CIP < 30 yrs	15	**10 Known CIP failures**
	Bare DIP or CIP < 30 yrs	10	
	Bare DIP or CIP < 50 yrs	5	
	Previous Leaks Bare, <100 yrs	2	
C. Pipeline Function	Sewer Force Mains	5	**5 Single Source Transmission Line**
	Single Source Transmission	5	
	W/ Copper Services/Grounds	4	
	Distribution Type Piping	0	
TOTAL ASSIGNED POINT VALUES SPECIFIC PIPELINE		**Total 58.5**	
Overall Risk Assessment Rating (Modified 10 Points From Dillon Values To Account For Additional Evaluation Items and Numerical Values)			
Risk Assessment Zones 1&2	**Severe**	**> 25**	
Risk Assessment Zone 3	**Appreciable**	**20.0 – 24.5**	
Risk Assessment Zone 4	**Moderate**	**15.0 – 19.5**	
Risk Assessment Zone 5	**Mild**	**0 – 14.5**	
* Table adapted from Table 20.1 “Assessment of Overall Soil Corrosivity to Steel” C. P. Dillon, “Corrosion Control in the Chemical Process Industries” Second Edition, Materials Technology Institute of the Chemical Process Industries, Inc. and Washington Suburban Sanitary Commission			
** Sample Values from Actual Project			
Utilize values from this table for overall corrosivity risk assessment to evaluate the level of corrosion control methods required.			
NACE Materials Performance July 2002			

Where sufficient data is available and verified, especially on existing pipe systems, it may be more economical to modify the proposed 25-point risk assessment chart to reflect the experience of that utility than to conduct additional soil chemical analysis. The risk assessment table in these cases may be more practical for new pipe construction, especially transmission lines, where there is limited information about the route. Or where there is limited soil chemistry information or operating experience, use of soil resistivity data used alone may be adequate to determine the corrosivity zone (especially if the resistivities are very low), similar to the U.S. Bureau of Reclamation procedure.

A 2004 article by Kroon et al. utilized the AWWA C105 10-point soil evaluation system as a basis to develop the Design Decision Model™ (DDM™). [34] The DDM™ is a proprietary risk-based corrosion protection design strategy for buried ductile iron piping that was developed in co-operation with DIPRA and some of the ductile iron pipe manufacturers. This risk model attempts to consider both the likelihood and consequence of pipe failure due to external corrosion. Likelihood factors related to soil conditions include moisture content, resistivity/conductivity, groundwater influence, pH, chloride ion concentration, sulfide ion concentration, and redox potential, and the presence of known corrosive environments and the impact of buried bi-metallic couples. Consequence factors include pipe diameter, pipe repair considerations, depth of cover, and availability of alternative sources of supply. The DDM™ then recommends the level of corrosion control options available. The corrosion control alternatives vary from bare pipe (with standard asphaltic shop coating and annealing oxide), to polyethylene encasement‘ to polyethylene encasement with joint bonding, supplemented at times with corrosion monitoring, life extension cathodic currents (partial protection levels) with or without polyethylene encasement, and full cathodic protection current densities.

While this DIRPA-supported model does finally acknowledge that other corrosion control measures in addition to polyethylene encasement alone may be appropriate at times, there are still some questions and concerns expressed by some corrosion engineers and owners with its use. One of the major difficulties with this evaluation process is that the risk assessment model is proprietary, so how the model works and the basis of the model recommendations cannot be evaluated and validated by the end user. The life extension corrosion control option (partial protection current densities) also requires an acceptance of some level of corrosion being allowed to continue. Polyethylene encasement electrical shielding with polyethylene encasement is also not addressed in this model. The author’s acknowledge that electrical shielding will occur under the intact polyethylene encasement but claim that the cathodic protection will provide protection at the damaged locations and the intact polyethylene encasement will provide protection at undamaged intact locations. The life extension current determinations and corresponding corrosion rate reductions were also based on short-term laboratory analysis testing and may not accurately reflect current densities required for long-term adequate partial protection levels under actual field conditions. Also, in the most corrosive environment, cathodic protection of bare pipe is recommended to minimize the chance of electrical shielding in the most corrosive conditions. The model does not reflect the practice of using tight-bonded coatings or address the reduction in current densities required for tight-bonded coated pipe versus either polyethylene-encased or bare pipe. Trying to protect bare structures will dramatically increase cathodic protection costs, shorten anode life, and because of the high amount of current required may increase the degree of interference problems.

CORROSION CONTROL CONSIDERATIONS

To provide similar estimated life between steel and ductile iron pipelines, the degree and type of corrosion control measures will differ, based on the corrosivity rating of the environment. Ductile iron and steel corrode at about the same rate in corrosive environments, so the corrosion control measures we recommend are similar in the most corrosive environments but different in the less corrosive conditions. The different levels of corrosion control methods do not cost the same and do not provide equal levels of corrosion protection. Selection should therefore be based on specific project requirements and risk assessment evaluations.

For ductile iron, the corrosion control options we recommend to the designer and owner includes the following:

- Tight-bonded coating with corrosion monitoring and cathodic protection
- Polyethylene encasement with corrosion monitoring and cathodic protection
- Polyethylene encasement with corrosion monitoring
- Polyethylene encasement alone
- Bare pipe only (shop asphaltic coated), optional increase of wall thickness

Since steel is a thin-walled pipe, we normally require the same corrosion control measures in all soil conditions. Since ductile iron corrodes at a similar rate as steel in the most corrosive environments, we utilize similar corrosion control measures as for steel in the most aggressive burial conditions. Therefore the corrosion control measures we normally recommend for buried metallic transmission pipe and appurtenances (steel, ductile iron, and cast iron) in Corrosivity Zones 1 and 2 for transmission lines are the same and consist of tight-bonded coatings, select backfill, electrical continuity, test stations, cathodic protection, and electrical isolation to provide complete protection and meet similar project design life.

Table 4
Typical Range of Corrosion Control Recommendations for Steel, Ductile Iron, and Plastic Transmission Pipes in Different Risk Assessment or Soil-Corrosivity Zones

Risk Assessment or Soil Corrosivity Zone	10% Probability Soil Resistivity (Ohm-cm)	Corrosivity Rating	Steel Pipe	Ductile Iron Pipe	Metallic Fittings (Steel, Cast Iron, or Ductile Iron) on Plastic Pipe
1	0 – 2,000	Extremely Corrosive	Joint Bonds, Insulators, Test Stations, Tight-bonded Coatings, and Cathodic Protection	Joint Bonds, Insulators, Test Stations, Tight-bonded Coatings, and Cathodic Protection	Tight-bonded Coatings, SST or FBE Bolts, Bonding, Zinc Galvanic Anodes, w/ Test Stations Approx. 10% of Time
2	2,001 – 3,000	Very Corrosive	Joint Bonds, Insulators, Test Stations, Tight-bonded Coatings, and Cathodic Protection	Joint Bonds, Insulators, Test Stations, Tight-bonded Coatings, and Cathodic Protection	Tight-bonded Coatings, SST or FBE Bolts, Bonding, Magnesium Galvanic Anodes, w/ Test Stations Approx. 10% of Time
3	3,001 – 5,000	Corrosive	Joint Bonds, Insulators, Test Stations, Tight-bonded Coatings, and Cathodic Protection	Joint Bonds, Insulators, Test Stations, (Ductile Iron Monitoring Stations), Micro-Perforated Polyethylene Encasement, and Cathodic Protection	Tight-bonded Coatings, SST or FBE Bolts, Bonding, Magnesium Galvanic Anodes, w/ Test Stations Approx. 10% of Time
4	5,001 – 10,000	Moderately Corrosive	Joint Bonds, Insulators, Test Stations, Tight-bonded Coatings, and Cathodic Protection	Joint Bonds, Insulators, Test Stations, (Ductile Iron Monitoring Stations), and Polyethylene Encasement	Tight-bonded Coatings, SST or FBE Bolts, Bonding, and Magnesium Galvanic Anodes
5	Over 10,001	Mildly Corrosive	Joint Bonds, Insulators, Test Stations, Tight-bonded Coatings, and Cathodic Protection	Bare or Polyethylene-encased and Joint Bonds Depending on Owner Preferences, Pipe Size, and Design Life	Tight-bonded Coatings, SST or FBE Bolts, and Bonding Light Walled DIP or Heavy Walled Fittings with PE (Polyethylene Encasement)

NOTE: Use of CP with loose-bonded coatings (PE encasement) assumes that an 80 to 90% level of CP of pipe is possible and that owner acknowledges and accepts some risk of corrosion even with adequate cathodic protection potentials. It is anticipated that protected protection levels and current densities may be provided to the majority of the pipe at torn or damaged polyethylene encasement locations, but may not reach all of the corrosion cell areas under undamaged encasement because of electrical shielding. CP of loose-bonded coatings not recommended per NACE SPO169 and DOT. Additional DI monitoring stations will be required to verify protection levels under loose-bonded PE encasement. Higher cost for additional CP including higher O&M costs and replacement should be factored into life-cycle costs of CP systems for loose-bonded coatings (polyethylene) because of higher current density requirements. Current density requirements can be 75 to 100 times higher than that of tight-bonded coatings in wet soils and 25 to 50 times in dry soils. If owner requires 100% level of protection with minimum risk of leaks, use CP with tight-bonded coatings or bare only (typically, tight-bonded coated options are more economical). Considering use of micro-perforated polyethylene encasement although no commercial installation to-date. Current requirements may be higher than standard polyethylene encasement but lower than bare pipe. Consider anti-MIC polyethylene encasement for all sewer pipelines and soils with possible MIC activity.

Life-cycle Costs

The corrosion control approach should assess risk and recommend solutions that provide equal design life for the different pipe materials being considered. A pipeline with a correctly designed, installed, and maintained corrosion control program will have lower life-cycle costs than a pipeline that fails prematurely and has to be replaced before the design life is met. To obtain actual life-cycle costs, one must calculate the costs for the different corrosion control methods, including anticipated leak repair costs. The life-cycle costs shown in Figure 14 are based on the corrosion protection methods cost with leak frequency and repair costs of Rossum's equations for pitting rates. [35 36] Field experience indicates that if the steel and cast iron constants are averaged for ductile iron in the Rossum calculations, the predicted values approximate actual corrosion pit depths more closely. [37]

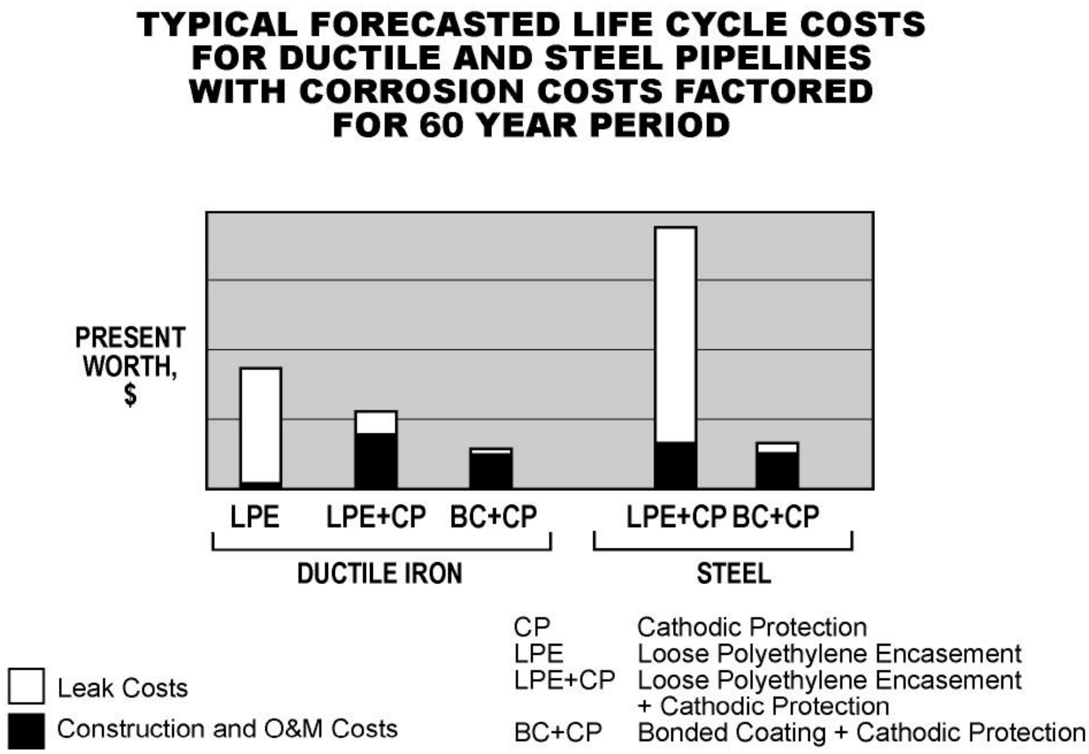

Figure 14
Comparison of Life-cycle Costs for South Dakota 24-Inch Pipelines

The life-cycle cost analysis example is for a major pipeline project in South Dakota. It matches our experience that ductile iron's heavier wall allows it a lower life-cycle cost compared to steel, given equal corrosion control measures in the more aggressive soils. Conversely, in the most aggressive soils, coated steel with cathodic protection will provide a longer life than polyethylene-encased ductile iron with or without cathodic protection. In aggressive soils, ductile iron with only polyethylene encasement will have a shorter life than cathodic protected ductile iron with either polyethylene encasement or tight-bonded coating. Although the initial construction and O&M costs are lowest for polyethylene alone, this option is the highest life-cycle cost for the given 60-year period because of the high leak repair costs based on a less effective coating value used for the polyethylene encasement in Rossum's equations.

This life-cycle cost difference will increase even more over a longer period of time. For this 24-inch transmission pipe project, the construction and O&M costs with the tight-bonded coating and cathodic protection corrosion control measures for both the ductile iron and steel pipe alternatives were within $1 per lineal foot. Surface preparation and coating application costs per square foot for either steel or ductile iron are approximately equal. Cathodic protection costs are the same except for the joint bonding costs. The major difference is the additional cost of joint bonding ductile iron on shorter 20-foot (6.096 m) joints rather than the longer 40-foot (12.192 m) joints for steel. Also, as shown in the life-cycle evaluation, the tight-bonded coated ductile iron life-cycle costs are lower than for tight-bonded coated steel, with leak costs included. This cost difference is simply a function of the thicker-wall ductile iron pipe compared to the thinner wall steel pipe in the leak calculations.

The life-cycle cost analysis indicates the same type of findings reported in an economical analysis comparison for different types of coatings by Noonan - that is, the better the coating quality, the less the life-cycle costs. [38] East Bay Municipal Utility District in Oakland, California, conducted a study based on more than 45 years of their experience with cathodic protection of water distribution and transmission lines. Bianchetti concluded that the benefit-to-cost ratio for cathodic protection of water distribution piping was 24 to 1, and for transmission water piping an even higher ratio of 42 to 1. [39] Bianchetti and Perry likewise demonstrates the economical advantages of using a coating with cathodic protection in the more corrosive environments in a paper that presented life cycle cost comparisons for six corrosion control mitigation options for various types of metallic pipelines.[40]

DUCTILE IRON CORROSION CONTROL EVALUATION FACTORS

Corrosion Control Evaluation Factors

If one depends on the pipe wall thickness for the sacrificial corrosion allowance with either bare pipe or a passive protection system (polyethylene encasement), there may be minimal pipeline structural integrity left at the end of design life. If you apply tight-bonded coating and cathodic protection to a metallic pipeline or fittings, at the end of design life you typically will still have the structural strength of the pipe or fittings left. Theoretically, it is possible to extend the life of a metallic pipeline or fitting almost indefinitely by providing adequate cathodic protection levels. This should be considered during the selection of the appropriate corrosion control methods based on the importance of the line, desired design life, and projected replacement costs. Other factors to consider for each of the corrosion control measures are summarized below.

Transmission versus Distribution Pipe Sizes and Pressures

The problem with leaks on small distribution size pipe is minor compared to the problems created when large transmission pipelines (>24-inch) fail. The use of polyethylene encasement on larger diameter piping must be considered carefully given that historically there have been numerous failures at damaged or undamaged polyethylene encasement locations on smaller distribution pipe size.

There is also the chance that more damage to the polyethylene may occur on larger, heavier transmission pipe sizes and will have more serious consequences. The expense and disruption of service when a larger line fails was dramatically demonstrated during January 2000 in Cleveland where an 80-year-old 36-inch-diameter cast iron line failed. This resulted in loss of more than 25 million gallons of water into the downtown area, closing schools, businesses, and streets and affecting more than 100,000 residents.

To account for this increased risk for larger size and pressure transmission lines and to take into account the increased problems with installing intact polyethylene on larger-diameter pipe, several approaches are utilized. For the purpose of the 25-Point Corrosion Control Recommendations (Table 4) for distribution-size ductile iron, the recommended corrosion measures are less conservative by one or two zones. For example, the distribution corrosion control requirements for Zone 2 allow the use of polyethylene encasement instead of requiring tight-bonded coatings.

Bare Pipe (Shop Asphaltic Coating)

In some cases, it may be economical to utilize bare pipe (shop applied asphaltic coated) with no other corrosion control methods. While bare pipe may be economical and may provide the level of protection needed, it is harder to cathodic protect bare pipe because of the higher current densities. Generally speaking, the asphaltic coating is normally intended for temporary protection during transit for esthetic purposes and offers little if any protection against soil or immersion corrosion. However, some state that the asphaltic coating and epidermal layer may provide some protection to the pipe. [41] Michael Szeliga and others report corrosion under undamaged asphaltic (bituminous) shop-applied coating. [42]

King showed that where the shop coat and epidermal layer is undamaged they offer some protection in sulfate reducing bacteria environments.[43] He also pointed out that they observed *"the slow degradation of the bitumen coating"* and summarized that signs of deterioration of the bitumen coating were evident at the end of the 250-day test period. King observed that the quality of the bitumen and oxide layer appear to be important in delaying the onset of microbiological corrosion. The thickness of the annealing layer seemed to influence the corrosion resistance of the iron pipe, with the cast iron oxide layer generally two and up to three times that of the ductile iron. Samples where the oxide layer were intact showed a delay before active corrosion began, but once corrosion was initiated, corrosion rates rose rapidly (fifty to ninety percent). Along with Washington Suburban, Gummow, and others, we recommend that the asphaltic coating be repaired so as to not allow formation of anodic areas on the pipe, even if it is to be polyethylene encased.

Polyethylene Encasement

Polyethylene encasement consists of a 4- or 8-mil-thick polyethylene plastic sheet or tube that is placed around the pipe in the field. The polyethylene encasement acts as an unbonded coating, theoretically preventing direct contact between the soil and the pipe or fitting. The polyethylene-encasement method is promoted as an easy passive protective system that is inexpensive, requires minimum expertise to install, and minimum maintenance. In theory, an intact polyethylene encasement prevents direct contact with the soil and limits the access of oxygen to the pipe surface under the encasement. The initial high rate of corrosion slows as the oxygen supply diminishes.

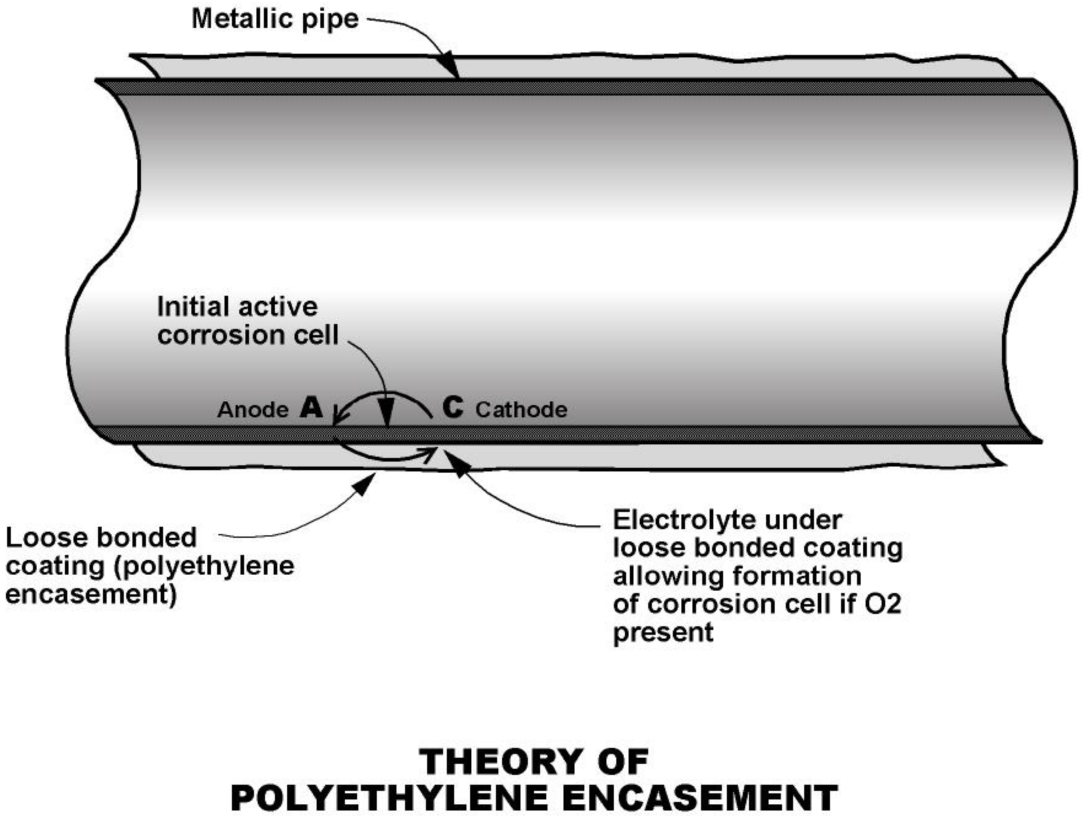

Figure 15
Theory of Polyethylene Encasement Protection

Both the ductile iron pipe manufacturers and DIPRA usually promote this passive type of protection as the principal method to control corrosion for all external ductile iron pipeline burial conditions. Although polyethylene encasement of ductile iron is an ANSI/AWWA Standard (C105)[44], it is not an NACE International Standard. Acceptance of polyethylene encasement as a successful corrosion control method is still a volatile and controversial subject in the corrosion control community.

In 1972, AWWA adopted the first standard for polyethylene encasement, ANSI/AWWA Standard C105. In 1993, the standard was revised to allow the use of either an 8-mil low-density polyethylene film or a 4-mil high-density cross-linked polyethylene film and a recommendation added that in wet conditions the polyethylene encasement should be taped every two feet around the pipe. In 2000, the standard was again revised to replace low-density polyethylene with linear low-density encasement material, and the soil resistivity ranges were modified to make the evaluation procedure values more conservative. A paragraph was added that acknowledges that other corrosion control methods besides polyethylene encasement may be required in certain “uniquely severe” circumstances.

Polyethylene Encasement Issues

Historically, the contention was that all that is needed for corrosion control on ductile iron is polyethylene encasement and that joint bonds (electrical continuity) and/or cathodic protection are not needed. For unbonded coatings such as polyethylene encasement, water and oxygen can enter under the polyethylene encasement. Corrosion activity can occur at these areas. Proponents maintain that the high initial corrosion rate on the ductile iron pipe underneath the polyethylene encasement will slow down as the oxygen is consumed and is not replenished. [45] They point to the success of polyethylene encasement in all types of burial environments, based on the amount of iron pipelines with this type of protection and results of test digs at selected locations around the United States. Typically, the test dig findings report that the polyethylene-encased ductile iron pipe is always in "*very good to excellent*" condition. However, other corrosion control experts and utilities have found differing conditions. Therefore, some corrosion consultants and utility corrosion departments recommend corrosion control measures for ductile iron and cast iron materials in the more aggressive soils that involve more than just polyethylene encasement, especially for transmission pipelines.

An article in the 2003 November AWWA Journal describes one method of protecting ductile iron pipe that is used overseas - a type of zinc-rich coating with or without a top coating or polyethylene encasement. This zinc-rich coating or metalized zinc spray application method is covered by various standards, including the ISO Standard 8179. [46] This approach, used since the 1960s, appears to have some benefit because the zinc coating acts as a sacrificial anode and provides some degree of cathodic protection to the pipe. The thickness of the zinc coating greatly affects its durability, life, and costs. [47] The zinc coating is generally top-coated with a thin asphaltic or resin coating and in more corrosive locations with polyethylene encasement or other type of top coatings (epoxy, tape, etc.) to help extend its life.

To date, there is no comprehensive long-term independent study that predicts the effect that polyethylene encasement has on the life of cast iron or ductile iron pipe. Our experience indicates that polyethylene encasement, if installed correctly and if the oxygen is not replenished, does offer improved protection compared to bare ductile iron pipe. This assumes the following conditions:

- The polyethylene encasement is installed and remains in an intact condition. Minimal damage from future construction activities occurs.
- The amount of oxygen under the polyethylene encasement is consumed and not replenished.
- The soils are not too corrosive and no high dissolved salts are present.
- No bacteria or microbiological corrosion (MIC) conditions are present.
- Not utilized for sewage force mains where a small leak and resulting anaerobic condition can create an environment where catastrophic type failures may and have occurred.

Polyethylene encasement is relatively inexpensive. In 1998, DIPRA estimated $0.05/pipe inch in diameter/lineal foot for material and installation costs. [48] Our experience is that the actual cost is somewhat higher, in the $0.15 to $0.20/pipe inch in diameter/lineal foot, but nevertheless relatively inexpensive. So the initial capital cost of ductile iron pipe with polyethylene encasement is very low compared to other supplemental measures for corrosion protection (bonded coatings, cathodic protection, joint bonding, monitoring stations, etc.).

We have had good experience with the use of polyethylene encasement in soils that are not too corrosive, such as in Boise, Idaho. However, in more corrosive soils we have seen problems in the use of polyethylene encasement with pipe failures in short periods of time, such as less than five years in Cape May, New Jersey. These performance differences may be for a number of reasons, some of which are summarized below.

Difficulty and Importance of Correct Installation. Since the passive polyethylene encasement protection system is totally dependent on an intact condition to perform correctly, proper installation is even more important than for a tight-bonded coated pipe backed up with cathodic protection. This is because typically the polyethylene encasement system is recommended by its proponents to be installed on electrically discontinuous pipelines with no cathodic protection. Corrosion will occur at any defects in the encasement at the same or higher rate than for bare pipe. Special care must be taken at fittings with sharp bolts, angles, and edges to not damage the encasement. The polyethylene encasement must be securely fastened to the pipe and sealed at joints to minimize locations where changing groundwater can replenish the amount of oxygen or salts under the encasement. It also needs to be carefully backfilled with materials and techniques that do not damage the polyethylene encasement. The polyethylene encasement should be carefully inspected and all defects repaired for the system to work correctly.

In their paper "Making Baggies Work on Ductile Iron Pipe," Bell and Romer caution that additional attention to design and installation items not described in relevant national standards are also required for polyethylene-encased pipelines. [49] They recommend that electrical isolation from attachments and appurtenances be provided, that the joints be intentionally bonded to provide electrical continuity, that corrosion monitoring stations be provided, and cathodic protection be provided if necessary. The additional steps they recommend for polyethylene encasement pipelines to effectively monitor it and preserve corrosion control options in the future include:

- Use thrust blocks instead of bolted restrained joints to minimize the chance of damage to the polyethylene encasement.
- Use wax tape coating (ANSI/WWA 217) to protect the fitting and minimize tears to the polyethylene encasement.
- Tape the joint ends with two complete wraps of appropriate polyethylene tape (AWWA 209), continuously seal the seams, and overlap the tube form encasement and secure in place with tape wraps at two-foot (2') increments in a spiral winding.
- Always bond the joints for electrical continuity to allow future monitoring and to allow application of cathodic protection if required. They advise that only joint bonds with exothermic welds be relied on for permanent electrical joint continuity. They also caution that bond plates should be used on polyethylene-lined pipe to minimize damage to the internal lining from the joint bond exothermic welds.
- Apply cathodic protection if required.
- Use select backfill to minimize possible damage to the polyethylene encasement and reduce the corrosivity of the environment.
- Wrap the appurtenances, including the tees, taps, valves, and copper services.

It is well documented that corrosion will occur at damaged polyethylene-encasement locations or at bare locations where the polyethylene is not installed correctly, is damaged, or decomposes prematurely. When the oxygen supply or corrosive salts are replenished at the pipe wall, at tears in the polyethylene encasement, or where the groundwater changes, the high initial corrosion rate can continue at the rate similar to bare pipe. Tests conducted by various sources, including a cast iron and ductile iron manufacturer, confirmed that corrosion damage will occur when the wrap is cut or damaged and the pipe is in direct contact with the corrosive soil. [50]

Part of the problem in accepting polyethylene encasement as the only corrosion control method is the perceived difficulty in installing an intact polyethylene-encasement protection system. Some people question whether it can be done correctly under actual pipe installation production conditions, while others point out the difficulties in providing an intact polyethylene-encasement system even when careful attention and inspection are provided. Some authorities express concern that accelerated corrosion may occur or be concentrated at defects in the polyethylene encasement (similar to that reported at tight-bonded coating defects), particularly in areas of corrosive soils, galvanic corrosion cells, or stray current (interference). Some utilities do not allow polyethylene encasement because they do not believe it can be installed correctly in an intact condition. Some require select sand backfill to minimize damage to the wrap. Others use geotextile fabric in rocky areas or soils to provide protection and minimize backfill damage. Others require double or triple layers to try to provide an intact condition. Some place size and weight restrictions on the pipe in an effort to minimize possible damage to the polyethylene encasement.

Researchers in Britain have concluded that there may be problems with polyethylene encasement in the following conditions *"…if the sleeving is damaged during installation or in service, if it acts as a channel for flowing groundwater, or if soil is trapped between the film and the pipe surface during the sleeving operation. Indeed, the small number of corrosion failure incidents which have been reported for PE sleeved iron mains have largely been attributed to one or more of the above factors. Such sensitivity of performance to installation practice is common to the majority of site-applied corrosion protection systems. Unfortunately, it is sometimes difficult to achieve the required quality of wrapping under field conditions, and this undoubtedly applies to routine water distribution mainlaying activities in the UK. In particular it is difficult in practice to avoid damaging the PE sleeving and trapping clods of soil between the film and pipe surface. Furthermore, the additional complications associated with sleeving pipes in the field tend to reduce mainlaying rates, which in operational terms make this technique less than entirely satisfactory."* [51]

DeRosa and Parkinson indicate that because of these problems with polyethylene encasement, supplemental protection of sprayed zinc metal with applied to the pipe. They claim that the zinc coating system is superior to the bituminous coating. They caution that in *"…certain environments in which the present zinc coating may not be adequate alone, e.g. particularly in acidic soils, in situations in which the pipeline is exposed to moving water, and in soils of exceptionally high corrosivity."* 1985 T

The use of polyethylene encasement was initially proposed for buried storage tanks as an in-expensive method of corrosion protection for a short time period. The difficulty in installing an intact polyethylene encasement was also demonstrated during initial testing by John Vrable of U.S. Steel Applied Research Laboratory.[52] He conducted a field test with polyethylene-encased steel drums to evaluate if polyethylene encasement could be used as a simple, inexpensive corrosion control method to protect underground fuel storage tanks, similar to that being promoted for cast iron pipe. This test showed that polyethylene encasement was not successful in protecting the steel drums with loss of air pressure in all drums in less than six months burial. His field test indicated that all corrosion pits on the test drums occurred at the polyethylene encasement coating defects. He concluded that *"Because the backfill used* *in this test contains little abrasive material, these results indicate that the 8-mil (203.2 μm) thickness polyethylene covering cannot withstand normal physical damage associated with underground application of steel."*

Also as pointed out in a 1972 paper by John Fitzgerald, III the polyethylene encasement is basically a disbonded wrapper. [53] He states *"corrosion can occur under the wrapper, however, if ground water enters the space between the tank and the wrapper, through, perhaps a tear in the wrapper. The wrapper is not adequate for use with cathodic protection since protective current will not readily flow under the wrapper at a holiday. As with disbonded pipeline coatings, corrosion can continue beneath the wrapper even if cathodic protection is applied. A good quality, well-bonded coating supplemented with cathodic protection is still considered the best approach for steel tanks."* Mr. Fitzgerald also cautioned that various other "gimmicks" are likely to appear in the corrosion field and stressed that the corrosion engineer must balance any initial cost savings against replacement costs and safety hazards caused by ineffective corrosion protection. As foretold by Mr. Fitzgerald, polyethylene encasement soon fell out of favor in the steel tanks market.

This is similar to that of true pipe installation conditions where the contractor is more concerned about production rates than an intact polyethylene encasement. The major problem is that installation of an intact polyethylene sleeve is difficult if not impossible to achieve because of field construction problems. Tears or rips in the sleeve are also difficult to detect by inspection at fittings or on the bottom of the pipe and during the pipe backfilling. DIPRA stresses that an intact polyethylene encasement can be installed very simply. [54] If there are problems, they routinely report that any leaks are at rips and tears in the polyethylene encasement and claim that it was caused by "contractor error." There is concern in the corrosion control community that the successful protection of the ductile iron pipe is dependent on an intact sleeve that may not be "constructible," as an example in an NACE Materials Performance article, "Corrosion of Ductile Iron Pipe: Case Histories," points out. This paper documents the difficulty in installing an intact polyethylene encasement system even when carefully installed and closely inspected. [55] To combat damage to the polyethylene encasement during construction, warning labels have been placed on the encasement highlighting that it is a corrosion protection method and that all damage should be repaired, as shown in the following photo.

Figure 16
Printed Warning on Polyethylene Encasement

However, there is still difficulty and problems with possible damage to the polyethylene encasement at bolted type fittings, if not carefully installed so as to not damage the polyethylene encasement as shown below. This is the reason that some recommend use of petrolatum wax tape at these types of locations or use of the multiple layers of polyethylene encasement.

Figure 17
Damage to Polyethylene Encasement at Bolted Fittings

Other problems with polyethylene encasement are to find the actual leak location and repair the pipe without getting contaminants and soil inside the encasement. In some cases, the water or wastewater has migrated for some distances under the polyethylene encasement before if enters the soil and then daylights. This makes locating and repairing the corrosion damage more difficult and expensive. Also during leak repairs, taps, or when the polyethylene encasement is exposed, additional care must be taken to not damage the polyethylene encasement or allow contamination under the polyethylene.

In Cape May, New Jersey, we observed a corrosion failure on ductile iron pipe in 500 ohm-cm soils in less than five years. DIPRA initially reported that this was due to stray current from a nearby power pole guy. After our testing indicated that the current flow was going the wrong direction on the pole guy to cause any interference, DIPRA changed their conclusion to say that the bottom of the pipe joint was not completely covered and it was “contractor error”. This is just another example of how hard it is to install and inspect the polyethylene encasement correctly in all locations.

Compounding the difficulty of installing undamaged polyethylene encasement in an intact condition is that some polyethylene encasement material may not meet AWWA C105 standards. This is especially disturbing since it is critical that the polyethylene encasement remain in an intact condition long term to perform correctly. Several ductile iron pipe manufacturers are attempting to correct this problem by conducting their own testing and certification of polyethylene suppliers, but are still having quality control issues. To minimize possible use of sub-standard polyethylene encasement products, we recommend that both the polyethylene-encasement manufacturer and the pipe manufacturer conduct the required AWWA C105 performance testing and certify all polyethylene encasement, and that the pipe manufacturer be required to provide the certified polyethylene-encasement material for the project.

Experience and problems with polyethylene encasement have been documented, mostly in the Canadian cities, which have aggressive soils. [56] [57] In a paper presented at the 2001 AWWA Infrastructure Conference, the City of Calgary compared their experience with bare and polyethylene-encased ductile iron (PDI) and concluded: *"From the two studies, we can say roughly that PDI offered us about a 30% average reduction in corrosion rate and consequently in corrosion break rate, where no (uninsulated) copper services are involved."* [58] Presently, they continue to require tight-bonded coatings and cathodic protection on ductile iron pipe in their corrosive areas. They also have experienced no problems with tight-bonded coated ductile iron pipe with extruded polyethylene (yellow-jacket), which they have used extensively in their water system since 1975.

Corrosion under Undamaged Polyethylene Encasement. Although the majority of failures on polyethylene-encased pipe are reported to be a result of damage to the polyethylene encasement or incorrect installation, studies for several other large water distribution systems have also reported corrosion of ductile iron pipe under loose, undamaged polyethylene encasement.

Vancouver, B.C., Canada

In 1986-1987 the City of Vancouver, B. C., conducted testing to determine the success of polyethylene-encased ductile iron that had been installed between 1970 and 1972 to replace corroding cast iron pipe sections. Three sections of polyethylene-encased ductile iron pipe were excavated, two approximately 100 feet (30.48 m) and the third approximately 170 feet (51.8 m) long. The pipe was approximately 14 years old and buried in 300- to 900-ohm-cm soil. The pipe sections were pressure tested to 650 psi with no leaks visible. After abrasive blasting, the pipe was found to have three corrosion penetrations through the pipe wall, with only the cement lining holding the water pressure. The replacement ductile iron pipe was tape coated and cathodic protected. The corrosion consultant at the site felt that some of the pipe corrosion occurred under undamaged polyethylene encasement, since it was difficult to align polyethylene-encasement damage with the corrosion pits. [59]

The most amazing thing that this study indicated was the ability of the cement mortar lining and the graphitized corroded ductile iron to still hold the 650-psi pressure, as shown on the following three Figures. This may be a major reason why we have not yet seen an appalling number of failures in distribution pipe pressures. It appears that although some polyethylene-encased ductile iron pipelines may actually be corroding, a significant number of leaks may not have appeared yet because of the ability of the cement mortar lining and/or graphitization to hold normal water or sewage liquid pressures. However, it is our experience, as shown by the examples in this paper, that the number of failures for both transmission-type bare and polyethylene-encased iron piping has been increasing as the lines grow older and the size of the corrosion-damaged areas become larger.

Figure 18
1986 Vancouver Polyethylene-encased Ductile Iron Pipe Evaluation Three Locations

Figure 19
Vancouver, BC, 445 Feet Removed and Examined in Three Sections, Replaced with Tape Coated DIP with Cathodic Protection

Figure 20
Vancouver, BC, Polyethylene-encased Ductile Iron Pipe After Sandblasting Where Graphitization and Cement Mortar Lining Previously Held 650-PSI Water Pressure

Laramie, Wyoming

In Laramie, Wyoming, the city historically had suffered few corrosion leaks on a 24-inch bare ductile iron and cast iron transmission line. But after the first leak occurred (from plug-type corrosion the size of a fist) on the 32-year-old ductile iron line and additional testing/excavations were conducted on both the ductile iron and cast iron sections of the line, it became apparent that both types of iron pipe were severely corroded in numerous locations and that the only thing holding the water pressure was the cement mortar lining and the graphite shell of the pipe. After several catastrophic leaks resulting in summer water rationing, the 5-mile-long ductile and cast iron pipeline was replaced at a cost of over $3 million, less than five years after the first leak was discovered in 1996. [60]

Sheridan, Wyoming

In Sheridan, Wyoming, approximately 18 feet (5.486 m) of a 16-inch (40.6 cm) ductile iron line that had been polyethylene encased was excavated. The ductile iron line was approximately 14 years old and buried in 1,350 ohm-cm soils. The polyethylene encasement appeared to be installed correctly and was folded and taped in place per ANSI/AWWA specifications (Figure 21).

Although no major tears were found, we observed corrosion under undamaged polyethylene encasement. The pit was located at 3 o'clock on the pipe and was approximately 3/16-inch (180 mil-depth) in the Class 50 (340 mil) DIP, as shown in Figure 22. However, we could not correlate the presence of soil or contamination inside the polyethylene encasement or a polyethylene defect at the pipe pit location, see Figure 23. Testing indicated that the polyethylene-encasement material met AWWA standards.

Figure 21
Sheridan, Wyoming, Ductile Iron Polyethylene Encasement Folded and Taped In Place, With No Encasement Damage Visible

Figure 22
Sheridan, Wyoming, Polyethylene-encased Ductile Iron Pipe With Major Pit at 3 O' Clock, 180 Mils in 340 Mil-Thick-Pipe Wall 14-Year Burial

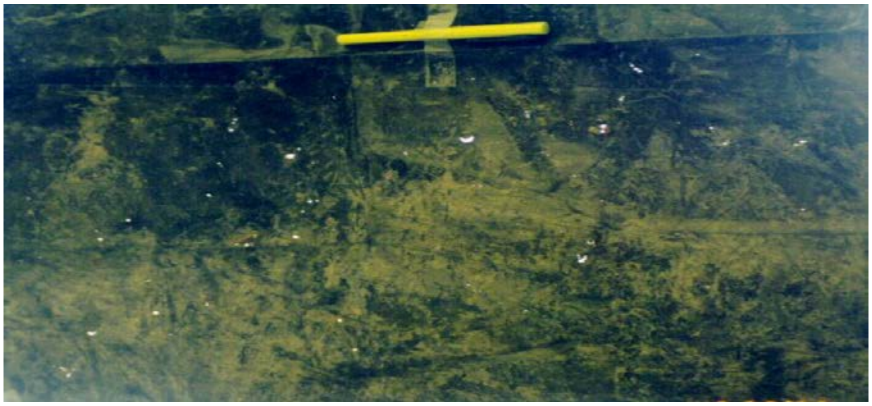

Figure 23
Sheridan, Wyoming, Polyethylene Encasement Minor Tears Unable to Line Up With Pipe Pitting Damage

Marston Lake (Denver), Colorado

A review of data also confirms that corrosion can occur under undamaged polyethylene encasement. At the Marston Lake-test location in Denver, Colorado, DIPRA conducted testing in moist to wet soils in the 1,350 ohm-cm range. The polyethylene encasement was intentionally damaged on the samples to determine the amount of protection under damaged and undamaged polyethylene encasement. In 1983, after 8.75 years of exposure, the last six samples were excavated and examined. After blast cleaning, several pipe samples displayed corrosion pitting under undamaged polyethylene encasement. One sample indicated that the pit depth was 43 mils at the polyethylene encasement-damaged location. However, there was deeper pitting damage (68 mils, 150 percent of original) on the opposite side of the pipe under undamaged polyethylene encasement. [61]

Figure 24
Marston Lake (Denver) Site 68-Mil Pit Under Undamaged Polyethylene Encasement in 8.75 Years

San Diego, California

In San Diego, California, a 24-inch (60.96 cm) polyethylene-encased ductile iron line that was installed in 1967 was considered a success story in 1981 [62] and 1986. This line was abandoned in 1995. [63] The City of San Diego also reported that the parallel 16-inch (40.64 cm) cast iron line installed in 1961, also cited as an example of successful polyethylene encasement [64] [65] , had corrosion problems and averaged two leaks per year. San Diego has seen corrosion of both ductile iron and cast iron under undamaged polyethylene encasement. [66] They now require tight-bonded coatings (polyurethane) and cathodic protection of their ductile iron lines. They also report good success with use of petrolatum wax tape for wrapping valves and fittings since beginning its use in 1989.[67] Figure 25 is an example of the corrosion damage that they observed in less than 8-year burial on the 24-inch polyethylene-encased ductile iron pipe that was initially thought to be a successful polyethylene-encasement project.

Figure 25
San Diego, CA, 8-Year-Old 24” Polyethylene-encased Ductile Iron Pipe at Former DIPRA Test Site

Honolulu, Hawaii

The City and County of Honolulu water system suffered numerous corrosion leaks on polyethylene-encased ductile iron; leaks have been reported as far as four to five feet from tear locations in the polyethylene encasement. [68] [69] The City and County of Honolulu Board of Water Supply now requires tight-bonded coating and cathodic protection on all ductile iron pipelines.

MIC Corrosion. An area of corrosion research and investigation that is receiving a lot of attention is the field of microbiologically influenced corrosion (MIC). This type of corrosion is influenced in some manner by the activities of bacteria in anaerobic conditions. Corrosion researchers in the pipeline industry report that the MIC situation allows continued metal consumption of shielded pipe surfaces under the disbonded coating films, even though the pipeline may be cathodically protected. MIC is often associated with disbonded coatings and pipe surface locations blocked from adequate cathodic protection current densities. [70] [71] Some pipeline corrosion control personnel report that MIC is one of the most serious forms of corrosion attack because it causes localized pitting, which can cause a more rapid rate of corrosion, even with protected cathodic protection potential levels in the immediate vicinity of MIC corrosion location. [72]

In 1972, Dr. John Harris of Kansas State University investigated the influence of sulfate-reducing bacteria on cast iron pipe with polyethylene encasement for the Cast Iron Pipe Research Association (CIPRA now known as DIPRA). [73] His evaluation of two test sites with 12- and 14-year burial at Overton, Nevada, indicated that the polyethylene encasement seemed to control corrosion from sulfate-reducing bacteria. The report concluded: *“Although this report indicates that sulfate-reducing bacteria are not a serious problem with the Poly wrap system, it also indicates that carefully controlled laboratory research is needed.”* It should be noted that the testing was conducted on pipe test samples that had been carefully encased in polyethylene, not a pipeline installed in changing burial and groundwater conditions. MIC researchers at Montana State University noted that MIC corrosion could be a major concern under loose-bonded polyethylene encasement in high sulfate soils. They also recommended further testing to determine the amount of possible attack. [74]

Colorado Springs, Colorado

One of the major problems with determining the relationship of leaks to polyethylene condition is that the leak repair crew is more intent on finding and fixing the leak, not assessing the condition of and preserving the polyethylene e encasement for evaluation. However, as utilities realize the importance of assessing the polyethylene encasement condition and vacuum excavation techniques become more common, the condition of the polyethylene at leak locations should be able to be better preserved and documented. Also, a 1999 AWWA article pointed out that as more sophisticated leak and pipe corrosion evaluation techniques are available, owners and utilities will be able to do more evaluations of pipe condition and detective work on why failures are occurring. [75]

Colorado Springs, Colorado, has utilized these types of pipe inspection techniques. Their two parallel 10-inch polyethylene-encased 18-mile (28.96 km) ductile iron force mains had a high number of external corrosion pits. In 1982, DIPRA had conducted a survey for these routes and indicated that the only corrosion protection needed was polyethylene encasement. In 1997, when the lines had two corrosion leaks that led to wastewater releases into a nearby stream and an EPA investigation, the City conducted additional testing to determine if the leaks were isolated problems or if corrosion threatened the integrity of the system and if the pipelines had to be replaced.

Pipe inspections for approximately 18,500 feet of the pipe were made with a "smart pig" located inside the pipe. Specialized smart pig testing (remote field eddy current) indicated that the corrosion was external and showed numerous areas of severe pits. This study reflected an alarming number of pits in some areas, and certain locations displayed uniform corrosion on the bottom portion of the pipe. The smart pigging data used to classify the wall thickness resulted in the following preliminary classifications.

- Class A – 81% of tested section – good condition – 76 to 100% remaining wall thickness
- Class B – 16% of tested section – moderate condition – 51 to 76% remaining wall thickness
- Class C – 2% of tested section – major corrosion – 26 to 50% remaining wall thickness

Two additional leaks occurred in 1998 in the Class A and B locations, so the pigging firm reevaluated the data. Since the pitting corrosion was so widespread and the parallel lines could not be considered to be reliable, the City in less than 18 years had to complete a phased $13 million replacement project using high-pressure non-metallic pipe. In some cases (as shown in the following three Figures), the polyethylene lining was the only thing holding the wastewater pressure. It is speculated that these areas of pitting concentrations and uniform corrosion damage most likely were caused by MIC from the sewage being trapped between the polyethylene encasement and the pipe wall. The consulting engineer's and the City's corrosion engineers both reported that they observed corrosion under undamaged polyethylene encasement on these lines. [76] [77]

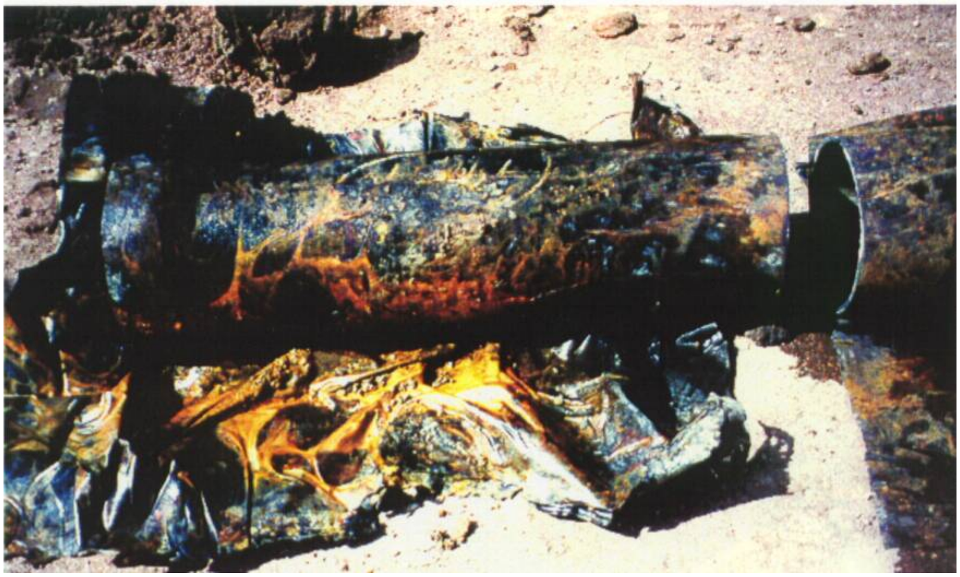

Figure 26
Colorado Springs Parallel Sewer DIP Force Mains With Major Corrosion Observed Under Both Damaged and Undamaged Polyethylene Encasement

Figure 27
Colorado Springs, Colorado, Force Main Corrosion Where Only Polyethylene Lining Was Holding Sewage Pressure

Figure 28
Colorado Springs, Colorado, Sewer Force Main With Uniform Pitting on Pipe Bottom from MIC Corrosion

A similar MIC corrosion failure on a polyethylene-encased wastewater line was reported in a July 2001 Materials Performance article on ductile iron corrosion case histories. [78] This raises concern as to whether there is an increased risk if wastewater pipelines and sewage mains are polyethylene-encased. An increased danger of MIC may occur when sewage (a food source) is trapped inside the polyethylene encasement, either from previous corrosion wall penetrations or naturally occurring leaks at joints.

In an attempt to minimize MIC concerns, one manufacturer has developed a polyethylene encasement with anti-MIC additives to minimize possible MIC problems. [79] These anti-MIC polyethylene-encasement materials appear to hold some promise and are now available for commercial distribution. We have used the anti-MIC polyethylene encasement on a project in Minnesota. Additional independent testing and long-term evaluations still need to be completed to confirm the influence of MIC under polyethylene encasement on both water and wastewater lines.

Cathodic Protection

Electrical Continuity. As with all metallic (steel, concrete cylinder, cast, or ductile iron) pipelines or fittings to be cathodic protected or where stray current needs to tested for or mitigated, electrical continuity is required by bonding all joints not welded, insulated, or threaded. All joint bond wires or bond straps should be insulated or coated to minimize creation of galvanic corrosion cells. Cast iron charges should be used for all cast iron and ductile iron pipe and fittings to avoid poor connections and high-resistant joint bonds.[80] Two or more joint bonds on 12-inch-diameter (30.48 cm) and larger pipe are recommended for redundancy. Joint bonding guidelines for electrical bonding of ductile iron pipe, with suitable conductor size and number recommendations for different pipe diameters, have been developed. [81] This guideline states that cast iron charges should be utilized with ductile iron to obtain better results and recommends that the joint bond resistance should be "*… such that its/their resistance is generally no greater than that of a single length of pipe.*" The Bureau of Reclamation guidelines and others allow a maximum resistance increase of 250 percent for each pipe joint length. For larger-diameter pipe (above 40-inch or 101.6-cm diameter), it may be appropriate to modify the total bond resistance per joint based on specific project requirements and attenuation calculations. Typically, joint bonds should be visually inspected, physically tested, and measured electrically with a digital low-resistance ohmmeter (DLRO) to assure a good low-resistance connection.

Cathodic Protection with Loose-Bonded Coatings. There are no industry standards for cathodic protection of polyethylene-encased ductile iron pipe. It is a controversial and volatile issue in the corrosion industry. There are diametrically opposed viewpoints with a wide variation in acceptance. The major problem is that no long-term, non-biased scientific study shows whether polyethylene encasement with cathodic protection works and to what degree. This controversy is based in part on whether and to what degree the polyethylene encasement may electrically shield (block) direct current from the pipeline surface.

It is well documented in the oil and gas field that corrosion failures occur on pipelines at locations where the cathodic protection current is blocked or shielded from the anodic area on the pipeline by a disbonded coating. We personally have witnessed corrosion failures on two oil pipelines in Wyoming and Utah that displayed adequate cathodic protected potentials at that location according to ground surface measurements, but the coating was electrically shielding the protective current from the pipe surface.

The most recognized standard for corrosion control on buried piping is the NACE Standard SP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems. This standard does not recognize and in fact advises against the use of loose or unbonded coatings with cathodic protection. It covers different pipe materials, including steel, ductile iron, cast iron, aluminum, and copper. In Section 4.2 under Corrosion Control, the following items that are directly attributable to both tight-bonded and loose-bonded (polyethylene encasement) coatings are covered:

> *4.2.1 Corrosion control must be the primary consideration during design of a piping system. Materials selection and coatings are the first line of defense against corrosion. Because perfect coatings are not feasible, cathodic protection must be used in conjunction with coatings. For additional information see Section 5 on Coatings and Section 6 on Criteria and Other Considerations for Cathodic Protection.*
>
> *4.2.2 New piping systems should be coated unless thorough investigation indicates that coatings are not required. (See Section 5 on Coatings)*
>
> *4.2.3 Materials and construction practices that create electrical shielding should not be used on the pipeline. Pipelines should be installed at locations where proximity to other structures and subsurface formations will not cause shielding.*

Section 5 of this standard also covers recommended coating selection and characteristics for cathodic protected pipelines:

> *Section 5.1.2.3 Pipeline coating systems shall be properly selected and applied to ensure adequate bonding is obtained. Unbonded coatings can create electrical shielding of the pipeline that could jeopardize the effectiveness of the cathodic protection system.*

The Federal Department of Transportation, Office of Pipeline Safety does not allow use of loose polyethylene encasement for ductile iron and cast iron pipelines (oil and gas) because of concerns about electrical shielding with cathodic protection and MIC corrosion. The ruling by the Office of the Secretary of Transportation as published in the Federal Register (Volume 36, No. 126) states:

"Because of the unique physical characteristics of its corrosion process (graphitization), and because of the normal allowance of extra wall thickness, it was argued in some of the comments and at the hearing on July 20, 1970, that it should not be required that newly installed cast or ductile iron be coated and cathodically protected, but that a loose polyethylene wrap should be considered adequate for proper corrosion control. But moisture and ground water, which can enter the loose polyethylene wrap, may form a breeding ground for bacteriological corrosion. Moreover, in the event there is a break in the polyethylene wrap and corrosion started, there is no way to apply cathodic protection to prevent further corrosion. The current would be intercepted by the insulation qualities of the polyethylene sheet, and cathodic protection would only reach the metal under the break. The other areas under the wrap that may be corroding from water and access to oxygen would not be cathodically protected. Therefore, new cast iron and ductile iron have not been treated differently from steel and a coating bonded to the pipe and cathodic protection are required."

The DOT was petitioned for reconsideration of this ruling, and a second review was granted. Upon further review the previous ruling was again confirmed and upheld by the Office of the Pipeline Safety as published in the Federal Register (Volume 36, No. 166).

Electrical Shielding Concerns. Fitzgerald points out that the polyethylene sleeves are not really coatings since they are not bonded to the pipe. [82] The polyethylene sleeve does help separate the pipe from the environment and will help increase the life expectancy of the pipe if installed correctly. However, he cautions that where the sleeve is torn, soil and/or water may create a corrosive condition *"under what is effectively a disbonded coating."* In these locations, he summarizes, cathodic protection can protect the area of the tear or puncture, but since cathodic protection is not effective under disbonded coatings, an active corrosion cell may develop. If these active corrosion cells are electrically shielded by the polyethylene encasement from the cathodic protection current, the corrosion can continue and result in an attack on the pipe wall under the loose or disbonded coating as shown on the Figure below:

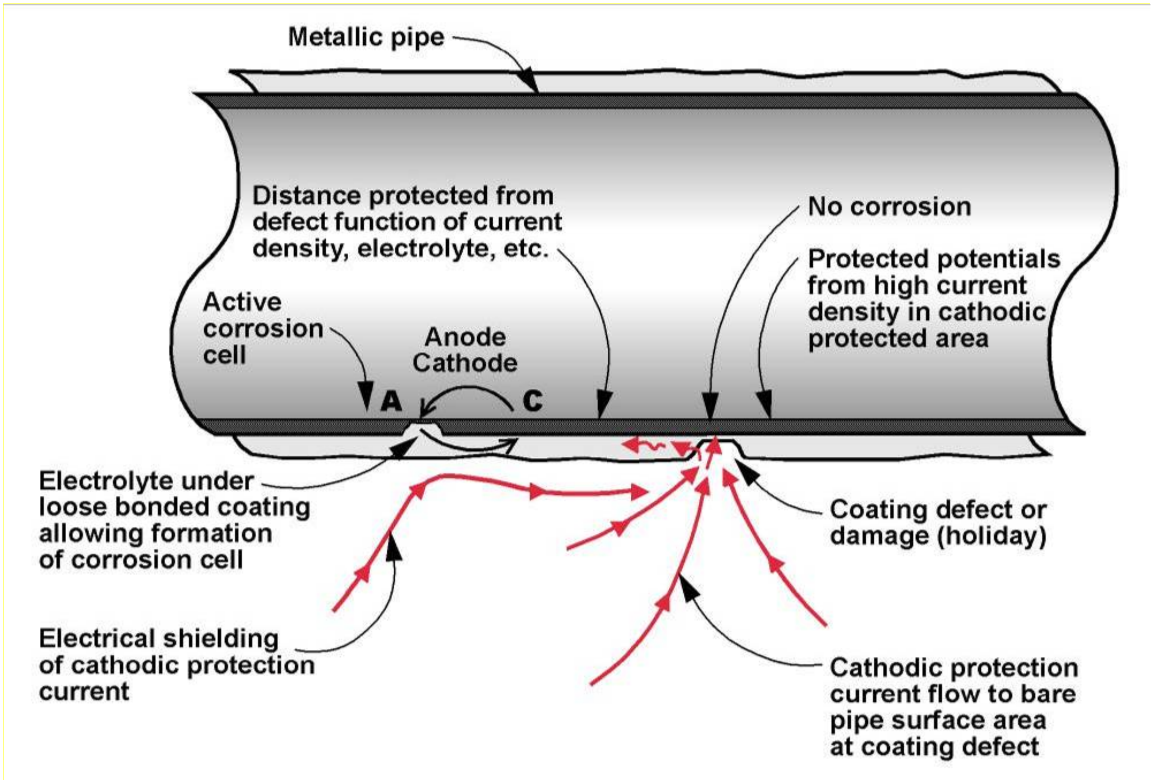

Figure 29
Cathodic Protection Electrical Shielding with Polyethylene Encasement

Because of the concern with electrical shielding of the cathodic protection current on metallic pipelines with disbonded or unbonded coatings, some corrosion control firms do not normally recommend cathodic protection of polyethylene-encased lines and utilize tight-bonded coatings with cathodic protection for lines that are critical. [83] This skepticism is based on the problems experienced in the oil and gas industry with electrical shielding of cathodic protection current from the pipe surface by loose or disbonded coatings. Based on his review of papers written from 1945 through 1992, Duane Tracy suggested that additional studies were still required, but concluded that cathodic protection may not be adequate under disbonded coatings when MIC corrosion is present. [84] The distance from a holiday or damaged coating location, that cathodic protection current can reach under disbanded coatings or loose polyethylene encasement is a function of the electrolyte resistivity, the current density and the annular space. Peabody reported that the practical distance that current can be projected into a small space is approximately 3 to 10 times the thickness of the annular space between the pipeline surface and the insulating barrier. [85]

In a paper given at the 1989 NACE national conference, DIPRA president Troy Stroud acknowledged: *"Polyethylene also possesses excellent dielectric properties, which enable it to effectively shield ductile iron pipe from low-level direct current and thus greatly reduce the possibility of stray current corrosion."* [86] Therefore, it seems logical to assume that polyethylene encasement may shield the pipeline to some degree from the protective effects of the cathodic protection direct current also. This is an area that needs additional independent long-term study.

Cathodic Protected Polyethylene-encased Pipelines. There has been limited use of cathodic protection on polyethylene-encased ductile iron pipelines. The one study most often referenced is a large transmission pipeline project in North Dakota, where an impressed current cathodic protection system was utilized to provide protection to both coated steel and polyethylene-encased ductile iron pipe. [87] For this project, steel electrical resistance probes were placed both in the pipe backfill and under the polyethylene encasement to try to determine cathodic protection levels under the encasement. The authors report that the corrosion rate of the steel probes with cathodic protection current averaged approximately 0.0189 mils per year (MPY) for probes located inside and outside of the encasement. Their testing indicated that the current requirements for polyethylene-encased ductile iron pipe are on average 28 times as great as the tape-coated steel.

The authors do not state whether their tests prove that cathodic protection can be successfully applied to polyethylene-encased ductile iron, but do conclude the following:

- The corrosion rates of DIP at undamaged encasement are low and governed by soil corrosivity, dissimilar metal, environmental corrosion cells, etc.

- A clean sand backfill reduces corrosion rates below that of native soil backfill.

- There is still an area of controversy regarding shielding of polyethylene-encased ductile iron pipe from cathodic protection currents and they recommend that probes be provided under encasement for other projects.

- They also state that to avoid technical issues, the probes should be made of the same material as the pipeline.

- They concede that the actual corrosion rates measured by the electrical resistance probes are most useful for comparison purposes only and *"may not be an accurate measurement of the true pipe corrosion rate."*

On a cathodic-protected polyethylene-encased parallel force main in Denver, Colorado, we installed a distributed impressed current groundbed in the mid-1980s to try to minimize electrical shielding problems on the two parallel polyethylene-encased sewage force mains. The anodes were laid at specific spacing next to the parallel lines along the entire pipeline route. Potentials made with both permanent reference electrodes and portable reference electrodes at the ground surface indicate that levels of potentials provided are adequate for protection and even along the lines. Some differences were noted between the inside and outside permanent reference cells.

On projects in Wyoming, Montana, and Minnesota, we utilized a ribbon-type anode system on the polyethylene-encased ductile iron line with ductile iron monitoring test stations We feel that it is be prudent to consider use of an impressed current distributed-type groundbed or a galvanic anode ribbon-type system next to the pipeline to help resolve or minimize electrical shielding problems on polyethylene-encased ductile iron lines.

<u>Corrosion Damage on Cathodic Protected Polyethylene-encased Pipelines.</u> While the projects in the Dakotas show some promise with cathodic protection of polyethylene-encased ductile iron pipelines, there is evidence of corrosion occurring on other cathodic protected polyethylene-encased pipelines. One project in South Dakota has reported one leak on the cathodic protected polyethylene-encased ductile iron pipe and some high readings were observed on one of the resistance probes.

Firewater and potable water impressed current cathodic protected ductile iron pipelines were excavated to repair broken test leads at a power plant in Vernal, Utah. Surface and corrosion was found at two locations under intact polyethylene encasement on the waterlines. The corrosion engineer who observed the corrosion damage stated that it was not from polyethylene-encasement coating defects, soil under the polyethylene, or cathodic protection stray currents at a broken joint bond. The soil resistivities at these locations were approximately 3,000 ohm-cm. Estimated pit depths were 30 to 60 mils at one location and 125 mils at the second location in less than 10 years' burial. [88]

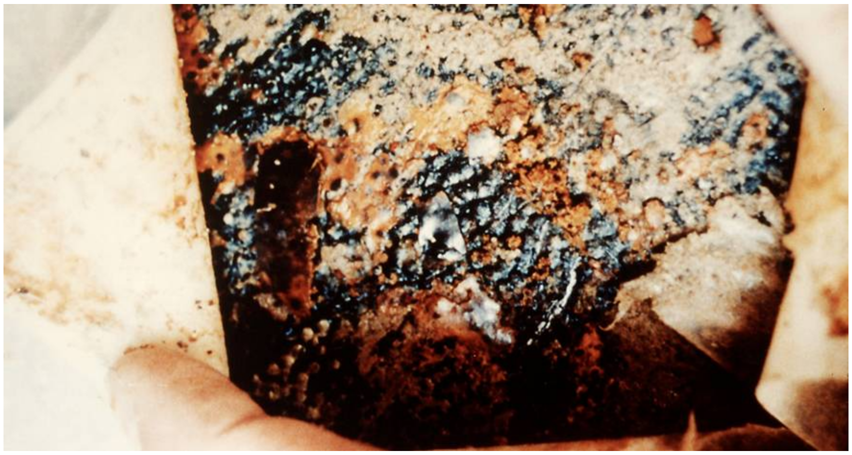

Figure 30
Vernal, Utah, Electrical Shielding Of 10-Year Old Cathodic Protected Pipeline With 30- to 60-mil Deep Pipe Under Intact Polyethylene Encasement

Figure 31
Vernal, Utah, 125-Mil, (0.3175 cm)-Deep Corrosion on CP Polyethylene-Encased DIP

Additionally on a sewer line at the same plant, a number of leaks occurred on the cathodic protected polyethylene encased ductile iron pipeline. In 2006, after only 22 years, this same ductile iron sewer line was replaced because of six leaks. The corrosion engineer stated that it was not possible to determine if the corrosion damage was due solely to external or internal corrosion or a combination of the two. The pipe was replaced and discarded before any additional forensic testing could be completed. It is possible that some of the external corrosion damage could have been influenced by MIC activity, which indicates that cathodic protection may not be able to prevent MIC corrosion because of electrically shielding of the protective current from the polyethylene encasement. The pipeline displayed a black layer with graphitization of the polyethylene-encased pipe (Figure 32). Even with a measured adequate protection levels with a potential of -1.1 volts to a copper-copper sulfate reference electrode at ground level at that location.

Figure 32
Vernal, Utah, CP Polyethylene-Encased DIP with Black Layer and Graphitization Under Polyethylene Encasement

Sheridan, Wyoming

In Sheridan, Wyoming, portions of two different polyethylene-encased ductile iron pipelines were removed for road construction after approximately 5 years' burial. The pipelines were installed with a galvanic anode system and adequate protection levels were indicated by surface potential measurements. The copper service was coated, insulated, and cathodic protected, and the polyethylene encasement was reported to be in good condition prior to the pipe removal. The pipe surface under the polyethylene encasement showed visual evidence of surface corrosion. Theoretically, if the cathodic protection system was working correctly and sufficient current was reaching the pipe surface, there should be no visible corrosion. The corrosion, albeit only surface, seems to be an indication that the polyethylene encasement was electrically shielding the pipe or influencing the potential measurements.

Figure 33
Sheridan, Wyoming, Surface Corrosion Indicating Possible Electrical Shielding Of Cathodic Protection With Loose-Bonded Polyethylene Encasement

California City, California

In a California City, a large corrosion leak developed on a cathodic protected 14-inch polyethylene encased ductile iron pipeline after approximately 8 years (1975 to 1983).[89] Cathodic protection had been installed in 1979 on the ductile iron pipeline that was located in extremely corrosive tidal muck soils (< 1,000 ohm-cm). When the pipe was excavated to repair the leak, it was found that there were three through wall penetrations. The leak was caused by the largest wall penetration, which was approximately 2.76-inches by 5.75-inches in size. Testing indicated that the joint bond wires appeared to be electrically good. Later conversations with the California City Engineering Department in September 2008 indicated that the ductile iron pipeline had been abandoned and replaced with a concrete cylinder pipeline in 1987 after only 12 years of service.

Figure 34
California City, California Corrosion Leak on Cathodic Protected Polyethylene Encased 14-inch Ductile Iron Pipeline

In 2001, Richard Bonds, DIPRA Research and Technical Director, said that at that time there were no standard or studies that could confirm or deny that cathodic protection can be effectively provided to polyethylene-encased ductile iron piping or that electrical shielding by the polyethylene encasement is a problem. He stated that within the next few years they will start excavating cathodically protected polyethylene-encased ductile iron pipe samples at their test locations. At that time they did not know to what degree it would work or the amount of electrical shielding or monitoring problems.[90] Discussions in 2001 with corrosion personnel Tom Johnson at the United States Bureau of Reclamation and Vince Hawk of the Army Corp of Engineers indicated that they have not completed or were not aware of any comprehensive study that confirmed if cathodic protection of polyethylene-encased ductile iron pipe can provide adequate protection to all areas on the pipeline. [91] [92] Additional independent long-term testing is still needed to verify and confirm the actual level of protection provided and degree of electrical shielding. Ash and Horton have also started preliminary testing in the Florida Everglades to determine electrical shielding, polarization, and current densities for polyethylene-encased pipe samples. [93] In addition, one polyethylene-encasement manufacturer is experimenting with perforated polyethylene encasement (similar to the perforated rock shield concept) in an effort to minimize cathodic protection shielding. [94]

Presently we believe the micro-perforated polyethylene encasement may show some promise in minimizing concerns about electrical shielding. Initial field trials in the Florida Everglades show positive results. Their initial data at current densities of 1.1 to 3.0 milliamps per square foot resulted in development of calcareous deposits at the perforations with no evidence of external corrosion under the polyethylene encasement. It is anticipated that the current density required for protection per square foot will be somewhere between the amount required for bare pipe and polyethylene encased pipe. It should be less than bare pipe and more than polyethylene encased pipe simply as a function of the amount of pipe exposed because of the micro-perforations. The size of the micro-perforations should be small enough to prevent soil and contaminants from contacting the pipe but large enough to allow current to reach the pipe surface. Presently we have specified the micro-perforated pipe on a project in Wyoming that was bid in 2010, but the ductile iron pipe alternative was not selected by the Contractor.

<u>Cathodic Protection Current Requirements for Polyethylene-Encased Pipelines.</u> Another consideration is the higher amount of cathodic protection current required on a polyethylene-encased pipeline compared to a tight-bonded coated pipeline. This affects not only ac power and maintenance costs, but also the number of groundbeds required and their future replacement costs. Historically, design current densities for achieving full cathodic protection for bare surfaces (as-manufactured cast or ductile iron) are often in the 10.8 to 32.4 mA/m^2, (1 to 3 mA/ft^2) range depending on soil corrosivity. [95] For as-manufactured ductile iron pipe with the standard asphaltic coating, Kroon reports that a design current density of about 1.08 mA/m^2, (0.1 mA/ft^2) may provide enough protection to effectively quadruple the pipe service life based on short-term E-Log I laboratory studies. [96]

The Schiff study on the North Dakota pipeline, where an impressed current cathodic protection system provided protection to both coated steel and polyethylene-encased ductile iron pipe, indicated that the initial current requirements for polyethylene-encased ductile iron pipe was approximately 15 to 30 micro-amps per square foot, depending on the different pipe sections. Comparison of the overall initial current density for all of the sections indicated an average of 23.3 micro-amps per square foot for polyethylene encasement compared to an average of 0.832 micro-amps per square foot (28 times) for the similar-sized tight-bonded coated pipeline. It is our understanding that the present current requirements for the tight-bonded coated sections are still the same as the 1991 initial current densities reported, but that the current requirements for some of the polyethylene sections have increased dramatically, doubling from the initial 28-time average to more than 60 times that of the coated pipe per square foot current density in some areas. Discussions with the pipe designers indicate that the increased current requirements are due to polyethylene-encasement damage from the sharp angular base rock placed for pipe support in the wet areas. [97] In these areas, larger rectifiers had to be installed to provide additional current. [98]

We have observed higher current density requirements on polyethylene-encased ductile iron structures than those initially referenced in the North Dakota project literature. Discussions with the cathodic protection designer/installer for another large water project in the Dakotas indicated that they utilized 50 micro-amps for the initial design current for polyethylene-encased pipe but because of problems they now use 75 to 100 micro-amps as their minimum initial estimated design current density. [99] In low-resistivity soils, we have observed that 103 to 137 micro-amps per square foot is required for protection on parallel polyethylene-encased ductile iron forcemains, which were initially installed with a distributed anode groundbed in 1984 (Denver, Colorado). In salt-contaminated soils, we have seen the polyethylene-encased pipe current density requirements increase to more than 670 micro-amps per square foot (Cape May, New Jersey, and Trinidad-Tobago). For these reasons, with polyethylene encasement, we typically use current densities of 25 to 50 times that of tight-bonded coated pipe for dry soil conditions and 75 to 100 times in wet and low resistivity soils.

Figure 35
Denver, Colorado, Distributed Impressed Current Anode System for Dual Force Mains (103 to 137 Micro-Amps/Square Foot Current Requirement)

Figure 36
Trinidad-Tobago Polyethylene-encased Ductile Iron Pipe High Current Requirement in Low Resistivity Salt Contaminated Soils (>700 Micro-Amps/Square Foot)

Schramuk and Rash report that a current density of 65 micro-amps per square foot (0.700 mA/m^2) was required for cathodic protection of a new polyethylene-encased ductile iron water transmission pipeline.[100] Other corrosion consultants report that the coating efficiency level of protection provided by polyethylene encasement can vary from 4 to 20 percent bare.[101] Waters states that the major influence of the higher cathodic protection current requirement for polyethylene encasement is the increased cost of the larger cathodic protection system including power costs. He concludes that a tight-bonded coated pipe is more cost effective to cathodically protect than a polyethylene-coated pipe of the same size and length. The increased costs to consider include additional power line extensions, right-of-way, design and installation, annual maintenance and testing, ac power and operations, and earlier groundbed replacement because of the higher current output required for the less electrically efficient polyethylene encasement compared to most tight-bonded coatings. Therefore, current requirement calculations must be carefully selected for design purposes based on the specific pipe conditions, route corrosivity, coating type, coating condition, and project design life. Higher current densities are also recommended for locations of possible MIC corrosion activity and graphitized pipe.

Where complete protection of the ductile iron pipe is desired, many large utilities are adopting the same corrosion control approach of using tight-bonded coatings and cathodic protection similar to that required for steel. [102] [103] Newport News (Virginia) Waterworks, among the top one hundred water utilities in the United States, experienced corrosion failures on some iron pipes in less than 10 years. They conducted corrosion studies and adopted specifications for both tight-bonded coating and cathodic protection on ductile iron pipe, depending on route corrosivity. [104] They gave consideration to expected pipe life, route corrosivity, and selection of proper corrosion control methods *"to assure competitive bidding on an equivalent life for different pipeline materials"* [105] [106] They concluded that while there is a cost associated with application of tight-bonded coatings, the major benefit is longer life of their pipelines and the ability to accurately monitor the condition of the ductile iron pipelines.

Accurately Monitoring Protection Levels with Loose-Bonded Coatings. The difficulty in being able to accurately detect cathodic protection levels and corrosion under disbonded or loose-bonded coatings is another problem that needs to be considered with polyethylene-encased pipelines. A 2003 article, "Corrosion Under Disbonded Coatings Having Cathodic Protection," in NACE Materials Performance, states: *"It is important to recognize that pipe-to-soil (P/S) potentials measured at the surface of the earth are not indicative of the level of CP under disbonded coating (the reference electrode cannot read through the coating to the underlying steel). Consequently, the corrosionist may believe that the pipeline is well-protected but be unaware of corrosion that could be occurring under a disbonded coating location."* The article raises concerns with electrical shielding and corrosion of cathodic protected pipelines with disbonded coating. The authors conclude: "*CP is not always effective under a disbonded coating. The general corrosion rate under a disbonded coating is determined by the O2 diffusion to the steel under the coating."* [107]

Additionally, according to an article by a researcher at Arco Technology: [108] *"A big concern regarding CP shielding is the inability to detect a problem using routine CP-monitoring techniques. If the coating has failed and is shielding, CP potentials measured along the pipeline will not indicate a problem. "Shielding" means the pipe is shielded from CP and from the ability to measure pipeline potentials. A problem is not detected until corrosion damage is discovered by use of smart pigging and bell-hole examination."*

As these articles summarize, one of the most disturbing problems and dangers with loose-bonded or disbonded coatings is that standard corrosion testing methods may not accurately indicate that there is a problem or even if the level of cathodic protection is adequate until a corrosion leak or pipeline failure occurs. Therefore, if loose-bonded polyethylene encasement is utilized, special test stations that allow adequate monitoring of the actual conditions under the loose polyethylene encasement should be considered.

Polyethylene-encased Ductile Iron Monitoring Stations. Measured potentials made inside intact polyethylene encasement will be different from those made outside of the encasement, as demonstrated in a water box. As the polyethylene encasement is perforated more frequently in the water box, the inside and outside potential values will more closely approach each other. The variation in potentials under buried conditions with different levels of polyethylene-encasement damage is not fully documented. The corrosion industry is presently trying to develop reliable methods to more accurately monitor and compare protection and corrosion measurement levels both inside and outside of the polyethylene encasement. Details of these various monitoring techniques are included below for reference.

Type T Monitoring Station

One test station is the Type PDI-T (polyethylene ductile iron-two wire) with two plastic monitoring pipes that are terminated above grade at each end of the monitoring test station. One of the perforated plastic monitoring pipes is installed inside the polyethylene encasement; the other is next to it on the outside of the encasement. The theory of the Type PDI-T test station with a plastic monitoring pipe when used with a portable Cu/Cu SO4 reference electrode is that this will allow potential measurements to be made both in the soil and under the polyethylene next to the pipeline to minimize IR drop concerns and electrical shielding questions. The moveable (portable) reference electrode and plastic monitoring pipe is based on technology originally developed for abovegrade storage tanks. With this monitoring technique, a plastic pipe is positioned under the tank. The plastic monitoring pipe is drilled or slotted to allow the reference electrode to electrically "see" the soil and metal surface potential as the portable reference electrode is moved through the plastic-monitoring pipe. This is done by pulling the portable reference electrode along the bottom of the tank inside the plastic monitoring pipe to confirm that the tank potentials from the center to the outside ring are all above protected values. The ductile iron plastic pipe monitoring station works on the same principal inside and outside of the polyethylene encasement, where a reference electrode can then be moved through the inside and outside plastic monitoring pipes and potential measurements compared to verify that the cathodic protection system is adjusted correctly to provide high enough current densities to minimize electrical shielding under the loose coating.

It is important that the polyethylene encasement is sealed at the plastic potential measurement pipe penetrations so as to not allow any additional oxygen underneath the polyethylene encasement. The inside plastic monitoring pipe should only be drilled or slotted in the area where the plastic pipe is inside the polyethylene encasement.

The beauty of the plastic pipe monitoring system is that is inexpensive and can be installed easily. It is simply a two-inch-minimum-diameter plastic pipe that is either predrilled or slotted. The plastic pipe if drilled should be inserted in a geotextile fabric sock to keep out dirt or debris. A pull wire allows a portable reference electrode to be pulled through the pipe. One plastic monitoring pipe should be placed inside the polyethylene encasement and one outside. The plastic monitoring pipe is terminated abovegrade at the monitoring test station. A portable reference electrode is equipped with a sponge and drawn through the plastic monitoring pipe. The portable Cu/Cu SO4 reference electrodes should be similar to those already used for the cathodic protection potential surveys. Some moisture inside the plastic monitoring pipes is necessary to obtain accurate potential measurements. The following three Figures show a typical Type PDI-T test station.

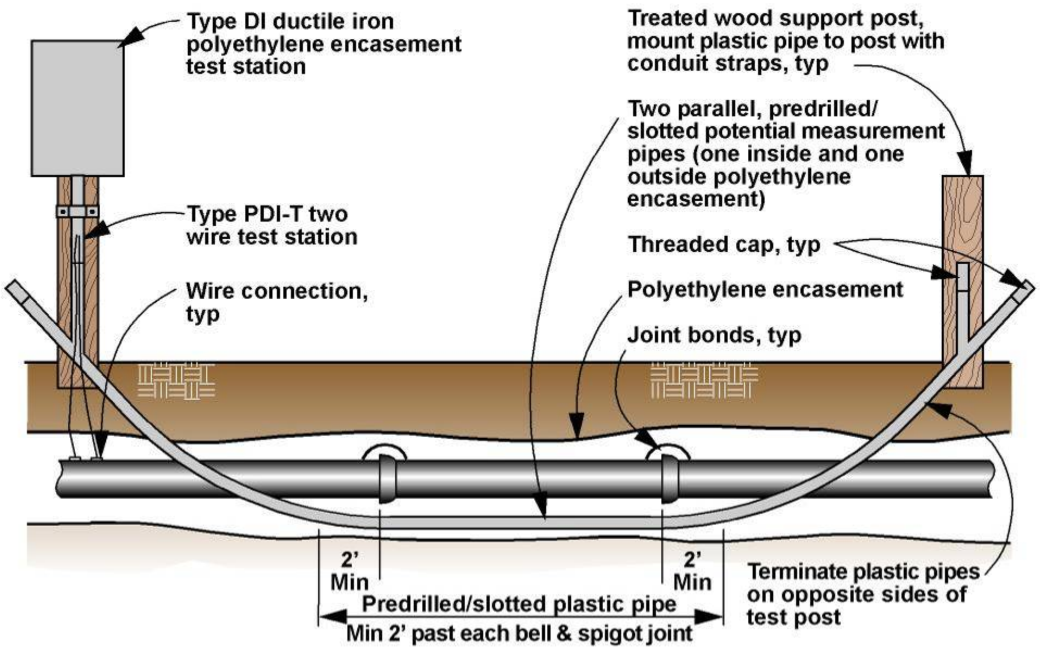

Figure 37
Typical Type T Test Station With Plastic Monitoring Pipe

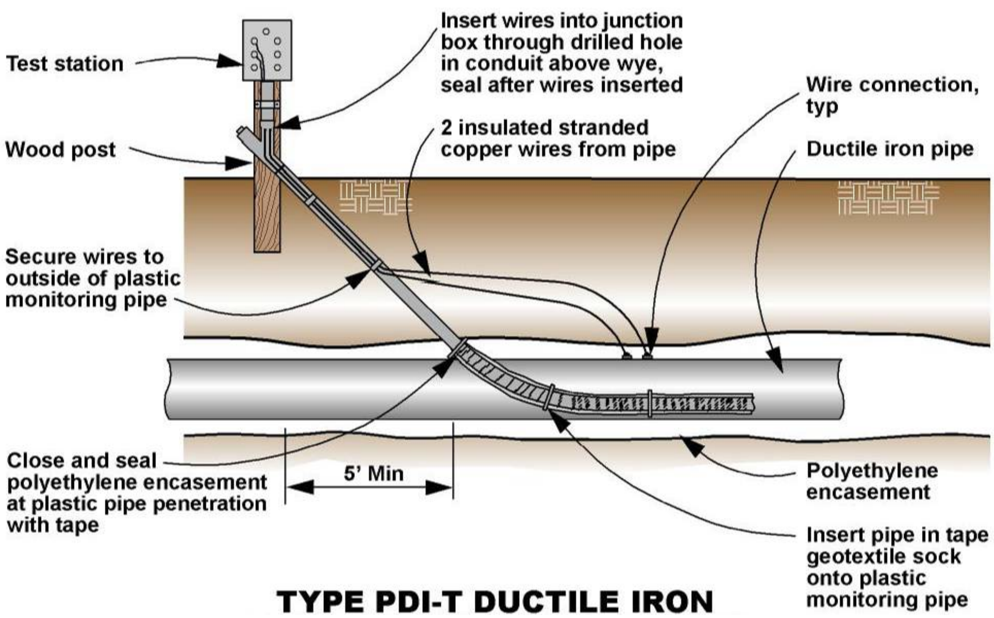

Figure 38
Test Station Installation

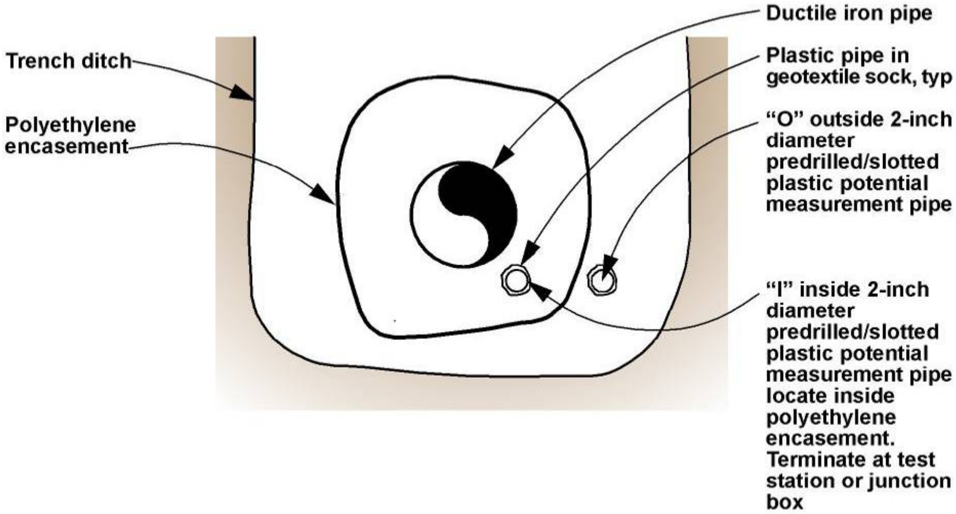

Figure 39
Ductile Iron Type PDI Plastic Pipe Monitoring System

Type M Monitoring Station

The second type of ductile iron test station, Type PDI-M (polyethylene ductile iron-monitoring), is more expensive and combines the concept of the plastic monitoring pipe with a number of other corrosion monitoring tools that have recently gained favor in the oil and gas community. The Type PDI-M combines the concept of the plastic monitoring pipes with ductile iron coupons, ductile iron corrosion resistance probes, and permanent copper/copper sulfate reference electrodes that are placed inside and outside the polyethylene encasement to more accurately determine both corrosion rates and cathodic protection levels. The following two figures show the more complicated Type PDI-M test station.

The theory of coupons is that the coupon (bare metal) is as large as the largest holiday (coating defect) on the structure or pipe. The coupon size is dependent on the application. The coupon is the same material as the structure or pipe. Normally two wires are connected to each coupon for redundancy. The wire connections must be completely insulated so as to not provide false potentials. For the purpose of our study, the coupons proposed by the different manufactures varied from 1.34 square inches to 3.85 square inches. The minimum size to be considered should be 1.34 square inches.

Two coupons are installed for each pipeline condition, so four are necessary (two inside the polyethylene and two outside). Test wires from both coupons are terminated on the test station head. One coupon is left to freely corrode and serves as the static or native state coupon. The other coupon (or protected coupon) is connected into the protected pipe by test wires through the test station and a small on/off switch. This coupon is provided cathodic protection current through the connection to the pipeline and polarizes to the same potential as a similar sized holiday or bare area on the pipe. This protected coupon serves as the polarized or cathodic protected coupon for testing.

A small on/off switch to the protected pipe test leads in the test station connects one of the coupons inside the encasement and one coupon on the outside of the encasement. This allows potential readings to be made to determine the polarized potential of the coupon and comparing them to the static coupon to determine the difference. The major advantage of the coupon technology is that it allows IR free measurements to be made without having to interrupt the cathodic protection source. The polarized potential of the coupon can be obtained by simply turning the current off to the coupon at the test station. The potential measurements can then be made either with a portable reference electrode inserted in the plastic monitoring pipe or permanent reference electrodes to minimize IR drop from current flow influences in the soil or electrical shielding from the polyethylene encasement. It is important that the coupons be electrically isolated from the pipeline under the encasement.

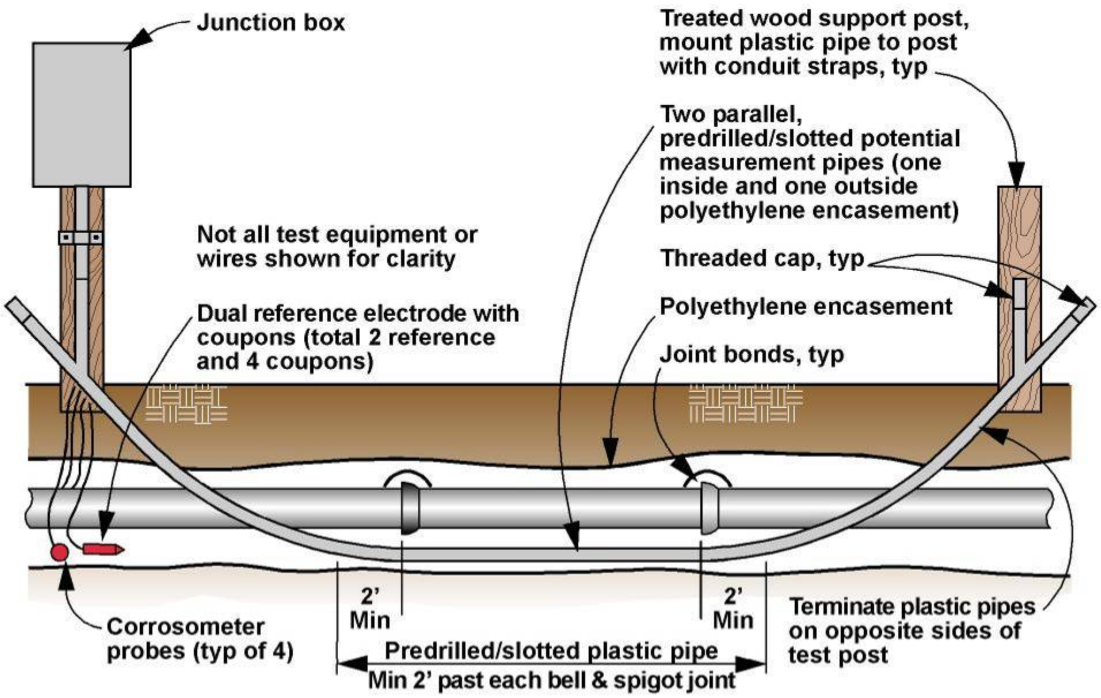

Figure 40
Typical Type M Test Station With Coupons, Resistance Probes, Reference Electrodes, and Plastic Monitoring Pipe

Another technology that has been used in the corrosion industry is to utilize a thin probe of the pipe or structure base material to measure the electrical resistance across the probe to monitor corrosion rates. This can be used for both internal and external conditions. This approach allows testing to confirm the actual amount of corrosion that has taken place. This testing consists of electrical resistance probes with an electrical resistance (ER) meter. The recommended soil side probes are approximately 50-mils thick with a 25-mil useful thickness. The proposed ductile iron probe would be similar to the Rohrback Cosasco 620HD or Tinker and Razor DIP-1 model but made of ductile iron. The resistance probes similar to the coupons would consist of one probe connected into and one not connected into the cathodic protected pipe. A special ER instrument (Corrosometer) is required to measure probe corrosion. The resistance probe test head consists of terminals to allow connection of the probes to the protected pipe with an on/off switch. A special military 6-pin terminal for connection to the Corrosometer is also required. Again a pair of resistance probes would be installed inside and outside the polyethylene encasement (four total for each test location) to determine corrosion rates both inside and outside of the polyethylene encasement for both the cathodic protected and unprotected resistance probes. Electrical isolation of the resistance probes should be maintained from the pipeline.

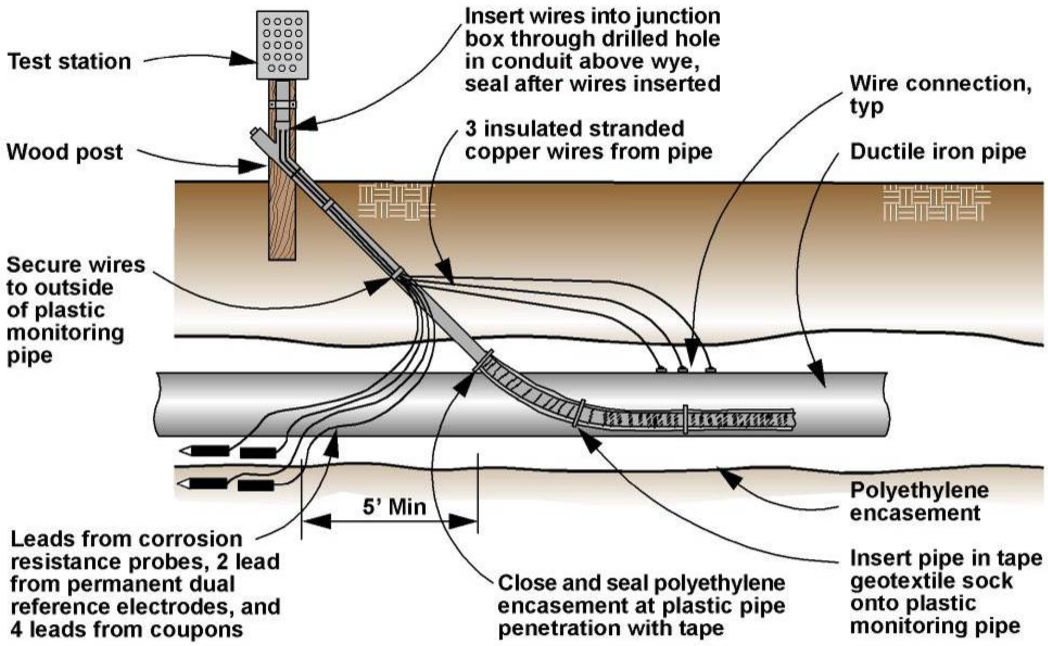

Figure 41
Type PDI-M Corrosion Monitoring System Junction Box Installation

The purpose of permanent reference electrodes is to allow testing to monitor the protection level at the pipe surface. Utilizing two permanent reference electrodes will allow the IR drop for the different locations to be determined and compared to a portable reference electrode measurement made at the ground surface and in the plastic monitoring pipes. Since there is a question on whether the plastic monitoring pipes would create an environment different from the normal polyethylene encasement, the permanent reference electrodes can be used to compare to these measurements to confirm if the plastic pipe did or did not allow different conditions and potential values. This information can be used with other data to determine if the Type PDI-T test stations with just plastic pipe will provide enough information or if the more complex and expensive Type PDI-M test stations are needed.

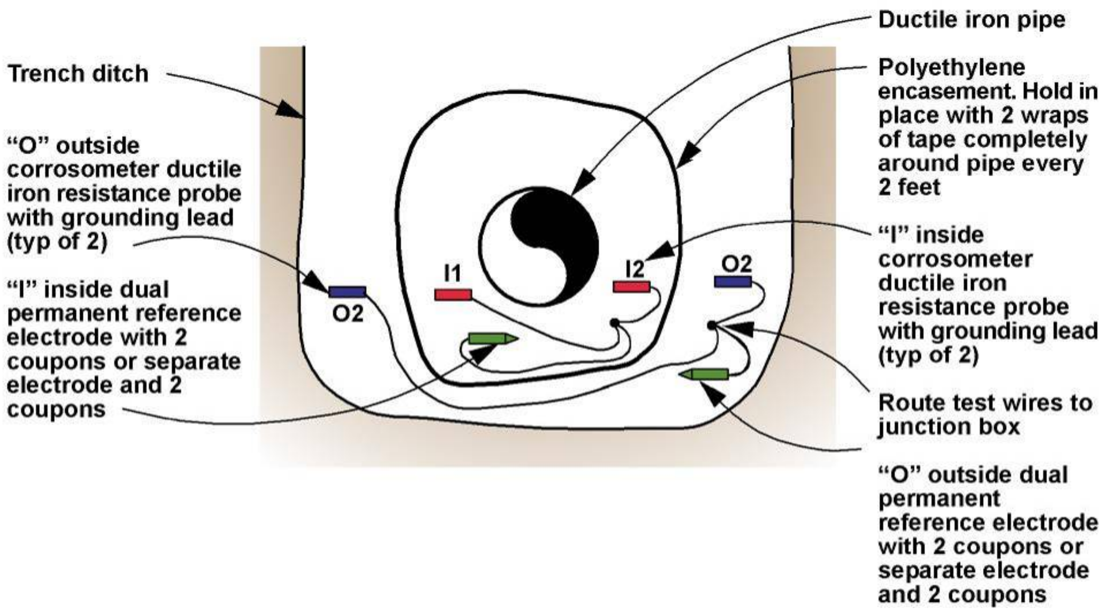

Figure 42
Ductile Iron Type PDI-M
Corrosion Monitoring System

The purpose of this type of polyethylene-encased ductile iron monitoring program is to more accurately correlate the ground surface reference electrode measurements with the different measurements made next to the pipe surface inside the polyethylene encasement. This needs to be done to account for technical concerns in the ground surface measurements, including possible IR drop errors between the surface measurement and the pipe surface, electrical shielding of the protective current to the pipe surface, and hiding of corrosion and/or low potential measurements by the disbonded or loose coating. Manufacturers have completed beta testing of the coupons and resistance probes and they are now commercially available. The pipeline project by Schiff and Associates was the first attempt we know of that used this type of test station on a cathodic protected polyethylene-encased ductile iron line. We simply tried to utilize and improve on their initial attempt to more accurately monitor corrosion and protection levels on polyethylene-encased pipe. We have installed both of these types of test stations on galvanic ribbon anode cathodic protected polyethylene-encased ductile iron pipelines in Wyoming, Montana, and Minnesota and are still evaluating the data. We are not aware of any comprehensive testing program that has monitored all of these items for any significant period of time. Additional independent long-term testing is still needed.

For the reasons mentioned above, one has to carefully evaluate that there are enough cathodic protection installations accurately monitored for a long enough length of time on polyethylene-encased pipelines to be able to prove whether cathodic protection is successful and to determine whether electrical shielding is a concern. These are considerations that should be based on the specific project requirements and the level of perceived corrosion risk.

Example of Recommended Polyethylene Encasement Installation Considerations and Techniques

Where we feel that the risk assessment for the project allows us to utilize polyethylene encasement with or without cathodic protection, we treat the polyethylene encasement like we would a coating and require that it meet certain physical characteristics with a minimum number of defects or holidays. Physical testing is required to confirm that the polyethylene-encasement material meets AWWA C105 performance criteria. We require a select backfill and require all fittings and restraints be coated with either epoxy or petrolatum tape. We require that both the pipe manufacturer and the polyethylene manufacturer provide certification and test results that prove the polyethylene encasement material supplied meets AWWA C105 performance criteria. We require tube-type encasement and require that the ends be overlapped at the joints and be taped with two full circumferential layers of polyethylene type tape suitable for burial conditions (do not use strings, rope, plastic ties, duct tape, etc.). The tube polyethylene encasement is folded over with the excess placed on top of pipe and sealed in place with tape every two feet to minimize migration of water and oxygen under the polyethylene encasement.

For all wastewater-type projects, an anti-MIC 8-mil polyethylene-encasement inner layer is used because of concerns with possible MIC from sewage leakage, similar to that used on the following sewer force-main project in Minnesota.

Figure 43
2006 Minnesota Forcemain Project Anti-MIC 8-mil Linear Low Density Polyethylene Encasement With Warning

Prior to installation of the inner wrap the pipe is visually inspected, cleaned of all dirt and contaminants, and any damage to the asphaltic shop coating repaired with a compatible (Royston 747) asphaltic-type primer. Then the anti-MIC 8-mil polyethylene-encasement layer is slid into place.

Figure 44
Inner Layer of 8-mil Anti-MIC Polyethylene Encasement

A second 4-mil cross-laminated polyethylene encasement was used for physical protection of the inner anti-MIC polyethylene-encasement layer. The encasement is folded over and taped into place every two feet to minimize the amount of oxygen available and the exchange of water under the polyethylene encasement.

Figure 45
Folding Over of 4-mil Outer Wrap of High-Density Cross-Laminated Polyethylene Encasement and Taping In Place With Identification Tape

The pipe is joint bonded and each individual bonded joint tested with a digital low-resistance ohmmeter (DLRO) shown in the following Figure as the yellow box with test leads. We recommend joint bonding for all ductile iron pipes, even bare or polyethylene-encased pipe, as it will allow the pipe to be monitored in the future for corrosion and interference. If leaks occur or if cathodic protection is installed at a later date, substantial savings can be realized if the pipeline is already electrically continuous. Not having the pipeline electrically continuous can severally limit future options if it becomes necessary to provide protection to the pipeline or if interference from other sources is suspected.

Figure 46
Joint Bonded and Polyethylene Encasement Overlap at Joint

The ends of the two layers of polyethylene encasement are overlapped and taped into place over the top of the joint with identification tape. The minimum distance past the joint for the inner wrap is one foot; the minimum distance of the second layer is at two foot spacing to minimize the seams lining up.

Cathodic protection was provided with a magnesium ribbon galvanic anode type system. To minimize the chance of electrical shielding as much as possible, the ribbon anode was placed next to the pipe for the entire distance. Ductile iron monitoring stations are installed at specified distances along the route.

Figure 47
Polyethylene-encased Ductile Iron Ribbon Anode Cathodic Protection System

Linings

Linings for ductile iron pipe for water lines generally consist of cement mortar lining with or with-out a seal coat (ANSI/AWWA C104). We normally recommend double thickness of the mortar lining. For waste water applications, historically polyurethane linings, fused polyethylene linings and ceramic epoxies have been used. Several linings that technically provided good characteristics are no longer available such as polyurethane and the Polybond II provided by ACIPCO (a fusion bonded epoxy primer with a fused polyethylene top coat). Ductile iron linings for waste water ductile iron pipelines still available in the U.S. are limited to ceramic epoxy coatings available are the Endurion Protecto 401 and Tnemec Series 431 Perma-Shield PL. Specialty linings such as glass linings are also available.

Tight-Bonded Coatings

Tight-bonded coatings provide an electrical and physical barrier against corrosion by isolating the structure from the corrosive environment. Tight-bonded coatings are attached or bonded to the underlying structure and are the “first line of defense” against corrosion. Our experience is that tight-bonded coatings, just as with polyethylene encasement, cannot be constructed in an intact condition and corrosion will occur at coating defects. Therefore, in areas where corrosive conditions or the risk assessment evaluation indicates that a tight-bonded coating is required, we recommend the types of tight-bonded coatings that will complement the cathodic protection system. This means that the coating type should not electrically shield the cathodic protection current if it becomes disbonded or fails, and should be a type that does not allow MIC corrosion under the coating.

Petrolatum Tape Coatings. One method to coat ductile iron fittings and short stub pipes is with a petrolatum wax tape coating. While not a loose coating, it is not a tight-bonded dielectric coating either. It provides protection to the ductile or cast iron pipe or fittings by physically isolating the metal surface from the corrosive environment. This type of field coating (ANSI/AWWA C217, NACE RPO375) requires minimum surface preparation and can be hand applied. It typically consists of four layers (primer, mastic filler, petrolatum wax tape, and outerwrap). It can be used both in buried conditions and abovegrade. It has been successfully utilized by San Diego since the mid-1980s as well as in Ottawa, Canada, and other utilities and agencies.

Ductile Iron Pipe Surface Preparation. Ductile iron pipelines to be coated with a tight-bonded coating should be provided bare with no asphaltic coating or provided with a primer compatible with the top coating. The surface profile of ductile iron is different from smoother steel pipe, so slight modifications in the degree of surface preparation may be necessary. Care should be taken during surface preparation to minimize delamination, slivering, or damage to the pipe surface from over blasting, high nozzle velocities, and excessive blast times for certain types of ductile iron pipe. The outer epidermal layer on some ductile iron pipe manufactured by the DeLavaud process is softer and susceptible to damage if over blasted. Typically this is not a problem on the ductile iron pipe lining, or on pipe or fittings made with sand molds, or pipe cast using a wet spray process. Some of these problems are discussed in an article by DIPRA and in the guidelines for a surface preparation standard developed by the National Association of Pipe Fabricators (NAPF).[109] [110] The NAPF 500-3 standard guidelines require that the amount and grade of cleanliness should be agreed to with the coating manufacturer and specified for the specific ductile iron pipe coating, similar to that used for the NACE and Society for Protective Coatings surface preparation standards. We recommend that the degree of surface preparation should be in accordance with the SSPC Standards and that the amount of cleaning required for ductile iron should be similar to that required for the same type of coating as steel. For example, if a near white SSPC SP-10 is required for steel, the same percentage of cleaning (90 percent) should be required for ductile iron; the only difference is in the color. Most major coating manufacturers and pipeline coating applicators are experienced with ductile iron pipe and can provide the necessary degree of surface preparation for the specific type of tight-bonded coatings with minimal to no damage to the pipe exterior surface, as shown in the following two Figures.

Figure 48
Successful Surface Preparation of Ductile Iron Pipe

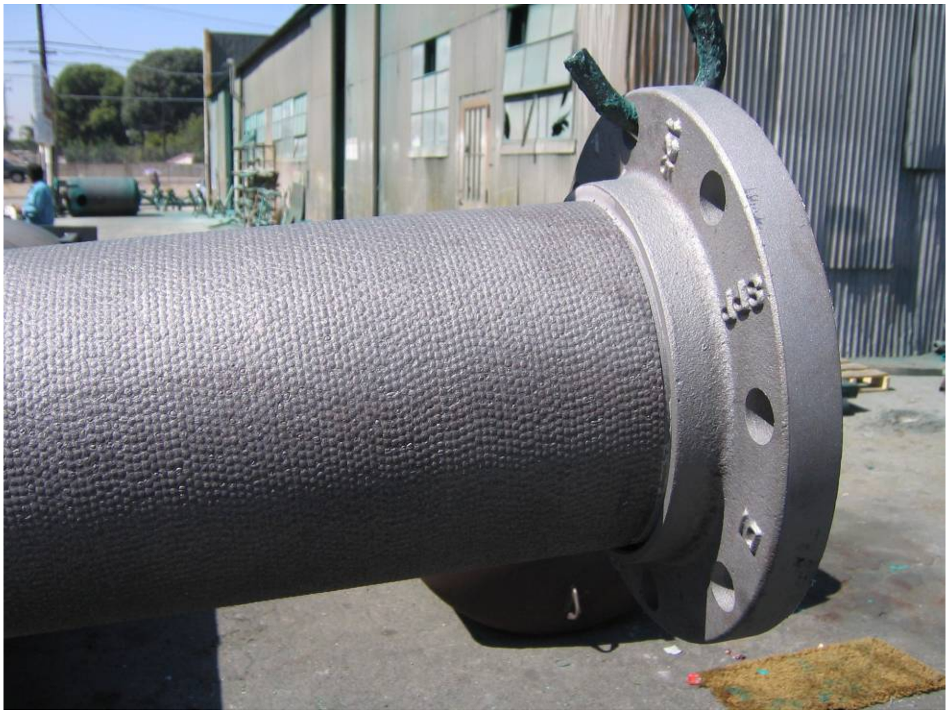

Figure 49
Abrasive Blast Surface Preparation of Ductile Iron Pipe With No Delamination or Epidermal Damage

Ductile Iron Exterior Tight-bonded Coatings. The use of tight-bonded coatings on the exterior of ductile iron pipe has generally been successful. [111] [112] [113] DIPRA has previously recommended that tight-bonded coatings be considered in areas of severe interference. Since ductile iron has a rougher surface than steel, just as with concrete pipelines, adjustments in the coating thickness, coating application, and/or the amount of holidays allowed must be considered in the selection of the tight-bonded coating. As with other types of pipelines, consideration of coating thickness and type should be given to fittings and joints so as to not restrict the function of the piece being coated. Most major coating manufacturers have developed standard coating application techniques and specifications for ductile iron or cast iron that allow successful surface preparation and coating of ductile iron. Special procedures and application methods have been developed to minimize surface porosity, holidays due to surface roughness (orange peel), outgassing, and other unique coating problems associated with ductile iron pipe.

According to a 1995 article by Mike Horton, Process Engineering Manager for U.S. Pipe, external coatings for ductile iron pipe that historically have been used *"…include, but are not limited to: polyurethane, coal tar epoxy, coal tar enamel, tapewrap, extruded polyethylene, metallic zinc, zinc/epoxy/polyurethane, and fusion bonded epoxy."* [114] Extruded polyethylene-type coatings (yellow jacket) have successfully been utilized since 1975; tape coatings have been used since the mid-1970s, with polyurethane coating use beginning in 1988. The Seattle Public Utilities has effectively utilized a bonded thermoplastic coating for their ductile iron piping, which previously had been used successfully in Europe for over 20 years. [115] Liquid epoxy, fusion bonded epoxy, or thermoplastic coatings have been used successfully for ductile iron and cast iron pipe and fittings. Brush and spray-applied coatings, tape, or heat shrink sleeves have also been successfully utilized for pipe joint coatings. A wider variety of tight-bonded coatings have been used more overseas than in North America. These include zinc rich, polyurethane, extruded polyethylene, tape, thermoplastic, and reinforced cementatious coatings. Noonan and Bradish wrote about the use of tight bonded coatings on ductile iron and considerations that should be modified in pipeline designs for successful coating of ductile iron and concrete cylinder pipe.[116]

Extruded Polyolefin Coating

One of the earliest tight bonded coatings that were successfully used for ductile iron pipe was the extruded polyolefin (AWWA C215) type coating (Yellow Jacket, Pritec, etc.). The City of Calgary applied and evaluated a number of different tight-bonded coatings for ductile iron pipe. Calgary worked with a local contractor in the early 1070's that allowed an extruded polyethylene type coating to be applied to ductile iron pipe. They modified the application procedure to allow the extruded coating to be successfully applied over the pipe bells. In 1975, the city selected the extruded polyethylene as their preferred coating and started to use it for coating of its ductile iron pipe. In a 2001 paper, they summarized their success with their tight bonded coatings. [117] In 2008, the city again confirmed that they have had no problems with their yellow jacket coated ductile iron pipe and were beginning a program to replace the galvanic anodes. [118]

Figure 50
Extruded Polyethylene (Pritec) Ductile Iron Coating Application

Figure 51
External Polyethylene Ductile Iron Coating Internal and External Coating with Water Quench

Figure 52
Adhesion Testing of Extruded Polyethylene Coating at Ductile Iron End Cut Back

Tape Coating

The largest tape-coating manufacturers have modified techniques and tape coating systems that work well for ductile iron pipe and have developed specific application specifications for coating ductile iron pipe.[119] [120] One method that has been successfully utilized to minimize the difficulty of tape coating and hand taping at bells is to overlap the bell with a heat-shrink sleeve, as shown in the figure below, for a ductile iron pipe project in Cairo, Egypt.

Figure 53
1992/1993 Tape-Coated Ductile Iron Pipe Direct to Shop Primed Surfaces With Heat Shrink Sleeves

Several tape manufacturers now offer a tape coating system for ductile iron pipe that can be directly applied over the asphaltic coating without having to abrasive blast the ductile iron pipe or remove the asphaltic coating or epidermal layer.[121] [122] This is similar to the approach shown for the Cairo, Egypt project. The tape manufacturers report that the adhesion and cathodic disbondment characteristics are better for ductile iron, even with no abrasive blasting than for abrasive blasted steel, because of the higher surface profile of the ductile iron peen pattern.

Figure 54
2006 Hand Taping of Ductile Iron Stub Pieces with FBE Fittings

Polyurethane Coating

According to the previously referenced article by U. S. Pipe, high-build polyurethane coatings have been used on ductile iron pipe both as an internal and external coating since 1988. The advantage of the polyurethane coating is that it is a 100% material can be applied with specialized equipment on a throughput system where either the pipe is moved by the spray gun or the spray gun is moved by a rotating pipe. The coating cures almost immediately and can be applied up to 100-mil thickness or more. The coating has good impact resistance; adhesion values over 2,000 psi, good cathodic disbondment characteristics, and good chemical resistance.

Madison Chemical, a polyurethane coating manufacturer, conducted a comprehensive literature search and produced an unpublished paper with a vast array of references. The author summarized a variety of data that showed that cast iron, ductile iron, and steel corrode at approximately the same rate. The data also presented different corrosion control methods that have been used on ductile iron pipe. [123] The paper makes a strong case for polyurethane coating as the most successful type of tight-bonded coating, just as DIPRA promotes use of polyethylene encasement as an inexpensive, simple coating for their member pipe companies.

Polyurethane coatings had found such acceptance in the ductile iron marketplace that in 1995/1996, U.S. Pipe *"…based on literally millions of square feet of experience…"* installed a polyurethane coating and lining plant in-house at a cost of approximately $2.5 million."[124] In 1998, the amount of material provided for ductile iron coatings and linings in the Birmingham area alone for the previous 10 years had been sufficient to coat more than 0.5 million square feet of pipe per year.[125] They have also found a greater acceptance in the steel pipe market in the last 15 years or so, with AWWA Standard C222 approved for polyurethane coating for steel pipe.[126]

Figure 55
Polyurethane-Coated Ductile Iron Pipe

San Diego and numerous other utilities have reported good success with the use of polyurethane coatings and linings.

Figure 56
San Diego Polyurethane and Lined Wastewater Force Main

We successfully used polyurethane-coated pipe on projects until approximately 2003. We were very satisfied with the ability of the polyurethane-coated ductile iron pipe to withstand shipping damage. The polyurethane coating provided a tenacious bond to the ductile iron as shown in the following Figure. Note the field chop saw marks on the stub pipe from a project in South Dakota with no disbondment of the coating.

Figure 57
2003 Polyurethane-Coated Ductile Iron Stub Pipe

Polyurethane coatings have been used longer in the overseas market than in the United States.[127] Ductile iron pipe manufacturers now refuse to provide it in the United States, but polyurethane linings and coatings to ductile iron pipe are still being applied in many countries, such as France and China, as shown below. Coating manufacturer representatives report that more than 3,000 miles of polyurethane coated ductile iron pipe have been produced in the Asian market alone.[128]

Figure 58
European Polyurethane Coated and Lined Ductile Iron Pipe

Fusion Bonded Epoxy Coatings and Linings

A new standard was released in 1998 for application of fusion-bonded coatings for ductile iron and cast iron fittings (AWWA C116). [129] Ductile iron pipe can be successfully abrasive blasted and fusion-bonded epoxy coated and lined in the United States in small sizes, as shown below.

Figure 59
Fusion-Bonded Coated and Lined Ductile Iron Pipe and Fittings

Bonded Thermoplastic Coatings

Seattle has recently used a bonded thermoplastic coating. The Seattle Public Utilities has required tight-bonded coatings on ductile iron and cast iron in corrosive soils since the mid 1980s. According to an article by Jeffrey Pimentel, Seattle has recently successfully utilized a bonded thermoplastic coating for their ductile iron pipe and fittings.[130] [131] This type of coating had been used previously for more than 15 years in Europe on ductile iron. Seattle was very satisfied with the surface preparation and application of this coating and curing in a local fusion-bonded epoxy-type coating oven. Advantages with this type of coating include ease of application, good performance in aggressive soils, good adhesion, good impact resistance, good electrical barrier characteristics, and good UV resistance. The ability to fully coat the joint, as well as ease of handling the coated materials and repair, and no need for a cutback at joints are all factors that make this type of coating very attractive. These were the reasons Seattle selected this type of bonded coating for their cathodic protected ductile iron pipe systems.

Figure 60
Seattle Thermoplastic Coated Cathodic Protected Ductile Iron Pipe With Fusion-Bonded Coated Fittings

Figure 61
2000 Seattle Thermoplastic Pipe Coating Allows Engagement of Spigot Directly into Bell

Within the last few years, thermoplastic coated restraints have also become available.

Figure 62
Tight-bonded Coated Restraints Now Available

Tight-bonded Coating Controversy

Although tight-bonded coatings and cathodic protection have been utilized on buried ductile iron with success, another ductile iron controversy has developed in the United States within the last few years. Tight-bonded coated pipe is still offered by overseas ductile iron pipe manufacturers, but the U.S. ductile iron pipe manufacturers are reluctant or even refuse to furnish or allow secondary applicators to provide external tight-bonded coatings on their products. They claim that abrasive blasting will void their pipe warranty (typically one year long). But what value is a one-year warranty if the pipe corrodes prematurely?

The latest objection to coatings raised by the U.S. ductile iron pipe manufacturers is that most exterior coatings are not NSF-61 approved, but their asphaltic shop coating is. They claim that since their pipe is sometimes field cut, the exterior coating should be NSF-61 approved to avoid any possible contact with potable water. This argument is not valid for waste water pipelines. It would seem that this objection for potable water pipelines could be handled by providing an NSF-61 material; there are a number of NSF-61 approved polyurethane, epoxy, and fusion-bonded epoxy coatings available. For tape coatings and other materials where an NSF-61 coating material is not readily available, it would be a simple manner to provide several bare ductile iron pipe pieces for field cut pieces. These pipe pieces could then field coated with a heat-shrink sleeve or hand taped. This is similar to the procedure used on steel pipe projects, where pipe ends are left bare for field cuts and then coated in the field.

For abovegrade and immersed ductile iron services, top coating with other liquid-type coating products (epoxy, coal tar enamel, etc.) is still being offered. The use of a water-soluble primer (Wasser MC FerroClad Primer, Tnemec Omnithane Series 1, or approved equal) is offered as a universal-type primer by some of the U.S. ductile iron pipe manufacturers. These coatings are single component, moisture-tolerant, micaceous iron oxide (MIO) holding primers. They are applied directly at the ductile iron pipe plant with minimum surface preparation required. The advantages with these types of coatings are that they are a surface tolerant, long recoat window type primer, and that they are solventless so safety and disposal problems are minimized. Testing by various coating top-coating manufacturers has indicated that their coatings work very well over these types of primers on ductile iron pipe.

Several tape coating manufacturers have also attempted to offer surface-tolerant primers that would not require the ductile iron pipe to be abrasive blasted prior to application of their tape coatings. Although tested with good results by the ductile iron manufacturers, and minimum surface preparation is required, they have not yet been accepted by the pipe manufacturers. One item that still needs to be resolved is the use of tight-bonded coating on ductile iron pipe that does not require abrasive blasting as long as the U.S. ductile iron pipe manufacturers continue to resist this type of surface preparation.

It is interesting that ductile iron pipe is still allowed to be lined and coated externally for immersion or atmospheric service, but not coated for buried applications. Since tight-bonded external pipe coatings have been successfully utilized on buried pipe for more than 30 years and the surface preparation and application procedures are similar for buried and immersion service, the U.S. pipe manufacturers' refusal to allow buried external coatings appears to be driven more by economic factors than technical problems.

It would seem that the decision to coat their own pipe should be the prerogative of the owner, when they determine it is justified by the corrosive conditions and/or the importance of the pipeline. If there continues to be difficulty or refusal in the ability to obtain tight-bonded external coated ductile iron pipe, the owner's only option may be to select a different pipe material, to obtain coated ductile iron pipe from an international source, or to arrange to coat the pipe at a secondary pipe coating applicator. Therefore, the ability to even obtain tight-bonded coated ductile iron pipe in the United States must be carefully considered during the corrosion evaluation and pipe material selection process and project design phases.

Perhaps because of these reasons and the economical climate, within the last year or two the U. S. ductile iron pipe manufacturers moratorium on the use of tight-bonded coating has relaxed somewhat. Several tight bonded coated ductile iron pipelines have lately been provided in the United States. Hopefully the ductile iron manufacturers will continue to allow the Owners and Engineers to choose the type of tight bonded coating or polyethylene encasement they desire for their projects. The following photographs are of recent tight bonded ductile iron pipe projects.

Figure 63
Tight-Bonded Ductile Iron Pipe Project October 2010 East Coast

Figure 64
Tight-Bonded Coated Internally Restrained Ductile Iron Bore Pipe 2011

Figure 65
Heat Cured Epoxy Primed Ductile Iron Joint

Figure 66
High Recovery Heat Shrink Bore Kit Sleeve

Figure 67
Water Activated Glass Impregnated Protective Sleeve at 50% Overlap 6 to 8 Layers

Figure 68
Tight-Bonded Coated Ductile Iron Bore Pipe Ready to be Pulled Under River

Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe

Recently the National Research Council (NRC) of the National Academies was requested by the Bureau of Reclamation to review their corrosion protection standards for ductile iron pipe as summarized in the Bureau's Technical Memorandum 8140-CC-2004-1 Corrosion Considerations for Buried Metallic Water Pipe.[132] The final NRC report was released in 2009 and provides a comprehensive review and evaluation of ductile iron corrosion control issues. [133] The book is available from the National Materials Advisory Board (www.nationalacademies.edu/nmab) or from the National Academies Press (www.nap.edu). A free PDF copy of this report can be downloaded from these sites.

NRC Committee Charge

The NRC formed a committee to review the Bureau's Corrosion Prevention Standards for Ductile Iron Pipe, specifically to address the appropriateness of Table 2 in the Technical Memorandum for ductile iron pipe. An example of this table was included earlier as (Table 2 in this report), which covers various corrosion control measures required for ductile iron, pretensioned concrete, reinforced concrete, and steel pipe materials. In this table, soils with soil resistivity values below certain levels require more conservative corrosion control methods, while pipelines in soils with higher soil resistivity values require less stringent corrosion control measures. The controversy with this table was that ductile iron pipe was required to be provided with a tight bonded coating and cathodic protection if there is a ten-percent (10%) probability that the soils are ≤ 2,000 ohm-cm or less. Reclamation believed that this was a prudent approach to ductile iron corrosion control measurers required given the types of pipelines they utilize (normally large single source transmission pipelines). However the ductile iron pipe manufacturers, DIPRA and some users argued that polyethylene encasement with cathodic protection would economically provide adequate and acceptable levels of protection and that tight bonded coatings for ductile iron was not necessary for soil conditions ≤ 2,000 ohm-cm. To try and resolve this difference of opinion, the Bureau in 2008 sponsored a review by NRC to form a committee of experts to study corrosion of ductile iron in highly corrosive soils. The NRC committee was tasked or charged with answering two major questions:

- Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?
- Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?

While the Bureau would preferably not have any leaks, they provided the committee a risk factor that they felt comfortable with based on the leak rates in the oil and gas industry for steel pipe. Based on their evaluation of the Department of Transportation (DOT) data the failure rate defined by the Bureau was 0.000044 failures per mile or approximately one failure every 450 miles in the first 50 years of service.

<u>NRC Evaluation</u>

The NRC committee reviewed data from numerous sources including end-users, corrosion consultants, DIPRA, and coating and pipe manufacturers. A review of the Bureau's records indicates that they have been specifying tight bonded coatings for iron pipe since 1954.

A review of the data that the committee was able to gather for polyethylene encased cathodic protected ductile iron pipe and tight bonded coated cathodic protected ductile iron pipe indicates that there is actually more tight bonded coated ductile iron pipe (877 miles) with cathodic protection compared to polyethylene encased ductile iron pipe (369 miles) with cathodic protection. In 1999, there were no failures reported on 860 miles of the tight bonded coated ductile iron pipe. The committee was able to verify that in 2008 there were still no leaks on 526 miles of this pipe. For the remaining tight bonded coated pipe, the committee was not able to obtain updated information. The committee also found that tight bonded coated and cathodic protected ductile iron pipe had been in use for 10 years longer than any known cathodic protected polyethylene encased ductile iron pipe in North America. In addition the Committee found that thousands of miles of tight bonded coated ductile iron pipe has and is being used and provided internationally (over 3,000 miles in the Asian market alone).

Corrosion pitting rates were evaluated by the committee and calculated from known data for bare, asphalt coated, polyethylene encased, undamaged PE, and cathodic protected polyethylene encased ductile iron for comparison purposes. Of particular interest to the committee were the maximum pitting rates where the first failures were expected to occur as represented by the corrosion behavior at the tails of the distribution, where corrosion will occur fastest and not by average corrosion behavior. Therefore, the committee recalculated some of the available date to arrive at different maximum or maximum means than the average pitting rate shown in the DIPRA published information. This information was utilized to evaluate estimated pipe life for different conditions (bare, asphalt coated, polyethylene encased, undamaged polyethylene encasement, etc.).

The NRC reports states that the committee did not endorse some of the data evaluation methods used by DIPRA in presenting pitting rates as averages of averages. The committee went on to say in the report that *"Particularly troubling to the committee were the use of weighted average or mean maximum pitting depths without maximum and minimum pitting depths, or the distribution of pitting depths reported, the combination of pitting data from various sites with very different corrosion behavior, the lack of reported time-dependent pitting depths (when such results are available), and unrealistically short burial times before excavation (as short as 1 year) combined with total study times as short as 3 years, for example, for* *the study of DIP with intentionally damaged PE."* The NRC report also states that *"The method of random digging to diagnose the corrosion behavior of pipelines is inadequate to predict the state of corrosion for the total pipeline and thus to examine fastest corrosion rates at the tail of the distribution."*

The report summarized that *"Considering the DIPRA data referred to above on the pipe measuring between 600 and 1,200 feet (121 samples at 4- to 8-foot lengths) that is presumably installed with ideal care, the committee does not find that the studies of DIPRA confirm that DIP with PE can meet the expected reliability of over 50 years of service life."*

Some have tried to incorrectly interpret data on a table in the NRC report (Table 5-1) on tight bonded coating for steel water pipelines to calculate a leak rate for coated and cathodically protected steel water pipelines. The committee was not charged with establishing leak rates for steel water pipelines and the table was neither all inclusive nor intended to provide leak rate comparisons. There were several steel water projects (East Bay MUD and Cheyenne) that were included as examples of pipelines that had leaks until adequate cathodic protection levels were restored and which were included in the table as the report text summarizes to only demonstrate the success of cathodic protection in reducing or stopping corrosion leaks when adequate protection levels are provided.

The committee used various assumptions and methods to calculate different desired threshold values. The committee deliberated extensively on the number of ductile iron failures and how to handle the DOT steel pipeline and ductile iron information. It was decided that failure rates for both types of pipe would be treated in the same manner. Although more failures were discovered on cathodic protected polyethylene encased ductile iron pipe, after much debate, it was finally agreed that only three of the cathodic protected polyethylene encased ductile iron pipe failures would be used in the evaluation. The NRC report calculated a failure rate of 0.00038 failures per mile for cathodic protected polyethylene encased ductile iron pipe (or approximately one failure in 50 years for every 53 miles of pipe). As explained in the report, this failure rate was based on the number of known failures and the amount (length) of known cathodic protected polyethylene encased ductile iron pipe in the United States. This value was greater than the originally desired Bureau failure rate or the other failure rates used by the Committee in the analysis.

NRC Conclusions

The committee therefore responded to the first question as follows *"the committee finds that if manufactured and installed correctly, polyethylene encasement with cathodic protection provides a **betterment** to bare and as-manufactured ductile iron pipe without cathodic protection in highly corrosive soils."* In response to the second question that the committee was charged with answering, they went on to say that *"The committee finds that the limited data available and the scientific understanding of corrosion mechanisms show that ductile iron pipe with polyethylene encasement and cathodic protection in not likely to provide a reliable 50-year service life in highly corrosive soils (<2,000 ohm-cm).*

For tight bonded coatings, the committee stated *"After considerable study and deliberation, the committee finds that using the performance of bonded dielectric coatings on steel pipe with cathodic protection as a benchmark for reliability, and based on available information, it is unable to identify any corrosion control method for DIP that would provide reliable 50-year service in highly corrosive soils."* This reservation by the committee to endorse any corrosion control mechanism appears to be due to the lack of sufficient data and length of service life to draw a conclusion in either the affirmative or negative for tight bonded coatings, anti MIC (microbiologically influence corrosion) PE, micro-perforated PE, zinc coatings with epoxy top coats, controlled strength material backfill, and additional corrosion allowances. The committee went on to say *"Therefore while the use of bonded dielectric coatings with cathodic protection (CP) on ductile iron pipe (DIP) appears to be more effective than the use of polyethylene encasement with CP on DIP, the committee finds that it has insufficient evidence to assure that bonded dielectric coating with cathodic protection will meet the expected level of reliability."* The committee continued and added that *"Despite these shortcomings in surface preparation and in ensuring adequate cathodic protection (CP), the committee finds that bonded dielectric coatings with CP may provide superior protection to ductile iron pipe when compared to the protection provided by polyethylene encasement with CP."* The committee also provided recommendations on the need for addition research and testing on all type of water pipelines to help provide the additional information needed to make more informed decisions on pipe material and selection of corrosion control measures.

In January of 2010, the Bureau of Reclamation responded to comments from DIPRA in a letter from the Commissioner of the United States Department of the Interior. [134] In their response the Bureau confirmed that they felt the NRC committee had fulfilled their technical obligations in answering the two questions placed to the Committee. The Bureau went on to state that they felt that their Technical Memorandum was technically correct and that they did not plan on changing it based on the information provided by DIPRA. They also reviewed economical considerations not considered by the NRC committee and stated that while Reclamation values completion on its projects, it is the US ductile iron pipe manufacturers decision not to provide bids on projects where tight bonded coatings are required. They concluded that *"However our analyses do not support DIPRA's claim that steel pipe bids are dramatically higher on those contracts where DIP do not submit a bid."* Based on information from 27 projects, their analysis showed that steel pipe prices were approximately 10% higher on previous projects where ductile iron did not bid and that ductile iron prices were about 8% higher on projects where steel did not bid. They stated that *"Using the more commonly employed cost per pound metric, Reclamation's analysis shows that the average bid submitted by the steel pipe suppliers on contracts where ductile iron did not bid was actually lower (about 4%) than bids they submitted when ductile iron also bid."* They conducted a life cycle cost analysis that showed the life cycle cost of a cathodically protected polyethylene encased ductile iron pipeline was approximately 5% higher than the life cost of cathodically protected tight bonded coated steel pipeline. They stated that despite the refusal of the U.S. ductile iron pipe manufacturer to provide tight bonded coatings, that their cost analysis indicates that initial and long-term economical impacts of this reduced completion is modest. They concluded that *"We consider this modest additional incremental cost acceptable given the increased likelihood that the pipeline will provide reliable performance for the long-term (50 year minimum) service life of the project."*

CONCLUSIONS

Because ductile iron is a thick, well-known, and readily available material, it is a good choice for pipeline projects if the correct corrosion control methods are utilized. Research shows that ductile iron corrodes at approximately the same rate as cast iron and steel. Because of its thinner wall compared to cast iron, ductile iron may not offer as long a service life as cast iron would in the same soils. There is no consensus among experts on the success or failure of polyethylene encasement related to long-term levels of protection, micro-biological influenced corrosion (MIC), electrical shielding, and use with cathodic protection.

This article summarizes the historical recognition of the different types of corrosion control available for ductile iron. It also presents the different arguments on this controversial subject and presents a 25-Point Corrosion Risk Assessment Analysis methodology for consideration. The purpose of the risk assessment is to evaluate a pipeline in a given environment to define and select corrosion control methods based on anticipated risk. The methodology is not intended to be definitive; instead it provides a preliminary outline of a thought process that may be modified to meet individual project and/or owner needs. It may be of some value simply as a checklist for experienced corrosion personnel to evaluate the pipeline in question.

Correctly evaluating corrosion risks and implementing appropriate corrosion control methods are critical to allowing owners to meet desired pipe reliability and service-life targets and to protect their investment at minimum life-cycle costs. Life-cycle cost analysis indicates that tight-bonded coatings and cathodic protection are good economical investments, especially for important transmission pipelines in corrosive environments or on pipelines located in areas where repair or replacement may be difficult.

Utilities need to form ductile iron pipe user groups similar to those for concrete pipe users. The major challenge to the corrosion community, owners, NACE, and the pipeline industry is to conduct independent, non-biased studies for all types of pipe to confirm what does or does not work. We need to resolve the controversy with polyethylene encasement, electrical shielding, MIC corrosion, tight-bonded coating, surface preparation, and the ability to accurately monitor and confirm cathodic protection levels on polyethylene-encased pipelines on a technical basis, not with rhetoric and conjecture. Additional training of contractors and utility crews is also necessary to stress the importance that installation of an intact polyethylene encasement or undamaged coatings are critical components, along with cathodic protection for successful corrosion control.

Historically, not addressing corrosion and its control has created a major crisis for our utilities infrastructure. Corrosion is a major problem for the utility pipelines, and it represents a significant portion of the billions of dollars that industry loses each year. Utilities, consultants, and corrosion professionals must correctly use the knowledge that has been gained in the last 40 years regarding ductile iron corrosion. Otherwise, industry will repeat the same mistakes and misconceptions that have led to the present infrastructure crisis. Owners and consultants can no longer ignore or accept corrosion and leak repair as the normal cost of doing business. Owners have to demand and be willing to pay for improved corrosion control and coatings. As the $36 billion annual cost of water and sewer infrastructure repair and replacement shows, it is just too expensive to continue to do it the same way as we have in the past.

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