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February 26, 2020

Sample Identification - **(2) Segments of Failed 16" Diameter Cast Iron Water Pipe**

Authorization: Q20-0010A

Project Number: P20-0162

Objective: We were requested to perform chemical analysis, mechanical testing and microstructural evaluation of the failed pipe sections. We were further requested to comment on any material conditions that may have contributed to the failure of the pipe.

Conclusions and Commentary: The microstructure of the pipe in the three examined locations (near the fractures in pipes #1 and #2 and at the cut end of pipe #1) consisted of predominantly Type B graphite flakes in a matrix of ferrite with 5-25% pearlite and 3-10% steadite and carbides. This microstructure is inherently brittle and would have significantly contributed to the fracture failure of the water pipe.

The poor microstructure has two issues: poor graphite morphology and the level of steadite and carbides. The less-than-optimal Type B graphite flakes are due to either rapid solidification or undercooling from insufficient inoculation. The carbides are also likely the result of rapid solidification or undercooling. The steadite is an iron phosphorous eutectic and was the result of high phosphorous content (0.54%). Phosphorous content is kept below 0.10% in modern gray iron production.

Other than the high phosphorous content, the chemical analysis found no other compositional factors that would have promoted the poor microstructure and low fracture resistance of this material. The slightly hypereutectic carbon equivalent of 4.43 and 0.75" section size should produce gray iron with a tensile strength of near 35 ksi rather than the 24-25 ksi achieved by the pipe material. The low impact test results are expected with this microstructure.

The corrosive attack to the OD surface of the pipe was found to a depth of 0.023" in the examined sections. This corrosive attack would have provided stress concentrating sites susceptible to fracture initiation.

Although the pipe microstructure is especially susceptible to fracture from impact, longitudinal cracks in water pipes are typically the result of high water pressure or compressive stress from the top (surface) or side. Surface compressive stress often causes longitudinal cracking on both sides of a pipe. Either side compressive stress or water pressure may have contributed to the failure of the pipe whose fracture resistance was compromised by the poor microstructure and the corrosive attack.

Procedures and Data:

Macroscopic Examination

Two segments of the failed water pipe were submitted. The pipe #1 segment exhibited an irregular transverse fracture of the pipe at one end with a saw cut at the opposite end (see Image #1). The pipe #2 segment exhibited an irregular transverse fracture on one end along with a longitudinal fracture splitting the pipe lengthwise and a T-joint fitting at the opposite end (see Images #2 and #3).

The transverse fracture surfaces on both ends as well as along the longitudinal fracture exhibited post-fracture rust-type corrosive attack, adherent soil, and various amount of mechanical damage (see Image #4). This post-fracture damage to the fracture surfaces prevented determination of the fracture origin(s), fracture mode, and the direction of fracture propagation.

Areas near the fractures on pipes #1 and #2 and near the cut end of pipe #1 were selected for longitudinal tensile test coupons, Charpy impact test specimens, and metallographic examinations (see Images #5 through #7). One chemical analysis was performed on a sample from near the cut end of pipe #1 (see Image #6).

Metallographic Examination

Metallographic sections of the pipes from the locations and orientations indicated in Images #5 through #7 were prepared in accordance with ASTM E3. Examination of the as-polished section from along the longitudinal fracture in pipe #2 revealed a graphite structure of predominantly Type B graphite flakes with small amounts of Types of A, D, and E flakes across the pipe wall thickness (see Images #8 through #10). The morphology of small Type B graphite rosettes with graphite-free areas suggests undercooling occurred along the OD surface, likely due to rapid solidification. The OD surface also exhibited rust-type corrosive attack extending up to a depth of 0.023". The fracture surface in this section was smoothed by post-fracture mechanical damage.

Etching the section of pipe #2 from near the fracture with Nital revealed approximately 5-20% pearlite along with carbides and steadite across the pipe wall thickness (see Images #11 through #13).

Etching with ammonium persulfate darkened the pearlite and ferrite revealing the level of steadite and carbides across the wall thickness (see Images #14 through #16). The steadite and carbides were difficult to differentiate in these samples and were combined approximately 3-10% in volume. A concentration of carbides was found along the ID surface.

The sections of the pipe #1 segment from the cut end and the fracture exhibited similar graphite structures and microstructures as the pipe #2 section. Both pipe #1 sections exhibited predominantly Type B graphite flakes in a matrix of ferrite with approximately 5-25% pearlite and approximately 3-10% steadite and carbides (see Images #17 through #22). A concentration of carbides was found along the ID surface near the fracture but not on the ID surface of the examined section from near the cut end.

Chemical Analysis

The results (expressed in weight %) of a chemical analysis of the sample from near the cut end of pipe #1 are as follows:

Lab File No. B0-03759				
Silicon	1.63		Vanadium	<0.01
Sulfur	0.060		Niobium	<0.01
Phosphorous	0.54		Tin	<0.01
Manganese	0.40		Lead	<0.01
Carbon	3.71		Aluminum	<0.01
Chromium	0.06		Magnesium	<0.01
Nickel	0.03		Titanium	0.05
Molybdenum	0.01		Iron	Base
Copper	0.08		CE*	4.43

**CE – Carbon equivalent = %C + %Si/3 + %P/3.*

Mechanical Testing

The mechanical properties were determined by tension testing coupons machined from the three locations (indicated in Images #5 through #7) in accordance with ASTM E8. Hardness testing was performed on an un-deformed end shoulder of the tensile test coupon in accordance with ASTM E10. The results are as follows:

	Pipe #1 Near Fracture	Pipe #1 Near Cut	Pipe #2 Near Fracture
Lab File No.	*B0-03758*	*B0-03759*	*B0-03760*
Specimen Diameter (in.)	0.360	0.360	0.358
Tensile Strength (ksi)	24.3	23.8	24.9
Hardness (HBW10/3000/15)	164	124	162

Impact Testing

Impact tests were conducted on three V-notched Charpy specimens machined in the longitudinal direction from the three locations (indicated in Images #5 through #7) in accordance with ASTM E23 using an 8mm striker. The results are as follows:

	Pipe #1 Near Fracture	Pipe #1 Near Cut	Pipe #2 Near Fracture
Lab File No.	*B0-03758*	*B0-03759*	*B0-03760*
Size (mm)	10 x 10	10 x 10	10 x 10
Impact Energy (ft-lbs)	1, 1, 1	1, 1, 1	1, 1, 1
Test Temperature	70°F	70°F	70°F

Anderson Laboratories, Inc.

Douglas Marcks
Metallography Group Leader

Lori Felber
Quality Assurance Manager

The above tests were performed using one or more of the following specifications: ASTM A48, A247, A262, A370, B117, B328, B368, B748, E2 (SM 11-22), E3, E8, E9, E10, E18, E21, E23, E34, E45, E92, E112, E212, E290, E340, E350, E352, E353, E381, E384, E404, E407, E415, E562, E663, E766, E883, E986, E1019, E1024, E1077, E1086, E1251, E1508, G053, G154, ASME IX, AWS D1.1, MIL-S-867A, NAVSEA S9074-AQ-GIB-010/248, SAE J81, EN 10002 Part 1, EN 10045 Parts 1 & 2, EN 10204 Section 3.1.C and Anderson Laboratories Quality Manual Revision P dated 01/02/20. This report is confidential and shall not be reproduced except in full, without the written approval of Anderson Laboratories, Inc. Results reported apply only to the sample submitted. Sample ID is not a confirmation of material identification. The recording of false, fictitious, or fraudulent statements or entries on this document may be punishable as a felony under Federal Statutes.

City of Milwaukee Water Engineering M029
Failed 16" Diameter Cast Iron Water Pipe: Pipe #1
Image #1

Magnification: ~0.07X

Pipe #1 is shown as it was received for evaluation. The fractured end is to the right; the cut end to the left.

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Failed 16” Diameter Cast Iron Water Pipe: Pipe #2
Image #2

Magnification: ~0.08X

Pipe #2 is shown as it was received for evaluation. The fractured end is to the left.

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Failed 16” Diameter Cast Iron Water Pipe: Pipe #2
Image #3

Magnification: ~0.12X

The longitudinal fracture is shown in the as-received pipe #2.

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Failed 16" Diameter Cast Iron Water Pipe: Pipe #2
Image #4

Magnification: ~1X

The image shows the condition of the fracture faces found on both pipe segments. Post-fracture rust-type corrosive attack, adherent soil, and various amount of mechanical damage are present.

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Failed 16" Diameter Cast Iron Water Pipe: Pipe #1
Image #5

Magnification: ~0.42X

The locations of the tensile test coupon, impact test specimens, and the metallographic section are indicated near the fracture on pipe #1.

Image #6

Magnification: ~0.36X

The locations of the tensile test coupon, impact test specimens, metallographic section, and chemical analysis sample are indicated near the cut end on pipe #1.

Magnification: ~0.35X

The locations of the tensile test coupon, impact test specimens, and the metallographic section are indicated near the fracture on pipe #2.

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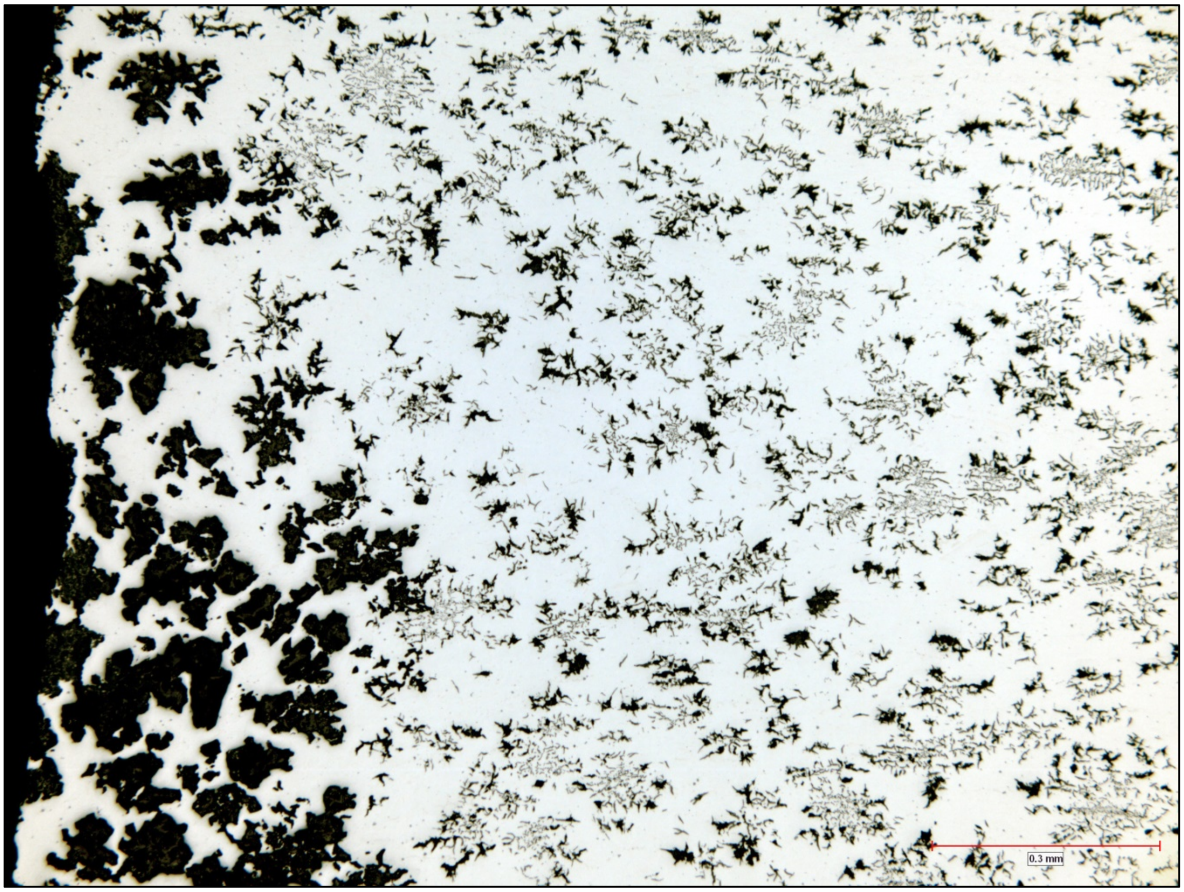
Failed 16" Diameter Cast Iron Water Pipe: Pipe #2 OD Surface Near Fracture
Image #8



Magnification: 100X Unetched

The image shows the typical graphite structure from the OD surface (left) near the fracture of pipe #2: predominantly Type B graphite flakes. Corrosive attack is propagating from the OD surface.

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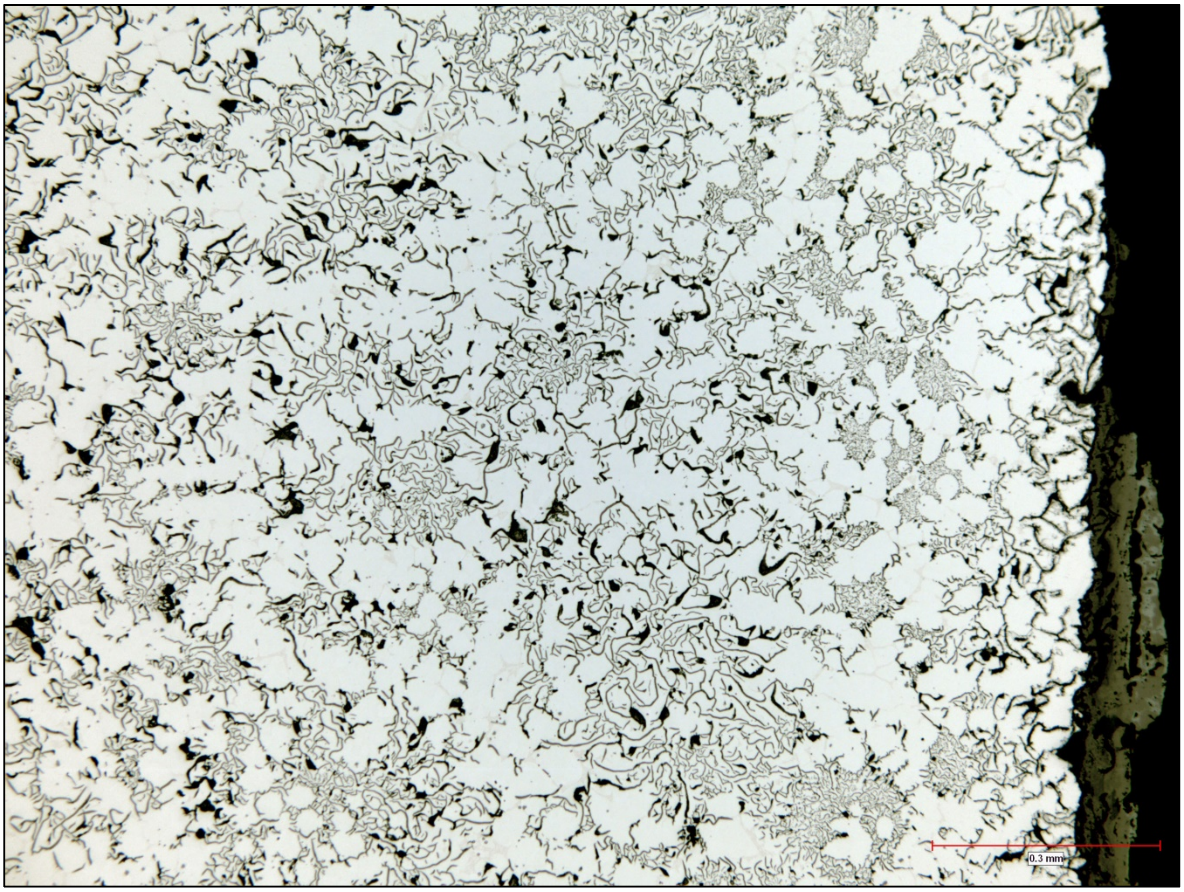
Failed 16" Diameter Cast Iron Water Pipe: Pipe #2 ID Surface Near Fracture
Image #9



Magnification: 100X   Unetched

The image shows the typical graphite structure from the ID surface (right) near the fracture of pipe #2: predominantly Type B graphite flakes.

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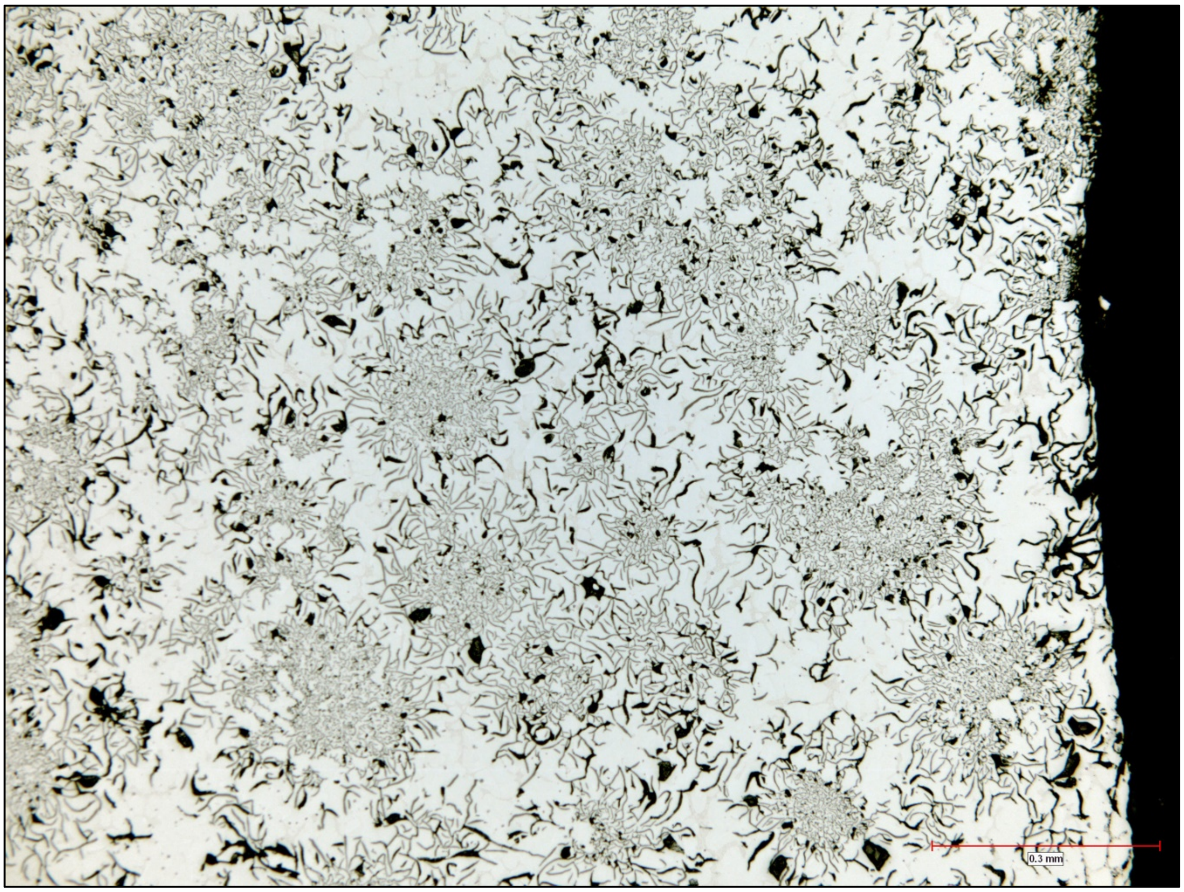
Failed 16" Diameter Cast Iron Water Pipe: Pipe #2 Centerline Near Fracture
Image #10



Magnification: 100X   Unetched

The image shows the typical graphite structure from the centerline of pipe #2 at the fracture face (right): predominantly Type B graphite flakes. Post-fracture mechanical damage has smoothed the fracture surface

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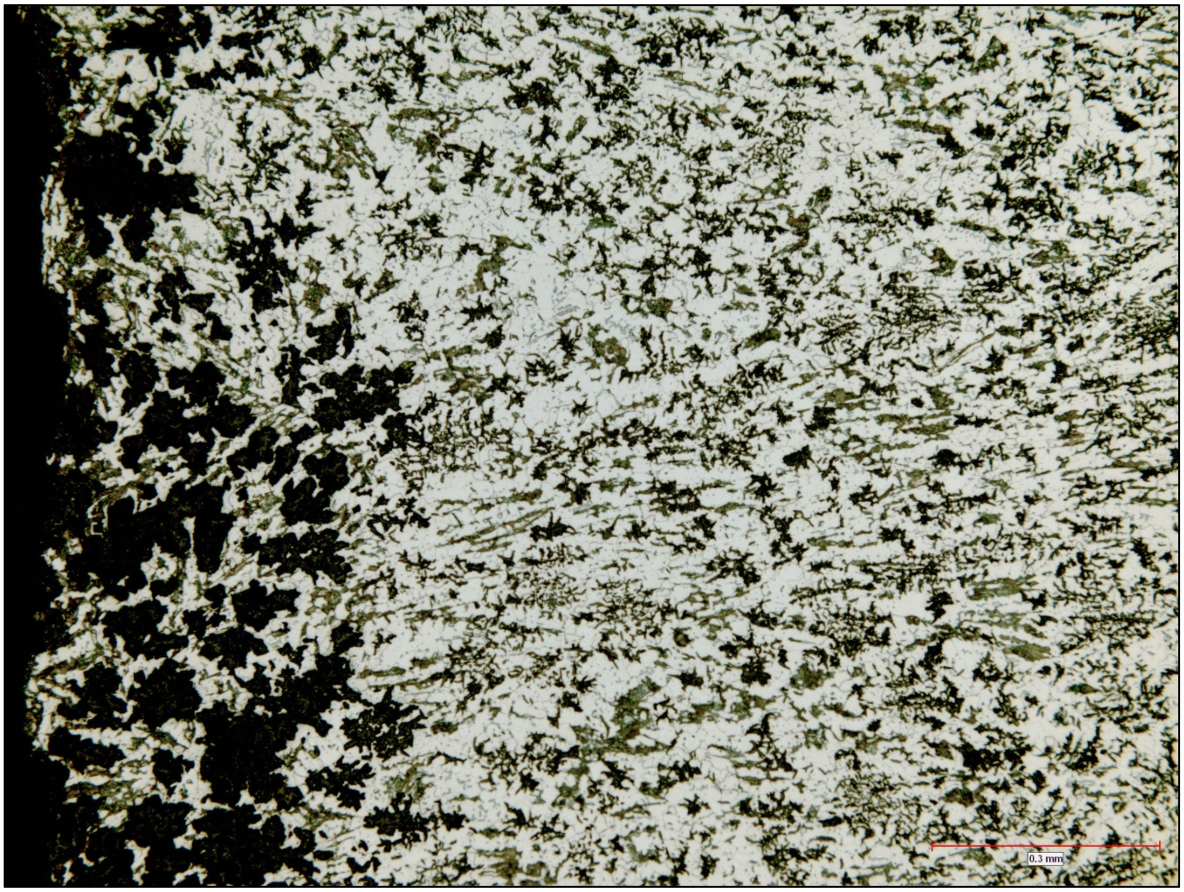
Failed 16” Diameter Cast Iron Water Pipe: Pipe #2 OD Surface Near Fracture
Image #11



Magnification: 100X Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the OD surface (left) near the fracture of pipe #2: predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides.

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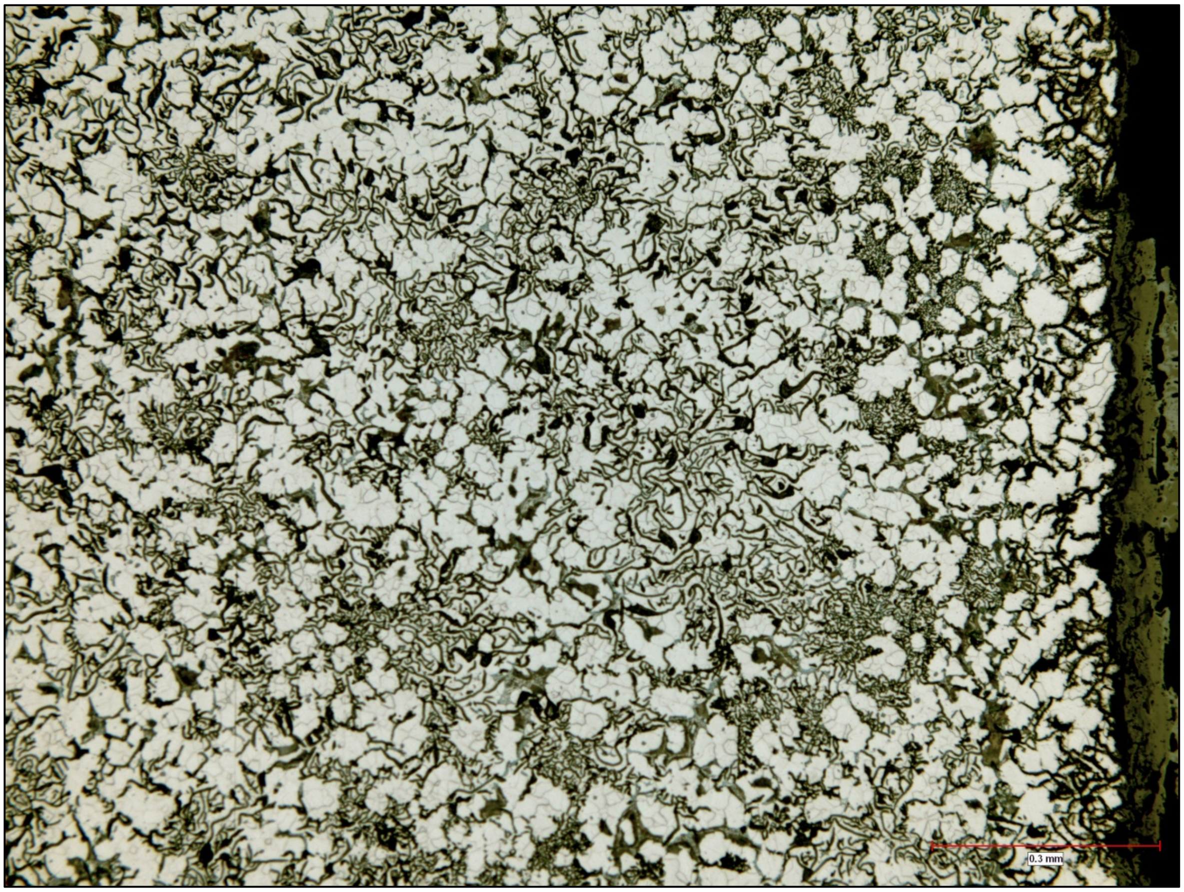
Failed 16" Diameter Cast Iron Water Pipe: Pipe #2 ID Surface Near Fracture
Image #12



Magnification: 100X Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the ID surface (right) near the fracture of pipe #2: predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides.

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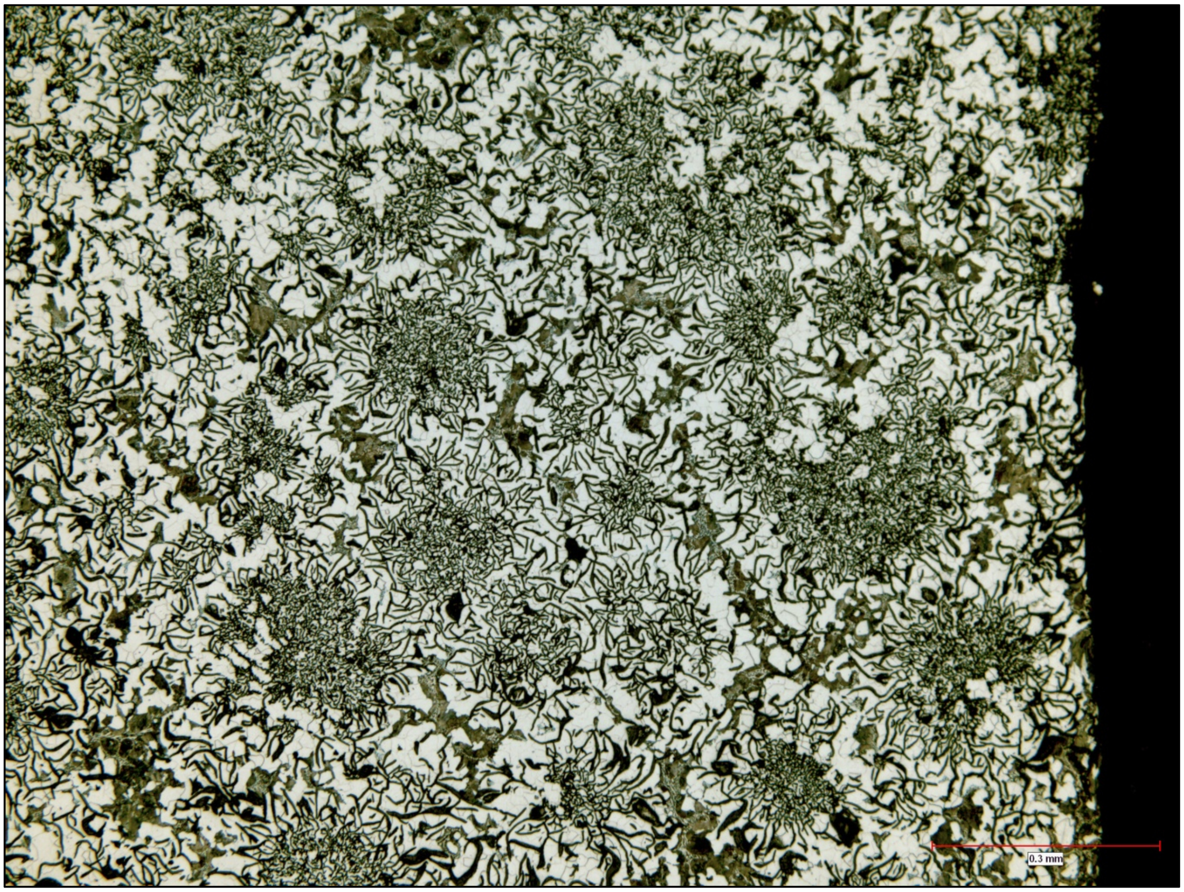
Failed 16" Diameter Cast Iron Water Pipe: Pipe #2 Centerline Near Fracture
Image #13



Magnification: 100X Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the centerline of pipe #2 at the fracture face (right): predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides.

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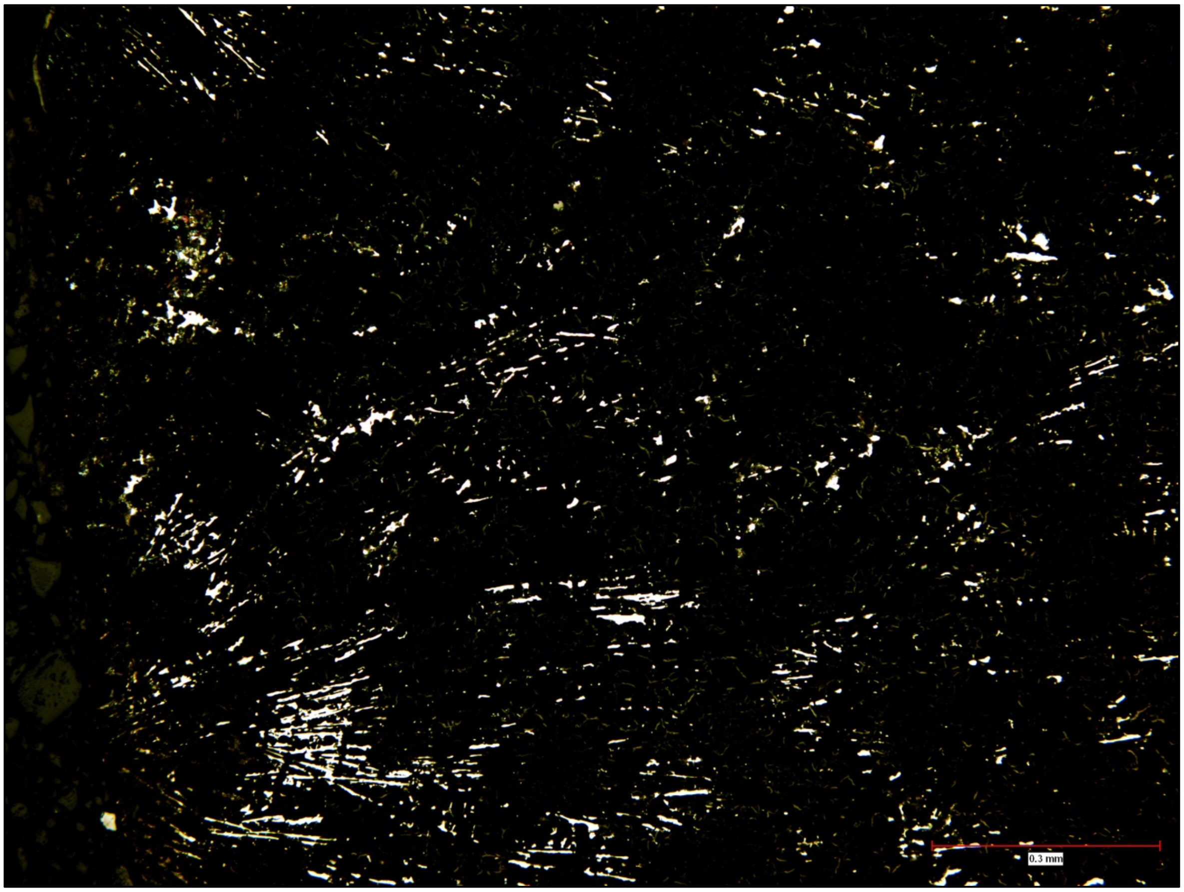
Failed 16" Diameter Cast Iron Water Pipe: Pipe #2 OD Surface Near Fracture
Image #14



Magnification: 100X Etchant: 10% Ammonium Persulfate

The image shows the typical level of steadite and carbides from the OD surface (left) near the fracture of pipe #2.

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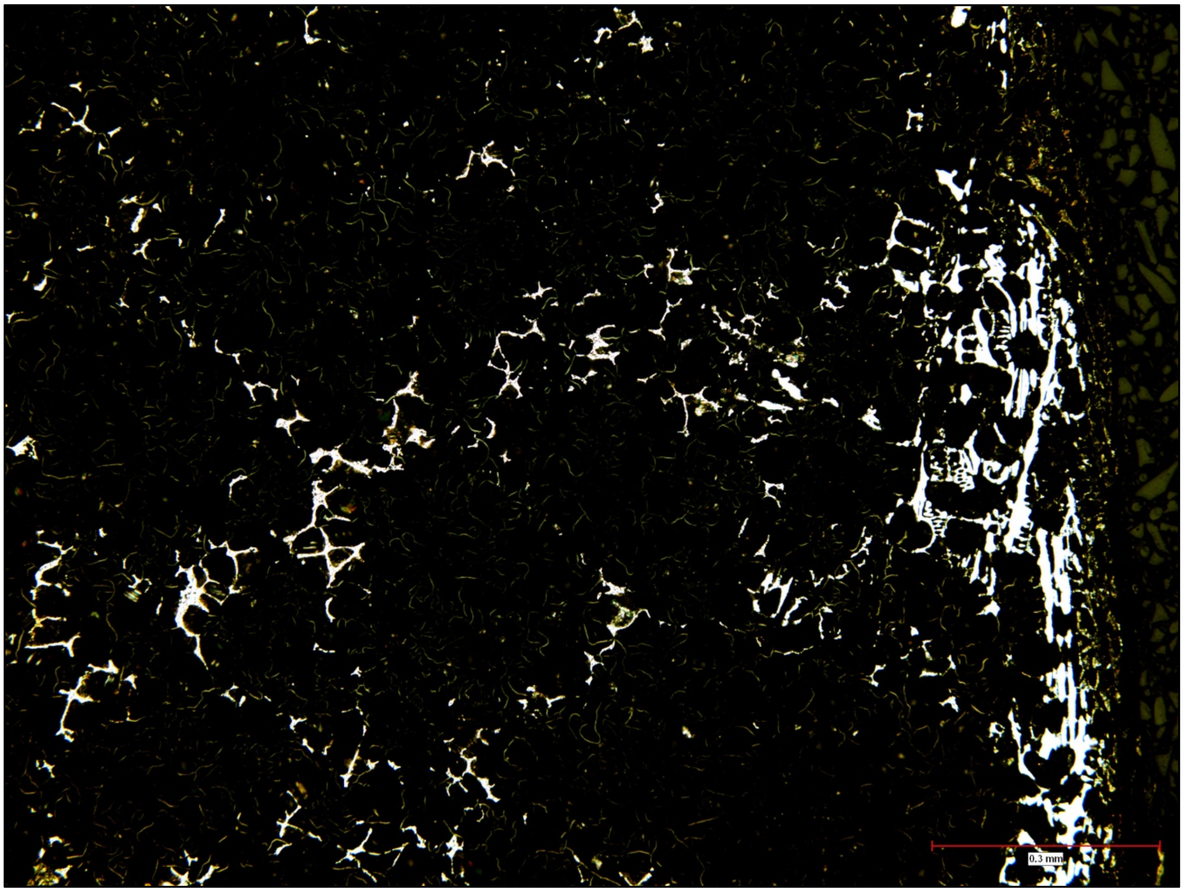
Failed 16” Diameter Cast Iron Water Pipe: Pipe #2 ID Surface Near Fracture
Image #15



Magnification: 100X   Etchant: 10% Ammonium Persulfate

The image shows the typical level of steadite and carbides from the ID surface (right) near the fracture of pipe #2. Carbides are concentrated on the ID surface.

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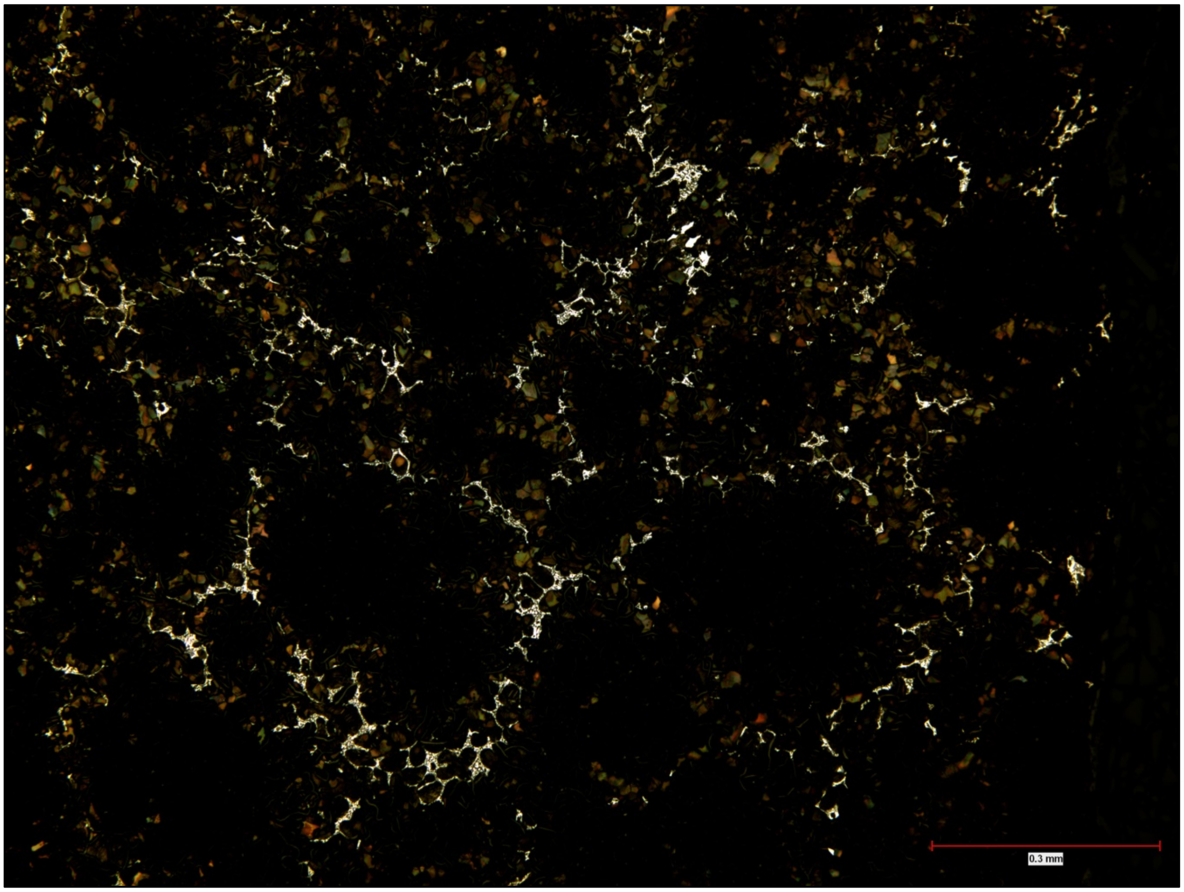
Failed 16" Diameter Cast Iron Water Pipe: Pipe #2 Centerline Near Fracture
Image #16



Magnification: 100X   Etchant: 10% Ammonium Persulfate

The image shows the typical level of steadite and carbides from the centerline of pipe #2 near the fracture face (right).

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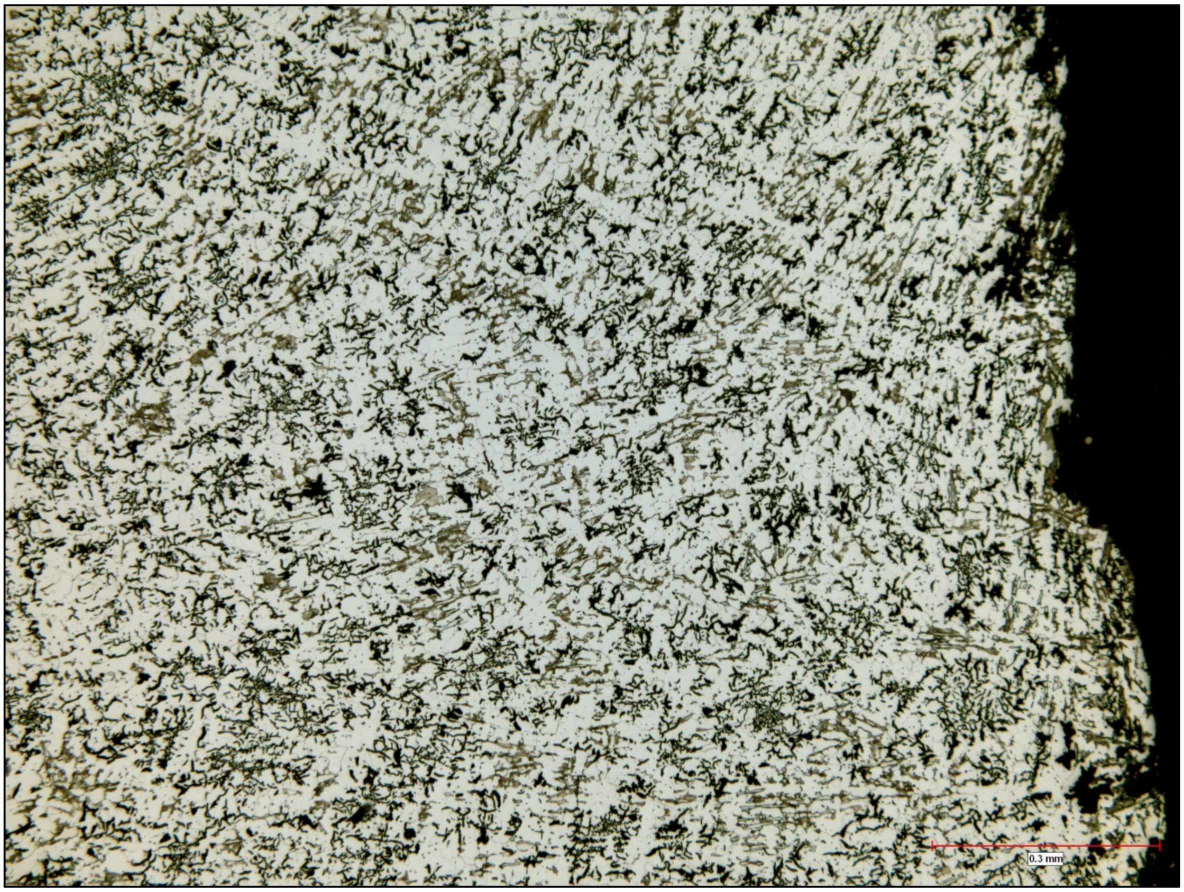
Failed 16" Diameter Cast Iron Water Pipe: Pipe #1 OD Surface Near Fracture
Image #17



Magnification: 100X   Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the OD surface (right) near the fracture of pipe #1: predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides.

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Failed 16” Diameter Cast Iron Water Pipe: Pipe #1 ID Surface Near Fracture
Image #18

Magnification: 100X   Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the ID surface (left) near the fracture of pipe #1: predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides. Carbides are concentrated on the ID surface.

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Failed 16” Diameter Cast Iron Water Pipe: Pipe #1 Centerline Near Fracture
Image #19

Magnification: 100X Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the centerline of pipe #1 near the fracture face (right): predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides.

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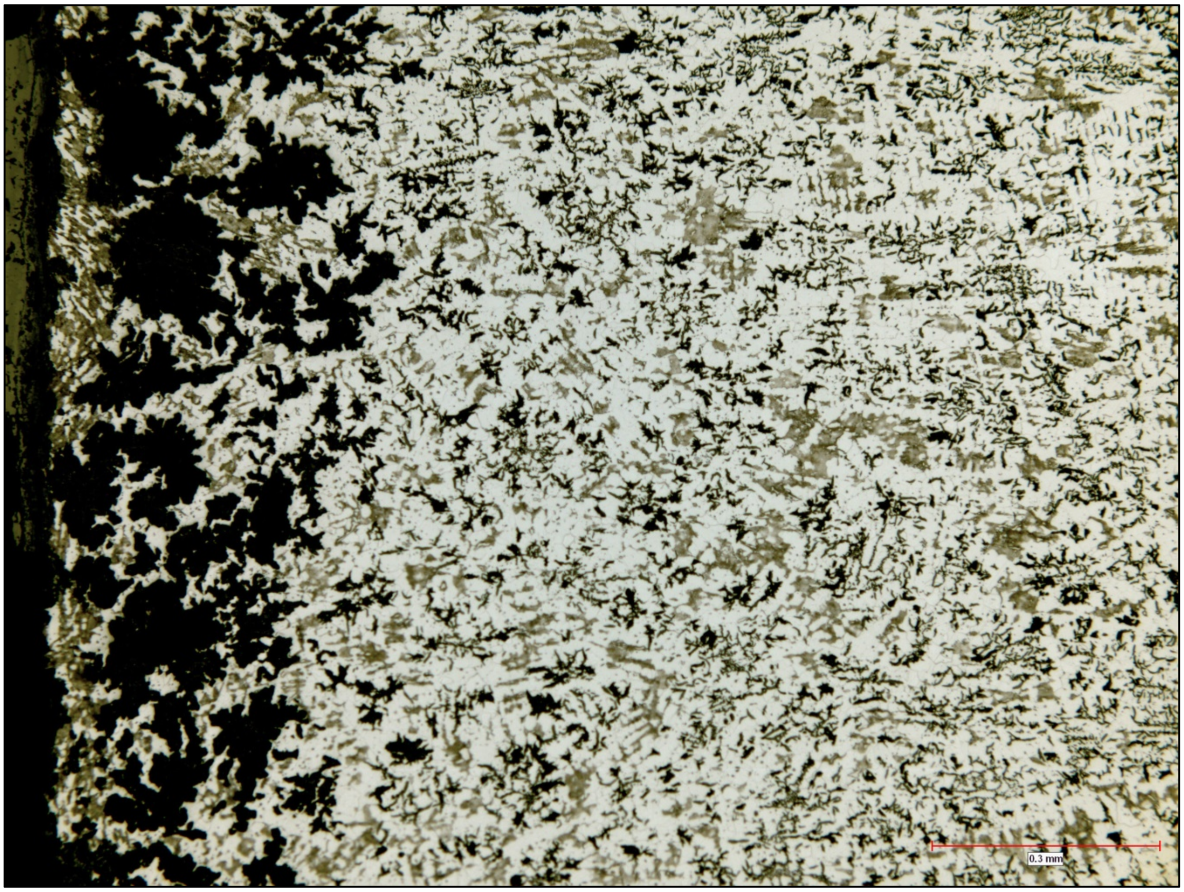
Failed 16" Diameter Cast Iron Water Pipe: Pipe #1 OD Surface Near Cut
Image #20



Magnification: 100X Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the OD surface (left) near the cut end of pipe #1: predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides. Corrosive attack is propagating from the OD surface.

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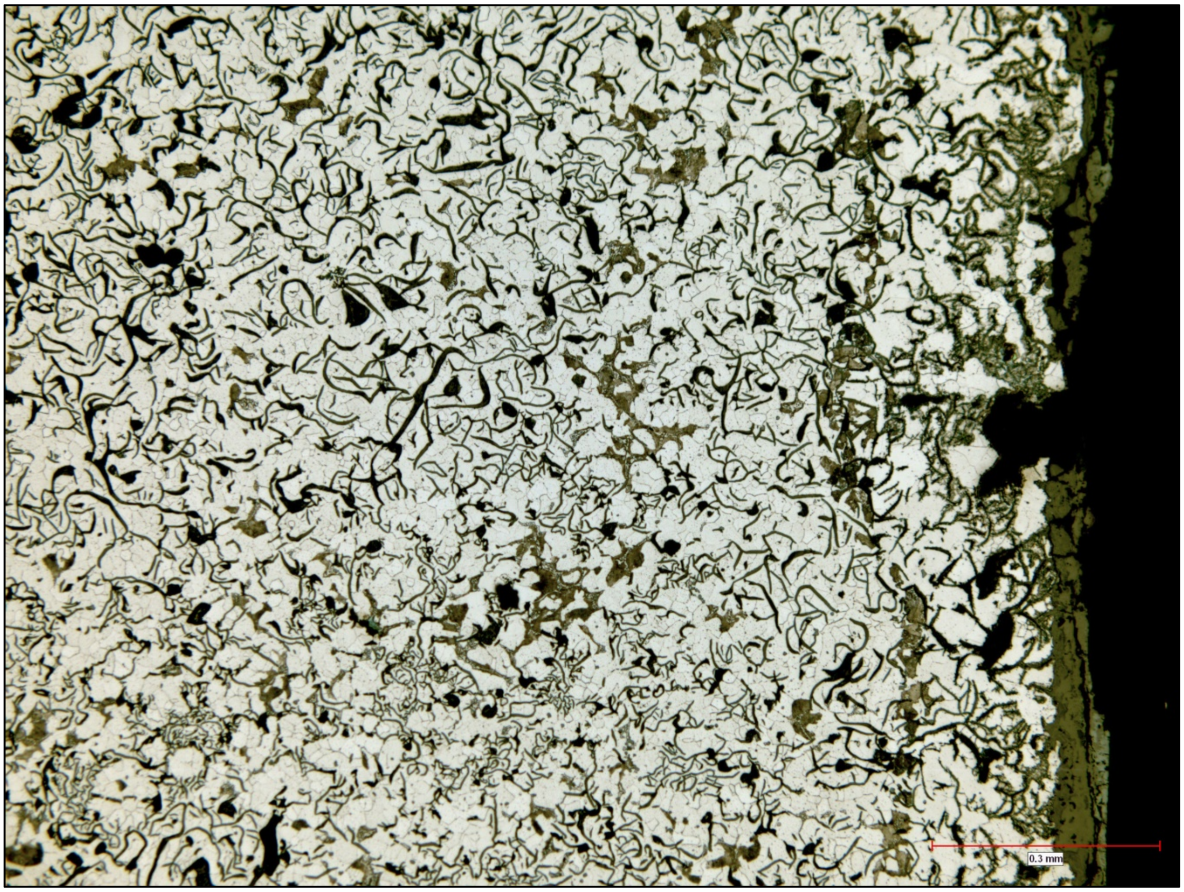
Failed 16” Diameter Cast Iron Water Pipe: Pipe #1 ID Surface Near Cut
Image #21



Magnification: 100X   Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the ID surface (right) near the cut end of pipe #1: Types A and B graphite flakes in a matrix of pearlite, ferrite, steadite, and carbides.

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Failed 16" Diameter Cast Iron Water Pipe: Pipe #1 Centerline Near Cut
Image #22

Magnification: 100X Etchant: Nital

The image shows the typical graphite structure and matrix microstructure from the centerline of pipe #1 near the cut end: predominantly Type B graphite flakes in a matrix of pearlite, ferrite, steadite and carbides.