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Watermain Breaks - Materials Does Matter

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ABSTRACT

Watermain failures result in the investments of millions of dollars for repairs and replacements. The rate of watermain failures is expected to increase as the existing cast iron infrastructure continues to age. It is estimated that the United States should spend over $1 trillion on underground water infrastructure work over the next 25 years, and $1.7 trillion over the next 40 years. This paper is a continuation of CORROSION 2021 paper no. 16837. We will highlight the failure mechanisms, failure analysis protocols, and corrosion mitigation strategies for watermains that experience breaks. Watermain breaks are mainly due to corrosive soil, pipe material, galvanic action, stray current corrosion, or microbiological induced corrosion (MIC). This paper provides specific case histories involving graphitic corrosion, stray current corrosion, and tuberculation.

Key words: Watermain Break, Ductile Iron (DI) Pipe, Backfill, Polyethylene Encasement, Corrosion, Graphitic Corrosion, Galvanic Corrosion, Stray Current Corrosion, Microbiological Induced Corrosion (MIC).

INTRODUCTION

Watermain failures are not often recognized as corrosion but are usually referred to merely as “watermain breaks” because watermain pipe appears sound prior to failure. Some of the causes of watermain breaks are poor design, improper installation, surge or water hammer, soil movement, manufacturing defects, impact, internal corrosion, and external corrosion. Figure 1 shows some of the possible causes of the DI pipe. [1] In several watermain projects that we were involved, from the analysis we observed that the service life was a mere 20 to 30 years; well below what most DI pipe manufacturers claim and what research indicates.

CASE HISTORY 1: GRAPHITIZATION[2] OF DUCTILE IRON WATERMAIN

INTRODUCTION

A 12-inch (30.48 cm) diameter ductile iron (DI) watermain failed catastrophically. The DI pipe was reported to be approximately 28 years old. We were notified that there were several such failures in that street within a month. By the time, we finished the analysis, one more leak has occurred in the same street.

LABORATORY INVESTIGATION

Visual Examination

The failed DI pipe section is shown in Figures 2 and 3. The pipe exhibited three perforations, and a large crack connecting the perforations. Figures 4 - 5 show closer view of the perforations. Figure 6 shows wall thickness loss due to corrosion.

Microexamination of the pipe section

For microexamination, a cross-sectional sample was extracted from the perforation. The cross section was metallographically prepared by grinding and polishing to 1-μm (1 micron) surface finish, etched with 2% Nital and examined under an optical light microscope. The overall microstructure of the steel both at the corroded region and the unaffected region consists of nodules of graphite, pearlite and ferrite which is typical of ductile iron (Figure 7). Similar microstructure at both corroded and non-corroded locations of the pipe indicates that the ductile iron microstructure has not contributory influence on the initiation of the corrosion noticed in the pipe.

Soil Analysis

Soil sample was collected from the failed location and tested for (1) soil resistivity in the as-received condition and again in the saturated condition; (2) moisture content in the as-received condition; (3) pH; (4) sulfate content; (5) sulfide content; (6) chloride content; and (7) redox (oxidation-reduction) potential. Corrosion rate measurements based on linear polarization resistance (LPR) methodology was also performed using a steel electrode (similar enough to ductile iron for the present purpose). The test specifications are given in Table 1 and the results are given in Table 2.

Table 1
Soil Test Parameter Specifications

Test	Specification(s)
Soil Resistivity	ASTM G57
Moisture Content	ASTM D2216
pH	ASTM G51
Sulfates	ASTM C1580, AASHTO T290
Sulfides	Colorimetric
Chlorides	ASTM D512, AASHTO T291
Redox Potential	ASTM G200
LPR Corrosion Rate	ASTM G102

Table 2
Soil Analysis Results
("Points" assigned for five of the parameters are shown in parentheses)

Soil Sample	Location	As Received Resistivity Ω-cm	Saturated Resistivity Ω-cm	LPR mpy	Sulfate ppm	Chloride ppm	pH	Moisture %	Redox mV	Sulfide mg/L
1	Near failed watermain	1,052	816 (10)	6.76	1000	455.00	7.93 (0)	12	319.4 (0)	< 0.04 (0)

In Appendix A of AWWA [(1)] C105/ANSI A21.5[3] the methods for determining the corrosivity of soil with respect to cast iron pipe and other ferrous alloys are given. Table 3 shows 10 point system. In this scheme (DIPRA (Ductile Iron Pipe Research Association) 10 point system), points are assigned to the severity of test results. The 10-point soil evaluation procedure was instituted by CIPRA (Cast Iron Pipe Research Association) in the year 1964. Such points were assigned to the results of the soil tests. Total point values of 10 or greater indicate highly corrosive soil conditions where additional corrosion protection should be used.

Table 3 Soil Test Evaluation for Ductile Iron Pipe
10-Point System as described in Appendix A of ANSI/AWWA C105/A21.5

Soil Characteristics	**Points***
Resistivity (ohm-cm)	
< 1,500	10
≥ 1,500–1,800	8
> 1,800—2,100	5
> 2,100—2,500	2
> 2,500—3,000	1
> 3,000	0
pH	
0–2	5
2–4	3
4–6.5	0
6.5–7.5	0**
7.5–8.5	0
> 8.5	3

Soil Characteristics	**Points***
Redox Potential	
> + 100 mv	0
≥ 50 to +100 mv	3.5
0 to +50 mv	4
Negative	5
Sulfides	
Positive	3.5
Trace	2
Negative	0
Moisture	
Poor drainage, continuously wet	2
Fair drainage, generally moist	1
Good drainage, generally dry	0

* Ten points or greater indicates that soil is corrosive to Ductile Iron Pipe. ** If sulfides are present and low (<100 mv) or negative redox-potential results are obtained, 3 points should be given for this range.

The soil samples tested positive for sulfate-reducing bacteria (SRB); therefore 3.5 points were assigned to the overall soil evaluation. The total of 13.5 points for soil sample indicates that soil at this location is corrosive to ductile iron pipe, and corrosion protection is needed to avoid exterior corrosion. Soil analysis also revealed that the soil sample contain chlorides and sulfates that further aggravates the corrosivity of the soil.

SUMMARY OF FINDINGS OF CASE STUDY 1

Primary Cause – The 12-inch (30.48 cm) diameter DI watermain failed as a direct result of graphitic corrosion of the outside diameter bottom surface due to the corrosivity of the soil and microbiologically-

[(1)] American Water Works Association, 6666 W. Quincy Ave., Denver, CO 80235 USA induced corrosion (MIC). The DI pipe wall at the perforation exhibited significant loss of sound metal thickness due to complete through-wall graphitization corrosion.

Root Cause – The soil chemistry in contact with the pipe was very corrosive in the area of the failure. This promotes graphitic corrosion and loss of wall thickness in service.

Other – There was no cathodic protection found, and no polyethylene wrap was present on the failed watermain. Potential measurements at the site revealed that there was no indication of DC stray currents. It was observed that metallic strap containing several metal types (brass, stainless steel, carbon steel bolts and nuts) was used around the DI watermain for tap hole to connect the service line (Figure 8). It can be clearly seen that galvanic corrosion failure could occur at these locations in future.

CASE HISTORY 2: STRAY CURRENT CORROSION OF DUCTILE IRON WATERMAIN

INTRODUCTION

A 16-inch (40.64 cm) diameter DI watermain failed and this was the third failure along this section of the road in the last two months. A 12-inch (30.48 cm) diameter water pipe almost directly above the 16-inch diameter pipe had also failed.

FIELD TESTING

Visual Examination

Visual examination of the failed 16-inch diameter water pipe indicated that the failure of the pipe occurred as a result of a hole in the bottom side of the pipe. Water was still leaking from the pipe and collecting at the bottom of the trench (Figures 9 - 11). After visual examination of the new pipe sections and the old pipe remnant, soil samples were collected near the pipe for laboratory analysis. Testing was also performed to look for the presence of stray currents.

Stray Current Corrosion Determination by Potential Measurements

One of the factors resulting in the external corrosion of the watermain pipes can be stray current the pipe conducts from the ground. Stray current enters the pipe at one location (pick-up area) and leaves (discharge area) at another location, then travel into the electrolyte (soil). This causes severe corrosion of the pipe at the discharge area. The corrosion caused by stray current is more serious than soil corrosion under normal conditions. Taking potential measurements is a testing method commonly used to identify the presence of stray current.

Pipe-to-Soil/liquid (water in this case) potential readings suggest that the potentials at the pipe are less electronegative than the potentials at a distance of 2 feet away from the pipe i.e., the potentials at the bottom portion of the pipe are electropositive compared to the potentials at a distance of 2 feet away from the pipe which indicates corrosion activity owing to stray current corrosion is taking place at the bottom areas. The observed less electronegative potentials are in the range -110 mV CSE to -212 mV CSE (Copper Sulfate Electrode) and the more electronegative potentials are in the range -336 to -399 mV CSE. Potential readings indicate stray current effects i.e., the pipe has experienced stray currents at some point in service. Stray current discharge over a distance of 2' might seem unusual, but we have noticed several such instances in the field.

Anode Installation

As PE wrap is not present, cathodic protection (CP) is the only standalone corrosion control to prevent corrosion of the new 16-inch watermain pipe section. Sacrificial high potential magnesium anodes were used (Figure 12) as a part of cathodic protection of the watermain pipe and these anodes become the new path of least resistance and degrades much faster than the watermain pipe. Henceforth, instead of having to repair major damage of the watermain pipe, only the sacrificial anodes can be replaced periodically.

LABORATORY INVESTIGATION

Soil Analysis

A soil sample was collected from the excavation trench near the failed pipe. The soil analysis test results are shown in Table 4.

Table 4
Soil Analysis Results
("Points" assigned for five of the parameters are shown in parentheses)

Soil Sample	Location	As Received Resistivity Ω-cm	Saturated Resistivity Ω-cm	LPR mpy	Sulfate ppm	Chloride ppm	pH	Moisture %	Redox mV	Sulfide mg/L
1	Near failed watermain	1,352	1,324 (10)	5.31	215	83.1	7.06 (0)	24	90.9 (3.5)	< 0.04 (0)

Soil analysis results indicate that the soil sample collected from the bottom of the 16-inch diameter pipe exhibited low resistivity values in the saturated condition indicating that the soil is corrosive. The redox potential was measured to be slightly less than 100 mv indicating that sulfate reducing bacteria (SRB's) might contribute to the pipe corrosion. A trace amount of sulfide was detected in the soil sample. As per Appendix A of AWWA C105/ANSI A21.5, if sulfides are present and low (<100 mv) or negative redox-potential results are obtained, 3 points should be given for this range. So, the sum of total points is 16.5 which indicates that soil is very corrosive to ductile iron pipe.

Visual Examination of the pipe

The failed pipe section with two adjacent holes in the bottom of the pipe is shown in Figure 13. As shown in Figure 14 many of the corrosion products had spalled away from the bottom pipe surface to reveal a very irregular remaining metal surface profile. The saw cut surfaces through the failed pipe revealed the presence of dark localized graphitic corrosion (Figure 15). Corrosion had penetrated completely through the metallic wall thickness of the pipe leaving only the cement lining intact at the location of the leak. The dark corrosion products were intact at most locations which is characteristic of graphitic corrosion. The pipe wall thickness in a relatively non-corroded area was measured to be 3/8 inch (0.95 cm).

Microexamination of the pipe section

Transverse cross section through the 16-inch diameter pipe was prepared for subsequent metallographic examination. In the as polished condition small graphite nodules were observed throughout the pipe wall thickness which is characteristic of a ductile cast iron. Etching with a 2% Nital solution revealed the microstructure of the ductile iron pipe which was found to consist primarily of white etching ferrite plus some dark etching pearlite as shown in Figure 16.

SUMMARY OF FINDINGS OF CASE STUDY 2

Primary Cause – The 16-inch diameter ductile iron watermain failed as a result of graphitic corrosion of the outside diameter. The ductile iron pipe at the point of failure exhibited a significant loss in wall thickness of metal due to complete through wall graphitization corrosion in several locations.

Root Cause – As per 10-point system described in Appendix A of ANSI/AWWA C105/A21.5, the sum of total points is 16.5 which indicates that soil is very corrosive to ductile iron pipe. Pipe-to-Soil potentials revealed that the potentials at the bottom portion of the pipe are electropositive compared to the potentials at a distance of 2 feet away from the pipe owing to stray current effects.

To conclude, 16-inch diameter ductile iron watermain failed as a result of graphitic corrosion due to synergistic effects of corrosive soil and stray current effects.

CASE HISTORY 3: STRAY CURRENT CORROSION OF DUCTILE IRON WATERMAIN

INTRODUCTION

A 8-inch (20.32 cm) diameter DI watermain failed catastrophically. It was observed that there was a gas pipeline at 2 – 3 feet distance from the failed watermain. Field testing such as in-situ soil resistivity measurements, potential measurements, and stray current measurements were not possible due to very limited time available to replace the pipe section.

LABORATORY INVESTIGATION

Visual Examination of the pipe

The failed pipe section is shown in the Figure 17. The pipe exhibited one large perforation on the bell at 6 O′clock position. Careful examination of the as-received pipe section showed deep pits around the perforation (Figure 18).

Microexamination of the pipe section

A longitudinal cross-sectional specimen was sectioned through the perforation. The cross section was metallographically prepared by grinding and polishing to 1µ (1 micron) surface finish and examined under microscope. The nodules of graphite were clearly visible in the as polished condition which indicates that the material of the pipe is Ductile Iron (Figure 19). Then, metallographic specimen was etched with 2% Nital and examined under a Nikon optical light microscope. The overall microstructure of the steel both at the corroded region and the unaffected region consists of nodules of graphite and ferrite which is typical of ductile iron (Figure 20). The microstructure in both corroded and the unaffected locations in the pipe indicates that the ductile iron microstructure was not responsible for the corrosion.

Soil Analysis

A soil sample was collected near the failed pipe. The soil analysis test results are shown in Table 5.

Table 5
Soil Analysis Results
("Points" assigned for five of the parameters are shown in parentheses)

Soil Sample	Location	As Received Resistivity Ω-cm	Saturated Resistivity Ω-cm	LPR mpy	Sulfate ppm	Chloride ppm	pH	Moisture %	Redox mV	Sulfide mg/L
1	Near failed watermain	8,770	5,420 (0)	2.34	120	38.4	7.47 (0)	8	465.4 (0)	< 0.04 (0)

Soil analysis results indicate that the soil is not corrosive to the DI pipe largely due to high soil resistivity values. The soil sample tested positive for sulfate-reducing bacteria, therefore 3.5 points were assigned to the overall soil evaluation. The total of 3.5 points for soil sample indicates that soil at this location is non-corrosive to ductile iron pipe.

EDS analysis of the deposits

Energy Dispersive Spectroscopy (EDS) analysis revealed that the deposits in the deep pits around the perforation had significant presence of chlorides compared to the deposits away from the pits (Figure 21). EDS on the deposits away from pits showed elemental composition similar to de-icing salts along with the presence of other regular elements (Figure 22). This particular finding suggests that the chlorides (Cl^-) in the soil is attracted to the pits so the deposits in the pit had higher chlorides.

The combination of test findings suggests presence of stray currents at this site. The location where the watermain receives the stray current is the cathodic area (does not lose metal) and the location where the stray current leaves the watermain will cause that location to be anodic and will corrode at an accelerated rate. Cl^- ions has migrated to anodic area.

SUMMARY OF FINDINGS OF CASE STUDY 3

Primary Cause – The 8-inch diameter ductile cast iron watermain failed because of stray current corrosion. Ductile iron pipes near a foreign structure with cathodic protection (CP) is at high risk of corrosion leading to failure due to stray current corrosion. PE wrap and or CP is highly recommended.

CASE HISTORY 4: CAST IRON WATER PIPE FAILED DUE TO COMBINED EFFECTS OF BOTH EXTERNAL AND INTERNAL CORROSION

INTRODUCTION

A 8-inch (20.32 cm) diameter CI watermain failed and it was reported that the internal surface of the failed watermain is plugged.

FIELD TESTING

Visual Examination

Figure 23 shows the location from which the failed pipe section was cut from the watermain. The failure of the pipe occurred directly as a result of a hole on the side of the pipe (i.e., the 9 o'clock position). Visual examination of the remaining pipe section in the trench has revealed a longitudinal crack that was present along the entire length of the pipe section. Further examination has revealed presence of tubercles at the internal surface of the failed water pipe (Figure 24). Careful examination revealed that cement lining was not present in the failed pipe section. PE sheet was not wrapped around the pipe. This important finding indicates that no basic corrosion control measures were in place at this location.

LABORATORY INVESTIGATION

Soil Analysis

Table 6
Soil Analysis Results
("Points" assigned for five of the parameters are shown in parentheses)

Soil Sample	Location	As Received Resistivity Ω-cm	Saturated Resistivity Ω-cm	LPR mpy	Sulfate ppm	Chloride ppm	pH	Moisture %	Redox mV	Sulfide mg/L
1	Near failed watermain	1,208	730 (10)	12.13	1000	158	8.04 (0)	17	437.1 (0)	< 0.04 (0)

After visual examination of the failed pipe in the trench, soil samples were collected near the pipe for laboratory analysis. The soil analysis test results are shown in Table 6. Soil analysis results indicate that the soil sample collected from the bottom of the 8-inch diameter pipe exhibited low resistivity values in the saturated condition indicating that the soil is corrosive. The soil samples tested positive for sulfate-reducing bacteria (SRB); therefore 3.5 points were assigned to the overall soil evaluation. The total of 13.5 points for soil sample indicates that soil at this location is corrosive to the pipe. Soil analysis also revealed that the soil sample contain chlorides and sulfates that further aggravates the corrosivity of the soil.

Visual Examination of the pipe

The pipe exhibited one large perforation as shown in Figure 25. Closer examination has revealed presence of tubercles at the internal surface of the failed water pipe (Figure 26) which indicates that the grey cast iron has experienced internal corrosion and developed tubercular scales. Further examination has revealed that this pipe section does not have cement lining. Scaling is most commonly found in unlined cast iron pipes. Ultimately, scaling reduces the diameter of the pipe and restricts water flow.

Furthermore, fine longitudinal crack was observed on the external surface of one end of the pipe section cut from the failed location of the 8-inch diameter failed water pipe. Examination of the wall thickness shows that the observed fine crack could have initiated at ID, travelled the entire length of the graphitized layer, deviated its path, and finally resulted in break.

Microexamination of the pipe section

A transverse cross-sectional specimen was sectioned from the location adjacent to the perforation. The cross section was metallographically prepared by grinding and polishing to 1-μm (1 micron) surface finish, etched with 2% Nital and examined under a stereo microscope. As seen in Figures 27 and 28, graphitic corrosion was observed at both external surface and internal surface. Indications of corrosion attack was also observed throughout the wall thickness. This particular finding suggests that at the failed location the graphitic corrosion fronts from both external surface and internal surface might have merged and finally resulted in failure due to the water pressure at the reduced thickness of the pipe.

After stereoscopic examination, the metallographic specimen was examined under an optical light microscope. Etching with a 2% Nital solution revealed the microstructure of the iron matrix which was found to consist of darker etching pearlite plus numerous, sometimes large, islands of phosphorous eutectic as shown in Figure 29. The microstructure of gray cast iron is typically made up of graphite flakes, which are embedded in a matrix of ferrite and pearlite. If a high level of phosphorus is present in the gray cast iron, it can form a eutectic microstructure. The eutectic microstructure is made up of a mixture of ferrite and iron phosphide (Fe_3P). The presence of iron phosphide in the microstructure can increase the brittleness and decrease the toughness of the gray cast iron. Additionally, the high level of phosphorus can also have a negative impact on the corrosion resistance of gray cast iron. The iron phosphide can act as a cathode, promoting corrosion and reducing the overall service life of the cast iron. Therefore, the amount of phosphorus in gray cast iron is typically kept low to prevent the formation of the eutectic microstructure and to improve the cast iron's mechanical properties and corrosion resistance.

Graphitic corrosion was observed at both the outside diameter surface of the pipe and at the inside diameter surface of the pipe. The depth of graphitic corrosion was observed to be greater at the outside diameter surface. In graphitic corrosion localized galvanic corrosion cells form between the graphite flakes and the iron matrix causing corrosion of the iron matrix. The graphite flake network keeps the iron corrosion products in place so pitting and metal wastage is rarely visible from the exterior surface. The graphitic corrosion of the inside diameter surface is the result of the absence of a cement lining on the inside diameter surface of the pipe. Within the areas of graphitic corrosion both graphite flakes and phosphorous eutectics are still visible while the iron matrix has turned into dark iron oxidation products (Figure 30).

SUMMARY OF FINDINGS OF CASE STUDY 4

Primary Cause – The 8-inch diameter cast iron water pipe failed as a result of graphitic corrosion of both external surface and internal surface. The graphitic corrosion of external surface is primarily due to corrosivity of the soil and the graphitic corrosion of internal surface is due to water corrosion and Microbiological Induced Corrosion (MIC), wherein iron from the unlined water pipe reacts with the corrosive ions and iron corrosion products within the water to form tubercles. To conclude, the 8-inch cast iron water pipe failed due to combined effects of both external and internal corrosion.

Cast iron pipes in corrosive soils are at high risk of graphitic corrosion leading to failure. Cathodic protection is recommended at such sites. Unlined cast iron pipes are at high risk of internal corrosion. Cement lining at the internal surface is always recommended to avoid scaling or tuberculation.

CONCLUSIONS

From the above case studies and the experience of field testing of more than 32 watermain breaks, the following conclusions are made:

- The corrosion resistance of ductile iron pipe is equal to cast iron pipe. However, the longevity of cast iron pipe is primarily due to wall thickness.
- PE wrap is a corrosion control method that is commonly used to protect underground watermains from corrosion, but it should be bear in mind that PE wrap reduces but does not eliminate the external corrosion of DI pipe.
- In addition to basic corrosion control measures, if possible, CP should also be considered. CP will prevent corrosion at the PE wrap damaged areas but not the other areas of the pipe under the PE wrap that is in contact with the soil or water.
- Benefits of PE wrap:
    - PE wrap is a cost-effective solution for protecting watermains from external corrosion when compared to other corrosion control methods such as cathodic protection or the application of bonded coatings.
    - PE wrap is a mechanical barrier that prevents corrosion of the pipe by preventing contact between the pipe and corrosive agents.
    - PE wrap is easy to install and can be applied quickly and efficiently, which can minimize disruptions to water service.
- Limitations of PE wrap:
    - PE wrap is not suitable and may not be effective in highly corrosive soils or environments.
    - PE wrap may not be as effective as other corrosion control methods, such as cathodic protection or the application of bonded coatings.
    - PE wrap can be easily damaged by external factors such as excavation or construction, which can expose the pipe to corrosive agents and reduce the effectiveness of the wrap.
    - PE wrap is not a good choice for pipes that are already corroded, as it does not address the underlying corrosion problem.
    - Cathodic protection is more likely than not ineffective when there is PE wrap, possibly limiting a future remedial option. However, as a proactive measure, it is advisable to install CP in the corrosive soils considering the possible damages to PE wrap during installation, and at service line connections.
- Alternatives to PE wrap:
    - *Bonded coatings:* Bonded coatings, such as epoxy, polyurethane, or ceramic are more expensive than PE wrap and may be less flexible, but they are more durable and can provide better long-term protection.
    - *Remedial cathodic protection:* Remedial cathodic protection systems can be installed on existing watermains to address active corrosion problems and extend the service life of the pipe.
- To control or reduce water main breaks, a corrosion control program must be in place. A corrosion control program for watermains typically includes several key elements, such as preassessment, indirect assessment, and direct assessment.
    - *Preassessment:* This involves collecting information about the watermain and its environment to identify areas of the pipe that may be susceptible to corrosion. This information might include the type of pipe, the age of the pipe, the water quality, the location of the pipe, and any known history of corrosion.
    - *Indirect assessment:* This involves using non-destructive testing methods to assess the condition of the watermain without physically damaging the pipe. Indirect assessment methods include in-situ soil resistivity measurements, and potential measurements.
    - *Direct assessment:* This involves physically accessing the pipe to assess its condition. Direct assessment methods include visual inspection, potential measurements, stray current measurements, and extent of graphitization measurements using sensors.
- Regularly reviewing and updating the program based on the results of the assessments is necessary to ensure that it remains effective in controlling corrosion and protecting the watermain.

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2. NACE /ASTM G193 – 12d, “Standard Terminology and Acronyms Relating to Corrosion”.
3. American Water Works Association, ANSI/AWWA Standard C105/A21.5-18 (2018): “Polyethylene Encasement for Ductile-Iron Pipe Systems, Denver, Colorado.

Figure 1: Photograph showing possible causes of external corrosion of DI pipe.

Figure 2: Photographs showing the failed watermain pipe section.

Figure 3: Figure 2 is retouched for better understanding to show the crack propagation. Main perforation and 2nd perforation can be seen in the photograph.

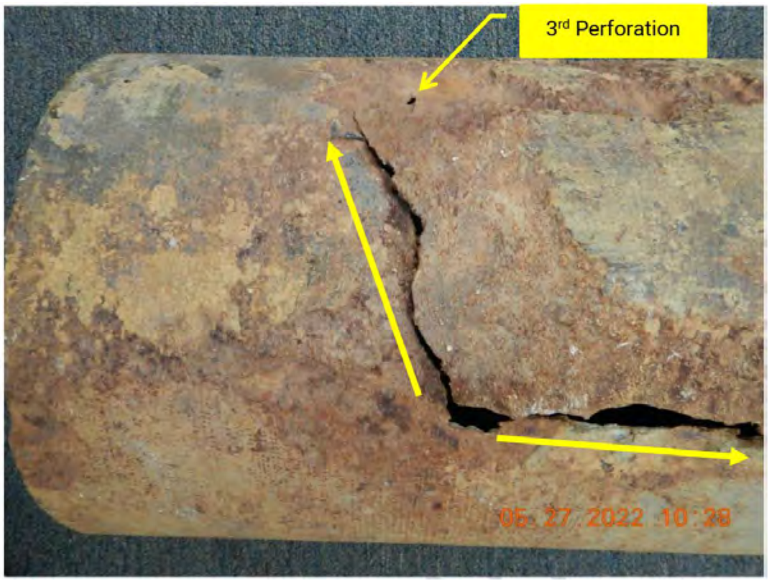
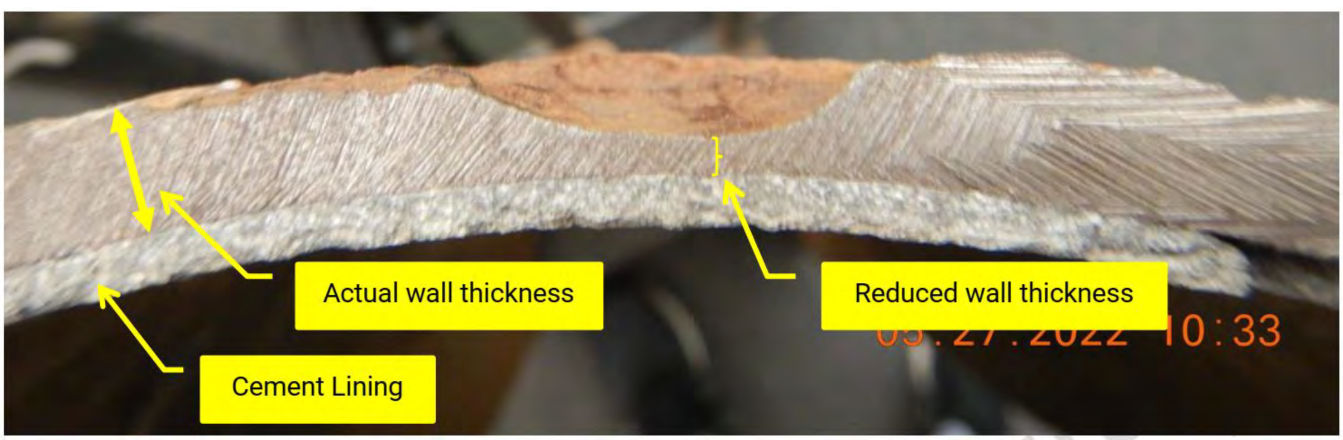
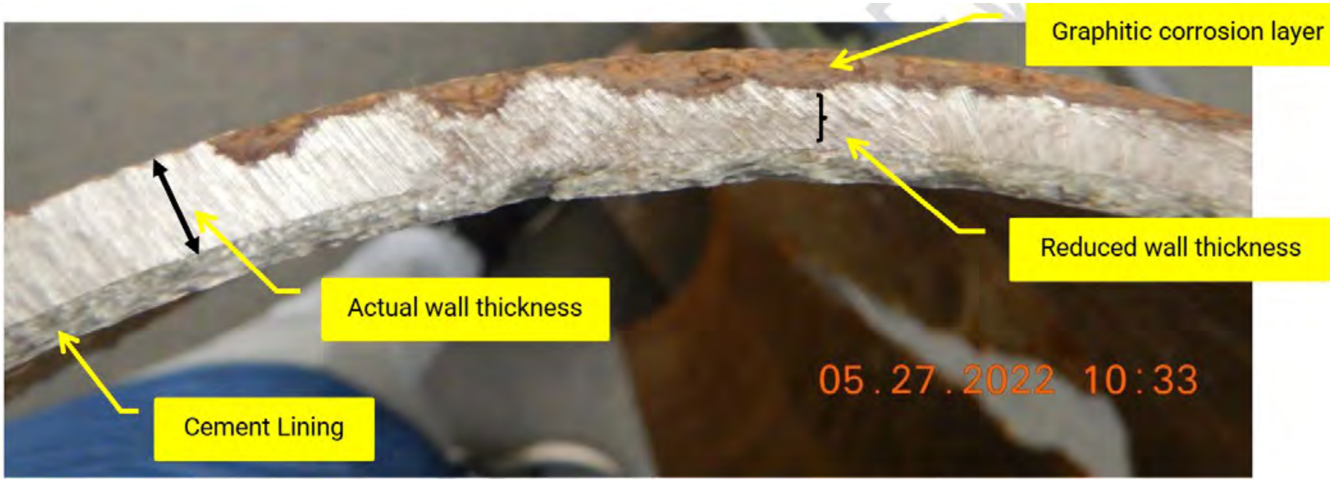


Figure 4: Closer view of main perforation. 3rd perforation can also be seen.

Figure 5: Closer view of 3rd perforation.



a)



b)

Figure 6: Photographs showing the thickness loss due to the corrosion.

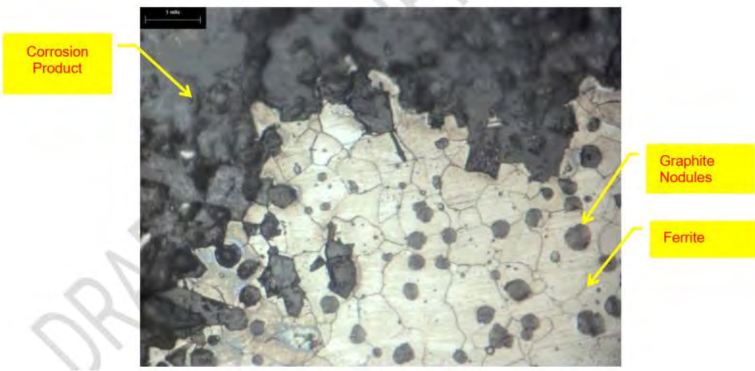


Figure 7: Photomicrograph taken at the perforation shows nodules of graphite, pearlite (dark islands) and ferrite (light background) which indicates that the material of the water pipe is ductile iron. Mag: 400X. Etched with 2% Nital.

Figure 8: Photograph showing the metallic strap used around the DI watermain for tap hole to connect the service line.

Figure 9: Photograph showing pumping out of the water to expose the 16-inch diameter pipe in the trench.

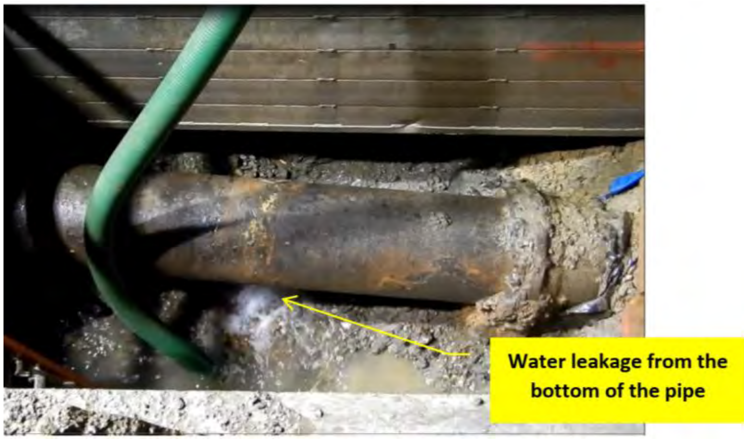


Figure 10: Photograph showing the water leakage from the bottom of the 16-inch diameter failed water pipe.

Figure 11: Photograph showing the water leakage from the bottom of the 16-inch diameter failed water pipe.

Figure 12: Photograph showing installation of anode and reference electrode.

Figure 13: Photograph showing the holes in the bottom side of the 16-inch diameter pipe.

Figure 14: Photograph showing the holes and other areas of corrosion in the bottom side of the 16-inch diameter pipe.

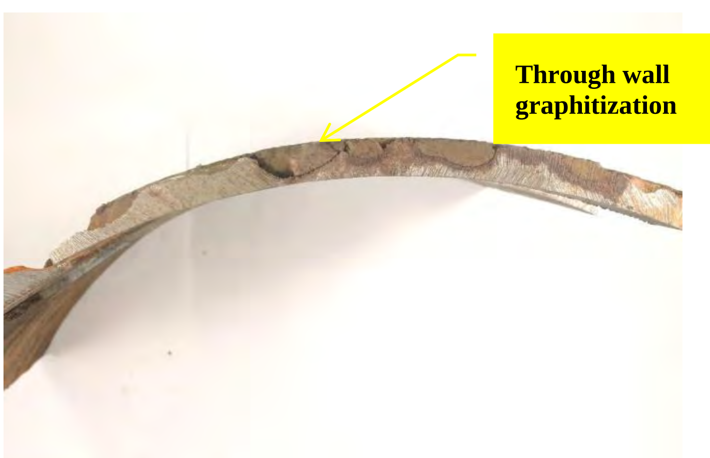


Figure 15: Photograph showing dark areas of graphitic corrosion in the bottom side of the 16-inch diameter pipe. Holes in pipe at left.

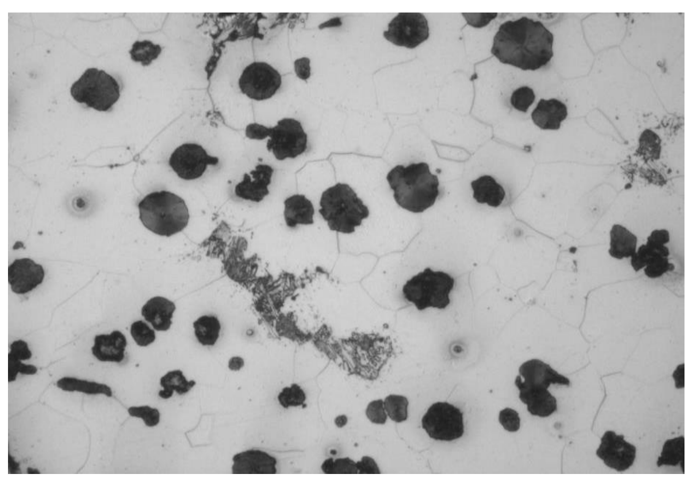


Figure 16: Photograph at 400x showing the microstructure of the 16-inch diameter ductile iron pipe. 2% Nital

Figure 17: Photograph showing the perforation and some deep pits around the perforation in the as-received pipe section.

Figure 18: Photograph showing the perforation and some deep pits around the perforation in the as-received pipe section.

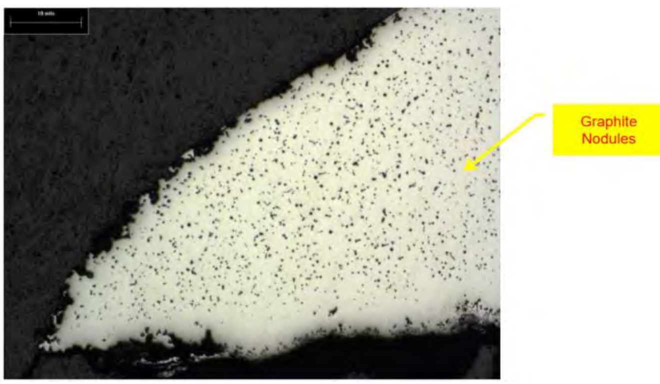


Figure 19: Photomicrograph taken at the perforation shows nodules of graphite in the steel substrate which indicates that the material of the water pipe is ductile iron. Mag: 100X. As Polished condition.

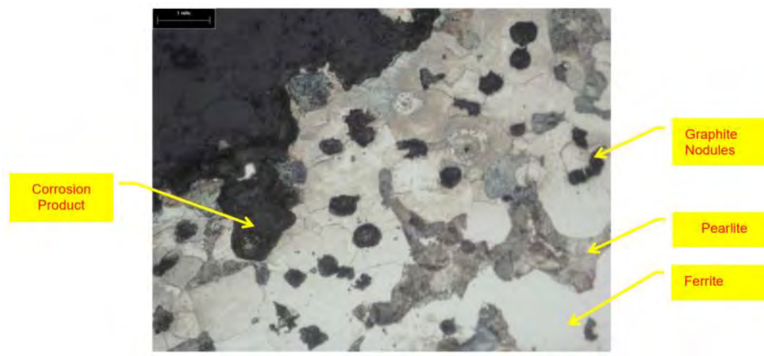
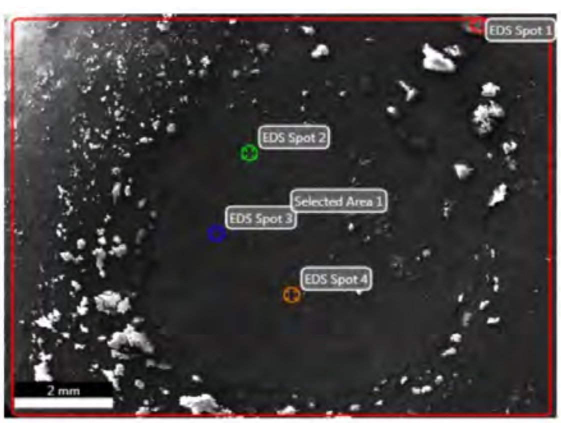
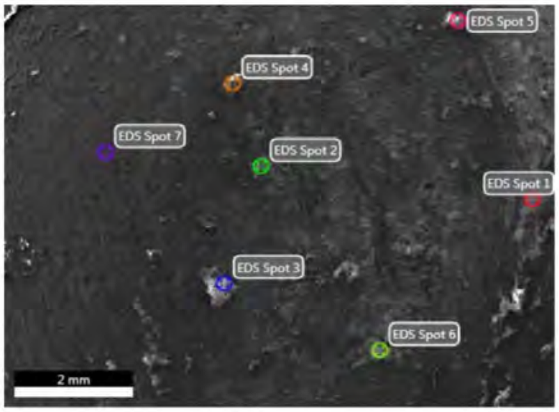


Figure 20: Photomicrograph taken at the perforation shows nodules of graphite, pearlite and ferrite (light background) which indicates that the material of the water pipe is ductile iron. Mag: 400X. Etched with 2% Nital.



Element	Weight %	Atomic %
O K	5.55	16.33
AlK	0.24	0.42
SiK	1.60	2.68
P K	1.17	1.78
ClK	2.72	3.61
CaK	2.56	3.01
FeK	81.54	68.74
CuK	4.62	3.42

Figure 21: EDS data (spot 2) shows that the deposits in the pit are rich in Chlorine (Cl). The other elements such as Oxygen (O), Aluminum (Al), Silicon (Si), Phosphorous (P), Calcium (Ca), Iron (Fe) and Copper (Cu) were also detected.



Element	Weight %	Atomic %
O K	23.89	38.63
NaK	0.31	0.35
MgK	0.28	0.29
AlK	20.94	20.08
SiK	31.51	29.02
ClK	1.03	0.75
K K	1.65	1.09
CaK	1.49	0.96
TiK	0.84	0.46
FeK	18.07	8.37

Figure 22: EDS data (spot 1) shows that the deposits away from pit are rich in Sodium (Na), Magnesium (Mg), Potassium (K), Calcium (Ca) and Chlorine (Cl). The other elements such as Oxygen (O), Aluminum (Al), Titanium (Ti) and Iron (Fe) were also detected.

Figure 23: Photograph showing the location where pipe section was cut from the failed location.

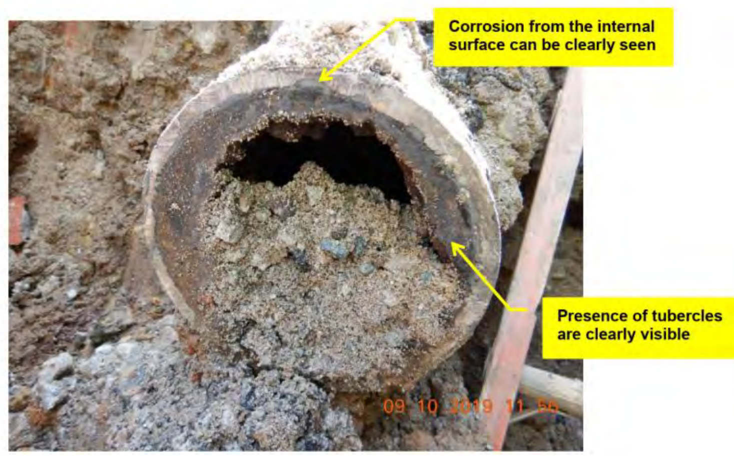


Figure 24: Photograph showing tubercles at the internal surface of the water pipe.

Figure 25: Photograph showing the pipe section cut from the failed location of the 8-inch diameter failed water pipe. Tubercles at the internal surface of the water pipe are clearly visible.

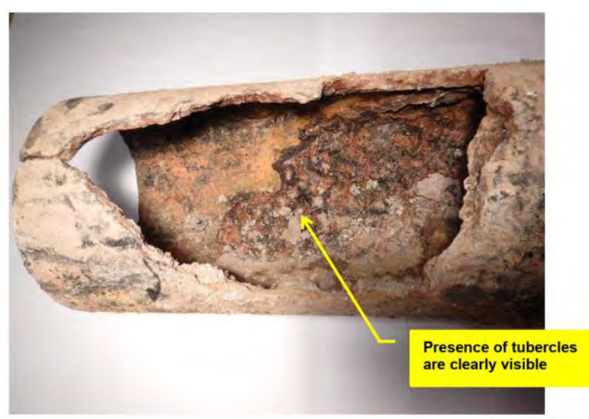
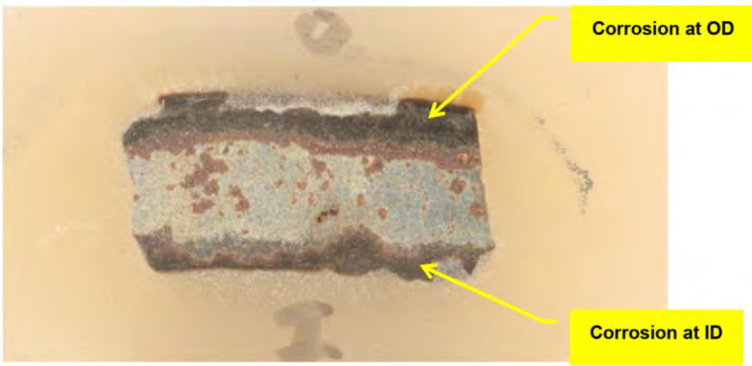
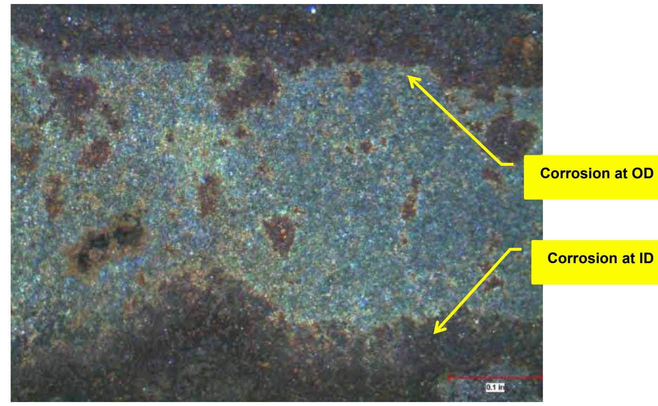


Figure 26: Photograph showing the failed location of the 8-inch diameter failed water pipe. Tubercles at the internal surface are clearly visible.



27: Photograph showing transverse cross-section specimen extracted from the pipe section cut from the failed location of the 8-inch diameter failed water pipe. Corrosion at both OD and ID is clearly visible.



28: Stereoscope image showing corrosion at both OD and ID. Indications of corrosion through wall thickness is also visible. Mag. 7X.

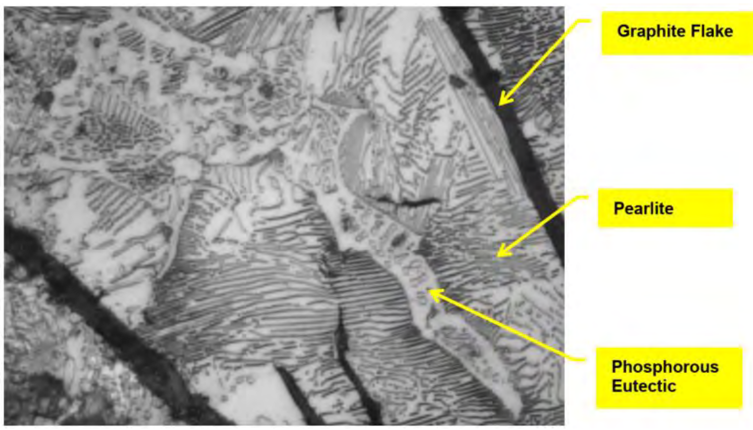


Figure 29: Photograph at 1000x showing the large phosphorous eutectics within the microstructure of the pipe. Etched with 2% Nital.

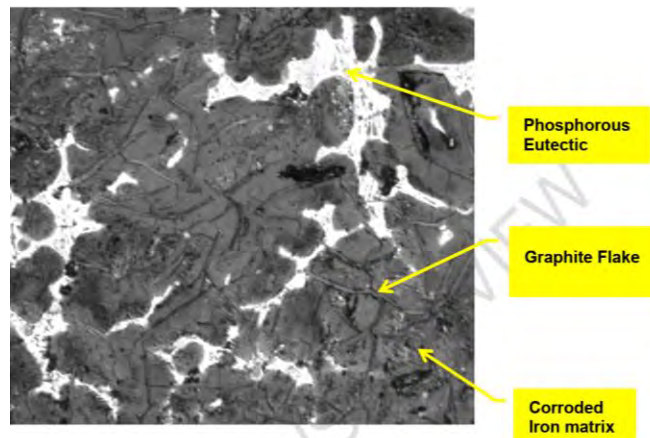


Figure 30: Photograph at 200x showing the graphitic corrosion products and non-corroded phosphorous eutectics. Etched with 2% Nital.