NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

August 4, 2014

MATERIALS LABORATORY FACTUAL REPORT Report No. 14-043

A. ACCIDENT

Place	:	Birmingham, Alabama
Date	:	December 17, 2013
Vehicle	:	Alabama Gas Corp (Alagasco) natural gas pipe
NTSB No.	:	DCA14MP001
Investigator	:	Ravi Chhatre (RPH-20)

B. COMPONENTS EXAMINED

Four segments of 2-1/4 inch nominal diameter cast iron pipe (distribution main) and two segments of 1-inch nominal diameter steel pipe (service lines)

C. DETAILS OF THE EXAMINATION

1.0 As-received Pipe Segments

Four segments of 2-1/4 inch nominal diameter cast iron main and two segments of 1-inch nominal diameter steel pipe were submitted to the Safety Board Materials Laboratory. After receiving the pipe segments, they were arbitrarily labelled “A” through “F” as shown in figure 1 and table 1. Table 1 shows a description of the as-received pipe segments and location of excavation. Table 2 shows the measured outside diameter, inside diameter, and thickness of the as-received pipe segments at the cut ends of the pipe. According to service records from Alagasco, the cast iron main pipe segment “A” and those in the vicinity of this segment were installed in 1951. The cast iron main pipe is owned and has been maintained by Alagasco since the installation date. Preliminary visual inspection by the Safety Board Materials Laboratory of the as-received pipes segments revealed segment “D” was marked in raised characters the year of manufacture “1951”. The service records from Alagasco did not specify whether the nominal diameter of the cast iron main was “outer” or “inner”, and did not specify a wall thickness. Similarly, the same service records did not provide more detailed information regarding the steel service lines except that they were 1-inch nominal diameter.

2.0 On-site Work

After the accident, Alagasco leak surveyed the area for indications of a natural gas leak and identified several locations where a pipe was suspected of having a gas leak. The pipe portion that was suspected of having a gas leak was excavated[1] to expose the suspect leak area. The pipe portion in the area of the suspect gas leak was pressurized with natural gas and the outer surface was coated with a soap solution. The pipe would test positive for a gas leak if the outer surface of the suspected region of the gas leak produced gas bubbles. The as-received pipe segments tested positive for a gas leak in the areas indicated by a white box in figure 1, with the exception of segment “E”. Segment “E” was of interest because it contained a sleeve and was submitted to the Safety Board Materials Laboratory for pressure testing.

On-site testing by Alagasco disclosed that cast iron main pipe segment “A” in figure 1 contained a gas leak. The leak emanated from the bottom of the pipe. The outer surface around the pipe in the area of the gas leak was cleaned on-site, and a 7.5-inch long sleeve (clamp with three bolts and their attachment nuts) was installed over the leaking portion. The sleeve is indicated by bracket “S1” in figure 1. The sleeve with the pipe was shipped to the Safety Board Materials Laboratory.

Excavation work disclosed cast iron main pipe “E” in figure 1 was encased with a 12-inch long sleeve (clamp with six bolts and their attachment nuts) in the area indicated by bracket “S2” in figure 1. The threads and attachment nuts for the sleeve “S2” in figure 1 exhibited brown oxide scale oxidation consistent with a sleeve that had been buried in the ground. A representative from Alagasco confirmed that sleeve “S2” in figure 1 was on the pipe when it was uncovered (exposed) by excavation.

3.0 Safety Board Materials Laboratory

The following individuals participated in the examination of the pipe pieces between May 27 and 29, 2014 at the Safety Board’s Materials Laboratory in Washington, D.C.:

Frank Zakar	NTSB
Edward Komarnicki	NTSB
Randy Wilson	Alagasco
Bob Gardner	Alagasco
Wallace Jones	Alabama Public Service Commission

On the dates described, participants examined/witnessed the bench binocular microscope and scanning electron microscope (SEM) examination of the east face portion of the fracture from segment “A”; leak testing of several pipe segments; preparation and examination of several metallurgical sections. The as-received pipe segments were removed from their respective crates and photographed prior to arrival of party participants.

4.0 Cast Iron Main Pipe Segment “A”

The sleeve on segment “A” was disassembled prior to May 27. Upon removal of the sleeve, the pipe segment in the area of the gas leak was found with a fracture that extended circumferentially all around the pipe (see figure 2). Figure 3 shows a photograph of the east face of the fracture. Bench binocular microscope examination of the east face

[1] The soil around the pipe was dug out to expose suspect leak area with the pipe remaining in its original position.

of the fracture surface revealed a radiating pattern that originated from the outer face at the bottom of the pipe. The fracture propagated up and radially outward. The fracture extended to each side of the fracture origin area and propagated circumferentially up toward the top side of the pipe, in the general direction indicated by unmarked arrows in figure 3. The fracture face exhibited five dark regions adjacent to the outside surface consistent with oxidized cast iron. The five oxidized regions are indicated by brackets "1" through "5" in figure 3. The largest oxidized region was located at the bottom of the pipe. The oxidized region at the bottom of the pipe extended through the thickness of the pipe, intersecting the outer and inner surfaces. On the outer surface, the circumferential length of the oxidized region measured approximately 1.6 inch. On the inner surface the circumferential length of the oxidized region measured approximately 0.7 inch.

Table 3 shows the measured size of the outer diameter, inside diameter, and wall thickness of the as-received pipe segment at the east face of the fracture. The locations of the measurements on the fracture face were described as if on the face of a clock. For the purpose of this report, the 12 o'clock position is located on the top of the pipe looking east, unless otherwise specified. The outer surface of the pipe contained a longitudinal seam at the top and bottom surfaces that extended along the length of the pipe. The seams extended above the outer surface and at the base of these seams exhibited smooth round relief radii consistent with the parting line of a casting.

A circumferential-radial saw cut was made through pipe segment "A" in the area located approximately 1 inch away from the east face of the fracture. The approximately 1-inch wide ring that contained the east face of the fracture was removed and ultrasonic cleaned with Alconox, a commercial soap solution. The cleaning process removed the oxidized regions and exposed black regions that were located within the oxidized regions. Figure 4 shows a composite photograph of the black regions on the clean fracture face. The black regions are located adjacent to the outer surface and were smaller than the oxidized regions in figure 3. The black regions adjacent to the outer surface in figure 4 are consistent with graphitic corrosion in gray cast iron. Graphitic corrosion is defined as deterioration of gray cast iron in which the metallic constituents are selectively leached or converted to corrosion products leaving the graphite phase intact.[2] The ultrasonic cleaning process exposed two additional graphitic corrosion areas indicated by brackets "C6" and "C7" in figure 4. The oxidized region indicated by bracket "C2" in figure 4 is barely visible after cleaning compared to the same respective area before cleaning (figure 3).

Scanning electron microscope (SEM) examination of the east face of the fracture using an electron backscatter detector[3] after ultrasonic cleaning revealed the graphic corrosion region at the bottom of the pipe in the area indicated by bracket "C11" in figure 4 extended as deep as 60% of the wall thickness. X-ray energy dispersive spectroscopy (EDS) analysis of the pipe fracture face in the area located outside of the graphitic corrosion region showed elemental peaks of iron, phosphorus, oxygen and carbon (see

[2] ASM Handbook, Volume 13A, titled "Corrosion: Fundamentals, Testing, and Protection", 2003 edition, Glossary of Terms, page 1019, ASM International.

[3] Backscatter electron imaging provides image contrast as a function of elemental composition. In backscattered electron image, higher atomic number material (such as iron) appear brighter compared with low atomic number materials that appear darker (such as carbon). Graphitic corrosion areas (where iron had leached out) appear darker compared to other areas of the pipe that contain iron.

figure 5). EDS spectrum of the graphitic corrosion regions showed iron peaks that were smaller and carbon, silicon, and oxygen peaks that were greater than the same respective elements in the areas located outside of the graphitic corrosion regions. The graphitic corrosion region at the bottom of the pipe in the area indicated by bracket “C12” in figure 4 extended as deep as 50% of the wall thickness. Figures 5 and 6 show SEM electron backscatter images of the extent of graphitic corrosion regions in areas “C11” and “C12”, respectively. The graphitic corrosion areas in electron backscatter images appear as gray areas in figures 5 and 6, whereas, fracture areas located outside of the graphitic corrosion region appear as light luster. The size of the graphitic corrosion regions observed on the electron backscatter images are consistent the size of those observed on the optical microscope and visual examination (figure 4), with the exception of the graphitic corrosion in the area indicated by bracket “C2” in figure 4. When viewing the fracture face with an SEM in electron backscatter mode, the graphitic corrosion area indicated by bracket “C2” in figure 4 did not exhibit a clear border. The graphitic corrosion area indicated by bracket “C2” in figure 4 was less severe compared to the graphitic corrosion areas “C11” and “C12” in figures 5 and 6, respectively.

A radial-longitudinal metallurgical section was made through a graphitic corrosion area at the bottom of the pipe, in the area indicated by section line “A-A” in figure 4. The section was encased in a metallurgical mount and polished. Figure 7 shows a photograph of polished section “A-A”. Examination of the polished section revealed the outer surface of the pipe and fracture face contained black areas consistent with graphitic corrosion in gray cast iron. Examination of the polished section revealed graphite flakes in a matrix of pearlite consistent with gray cast iron. The graphite flakes at the core of the pipe where consistent with graphite flake type B (rosette groupings, random orientation); graphite form VII; and graphite size 5 when compared with template standards in ASTM A247, titled “Evaluating the Microstructure of Graphite in Iron Castings”. Section “A-A” was etched with 2% Nital reagent. The etched section showed a microstructure of graphite flakes in a matrix of pearlite.

In preparation for chemical analysis, a three inch long ring portion of the pipe was cut from an area located approximately 2 feet from the west side of the fracture. Chemical analysis of this ring sample was contracted to Lehigh Testing, Delaware. The results of the chemical analysis is reported in table 4. According to ASM Metals Handbook, gray cast irons typically contain 2% to 4% carbon and 1% to 3% silicon. The gray cast iron sample contained 3.43% carbon and 1.92% silicon, consistent with the composition of gray cast iron.

Prior to cutting and preparing metallurgical sections, pipe segment “A” was scanned by X-ray Computed Tomography (CT) method in an area that extended approximately 5 inches west of the fracture and 5 inches east of the fracture, and another longitudinal segment that was located between approximately 1 foot and 1.4 feet west of the fracture. A saw cut was made through the pipe in an area located approximately 2 feet west of the fracture to facilitate handling of the pipe. X-ray CT scanning was contracted to Chesapeake Testing in Belcamp, Maryland. A Nikon Metrology 450 kV Microfocus X-ray tube was used to inspect the pipe segments. Each CT volume was evaluated using the Volume Graphics Studio Max software package to create a three-dimensional reconstructed image of the pipe segment.

Examination of the X-ray CT images revealed the outer surface of all pipe segments contained isolated areas of low density material (radio-opacity) compared to the core and inner surface of the pipe consistent with graphitic corrosion. Appendix “A” show typical X-ray CT images of pipe segment “A” (graphitic corrosion indicated by black-gray areas). On the fracture faces, the size and distribution of graphitic corrosion areas were consistent with those visually observed on the east face of the fracture. The X-ray CT images showed evidence of graphitic corrosion at five isolated areas of pipe segment “A” and at various clock positions. The graphitic corrosion areas extended as deep as between 50% and 60% of the wall (areas indicated between arrows “G” in Appendices “A3” through “A8”).

5.0 Leak Testing

Prior to destructive testing, several pipe segments were pressure tested with compressed air at the Safety Board Materials Laboratory to verify the location of leaks (see section 5.1); determine pressure decay with time (see section 5.2); and determine the rate of air leak (see section 5.3). In summary, the leak tests showed that pipe segments “C”, “D”, and “F” contained leaks in the same respective areas as those identified during the on-scene investigation after the accident, and in addition, revealed evidence of a leak at the ends of the sleeve “S2” in figure 10 that was not detected by Alagasco.

5.1 Leak Testing with Compressed Air

Pipe segments “C”, “D”, “E”, and “F” were each pressure tested with compressed air at 5 pounds per square inch gage pressure (psig) to verify the location of a leak. Pipe segment “A” was not pressure tested because it was found with a fracture after the sleeve was removed. Pipe segment “B” was not pressure tested for a leak since Alagasco reported the leak to be at one extreme end of the pipe segment (pipe internal plugs would have overlapped with the leak area and would interfere with finding leaks at the ends of the pipe). The inner surface at each end of a pipe segment was brush cleaned with a machine driven rotating stainless brush. The inner corner at the ends of each pipe was cleaned with a file to eliminate sharp burrs. The internal plugs for the pressure tests were manufactured by Petersen Products, Fredonia, Wisconsin. One end of a pipe segment was fitted with a pipe internal plug and the other end was fitted with a pipe internal plug that contained a bypass port. The bypass port was used to allow compressed air to enter a pipe segment. The pressure entering the pipe was controlled by a pressure regulator and monitored with a pressure gage. As indicated earlier, a pipe segment was filled with compressed air to 5 psig, and the outer surface of a pipe segment was coated with a soap solution. A pipe would test positive for a leak if the outer surface produced soap bubbles. Table 5 provides a summary of the leak tests, such as segment identification letter; consecutive leak number that was arbitrarily selected by the Safety Board Materials Laboratory; the position of the leak based on a clock dial; and appearance of the leak. The appearance of a leak fell into two categories. The two categories are “linear” indicating a long crack-like feature on the surface or “irregular and in one area”. Sections 5.11 through 5.1.4 provide details of the leak areas.

5.1.1 Leak Testing of Pipe Segment "C"

Leak testing of segment "C", a 1-inch nominal diameter steel pipe, revealed a leak in the same general vicinity as described by Alagasco in figure 1.

5.1.2 Leak Testing of Pipe Segment "D"

Segment "D" is a 2-1/4 inch nominal diameter cast iron pipe. During pressure run-up in preparation for the gas flow test described in section 5.3, a conical-shaped fragment referred as fragment "DD" in figure 8 fractured from the wall, leaving behind an irregular hole in the wall of the pipe. This segment had remained intact during the "Pressure Decay Test" that was conducted in section 5.2 of this report. The largest dimensions of the fragment measured approximately 1 inch by 1.5 inch. The diameter of the hole in the wall of the pipe measured approximately 0.3 inch. Visual and binocular microscope examination of the particle revealed the fracture surface contained multiple irregular bands that extended around the fracture face (see figure 8). The color of the bands on the fracture face varied between brown, black, gray, and tan-like (in no specific order). The fracture surface showed evidence of corrosion deterioration. The outer and inner surface of the fragment showed evidence of multiple cracks that in many areas intersected each other.

At the Safety Board Materials Laboratory, fragment "DD" was intentionally broken in half to expose internal fracture features. Figure 9 (top of page) shows the laboratory induced fracture that was in the longitudinal-radial orientation and shows internal cracks and discolored fracture regions. Figure 9 (bottom image) shows image of the same fracture face after it was ground down with grit paper, encased in metallurgical mount, and polished to further reveal the internal structure. The polished metallurgical mount in figure 9 (bottom of page below) shows evidence of internal cracks and graphitic corrosion. The metallurgical mount shows porosity and graphitic corrosion in all areas of the fragment.

5.1.3 Leak Testing of Pipe Segment "E"

Leak testing of segment "E", a 2-1/4 inch nominal diameter cast iron pipe, revealed evidence of a leak at the ends of the sleeve "S2" in figure 10 that was not detected by Alagasco (during the on-scene evaluation of the pipe after the accident).

5.1.4 Leak Testing of Pipe Segment "F"

Visual examination of segment "F", a 2-1/4 inch nominal diameter cast iron pipe, revealed a linear indication at the 12 o'clock position. The length of this linear indication measured approximately 4 inches. Leak testing of segment "F" showed soap bubbling that emanated from this linear indication (12 o'clock) and two additional linear indications (10 o'clock and 1 o'clock positions) as summarized in table 5. The length of the 10 o'clock and 1 o'clock crack measured approximately 3.6 inches and 2 inches, respectively. Based on the soap bubbling pattern observed during pressure testing, the cracks were oriented longitudinal relative to the length of the pipe, with the ends oriented slightly diagonal relative to the length of the pipe. A metallurgical section was made through the pipe that included the three linear indications, in the orientation indicated by section line "F-F" in figure 11. The section was made approximately 10 inches west of the bell and spigot assembly. Examination of section “F-F” revealed the three linear indications were cracks that penetrated the wall of the pipe (see figure 12). The three cracks showed evidence of graphitic corrosion at the outer surface that did not exceed 20% of the wall thickness. The portion of the three cracks that extended below outer surface graphitic corrosion regions showed no evidence of graphitic corrosion.

5.2 Pressure Decay Test

For the purpose of this report, a pressure decay test is defined as a test where a pipe segment is initially pressurized with air to 20 psig (reported operating pressure for the pipe). and the supply of air to the pipe segment is cut off from the air compressor. After the compressed air supply is shut off, pressure decay is monitored as function of time.

The pressure decay test was performed for segments “C”, “D”, “E”, and “F” with the air pressure set to 20 psig. The ends of a pipe segment, pipe internal plugs, and connections were coated with soap solution to verify that air was not leaking from those ends and connections. At 20 psig, the valve leading to the bypass port was turned off. The pressure gauge was monitored for indication of a pressure drop. The time required for the pressure to drop to zero psig for each pipe was recorded and reported in table 5. Each of the pressure tested segments held pressure in the range between 16 seconds and 5 minutes and 55 seconds.

5.3 Gas Flow Measurements

Each pipe segment was pressurized with a continuous and uninterrupted supply of compressed air at a pressure of 20 psig. The rate of air leak was measured with a flow meter. Four borosilicate glass metering tubes, each manufactured by King Instrument Company, and VPFlowcope® in-line electronic flow meter, manufactured by Van Putten Instruments, Netherlands, were available to measure the air leak rate. The four King Instrument Company flow meters when combined were able to measure flow rate in the range between 0.034 standard cubic feet per hour (SCFH) and 43 SCFH. The electronic meter measured an air flow in the range between 7.8 SCFH and 3,000 SCFH.[4] Table 5 shows the measured leak rate for air for various pipe segment and the adjusted leak rate if the pipe segments were leaking natural gas. For educational purpose, Appendix B show the basic formulas and their derivation for converting the volumetric leak rate in air to volumetric leak rate for natural gas. The specific weight of natural gas is dependent on the composition of the natural gas and can vary in the range between 0.554 and 0.87. For the purpose of this report, the value of 0.7 was used in the formula for converting volumetric leak rate in air to volumetric leak rate for natural gas.

Frank Zakar
Senior Metallurgist

[4] The electronic flow meter measured flow in standard cubic feet per minute and values read on the meter were converted to standard cubic feet per hour.

Table 1
Description of As-received Pipe Segments

Pipe Segment	Nominal Diameter (inches)	Material	Length (feet)	House Unit # and Address
A	2-1/4	Cast Iron Main Pipe	8	Unit #80 of 7546, 64th Court Way South
B	1	Steel Meter Riser	1	Unit #72 of 7530, 64th Court Way South
C	1	Steel Pipe	4	Unit #33 of 7547, 64th Court Way South
D	2-1/4	Cast Iron Main Pipe	6	Unit #69 of 7524, 64th Court Way South
E	2-1/4	Cast Iron Main Pipe	3	Unit #69 of 7524, 64th Court Way South
F	2-1/4	Cast Iron Main Pipe	6.6	Unit #453, 6807 Joppa Avenue

Table 2
Measured Pipe Dimensions at the Cut Ends of the Pipe Segments

Pipe Segment	House Unit	Length (feet)	Outside Diameter (inches)	Inside Diameter (inches)	Thickness (inches)
A	#80	8	2.73 - 2.75	2.18 - 2.23	0.25 - 0.29
B	#72	1	1.32	1.03	0.15
C	#33	4	1.32	1.03	0.15
D	#69	6	2.72	2.17 - 2.18	0.27 - 0.28
E	#69	3	2.74	2.18 - 2.21	0.27 - 0.28
F	#453	6.6	2.74	2.17 - 2.22	0.26 - 0.29

Table 3 Measured Pipe Dimensions at East Face of Fracture			
Position (o'clock)	Outside Diameter (inches)	Inside Diameter (inches)	Thickness (inches)
12	2.75	2.18	0.279
3	2.74	2.17	0.262
6	--	--	0.270
9	--	--	0.294
10	2.72	2.17	0.291
10:30	2.73	2.18	0.280
11:30	2.73	2.18	0.276

Notes:
The positions of features on the fracture face were described as if on the face of a clock. The 12 o'clock position is located on the top of the pipe looking east.

Table 4 Composition of Cast Iron (weight %)	
Element	Measured
Carbon	3.43
Silicon	1.92
Manganese	0.24
Phosphor	0.776
Sulfur	0.083
Chromium	0.01
Nickel	0.007
Copper	0.03
Molybdenum	0.002
Vanadium	0.05
Magnesium	0.009
Titanium	0.06
Cobalt	0.01
Aluminum	0.01
Boron	0.0029

Table 5
Pressure Testing of Pipe Segments with Compressed Air at NTSB,
After Coating the Outer Surfaces with Soap Solution

Pipe Segment	Leak #	Location of Leak	Clock Position of Air Leak Looking East (o'clock)	Appearance Of Soap Bubble Pattern in Area of Air Leak	Pressure Decay Test: Time for Air Pressure to Drop to 0 psig from 20 psig, after Air Pressure is Cut Off (minutes: seconds)	Measured Air Leak Rate, at 20 psig (SCFH) and [SCFM]	Calculated Leak Rate if it was Natural Gas[5] (SCFH) and [SCFM]
A	#1	Wall	6:00	Irregular and in one area; no specific pattern.	Not tested; Pipe found with fracture	N/A	N/A
B	#2	Not verified by NTSB testing	N/A	N/A	Not tested; leak located at threaded end	N/A	N/A
C	#3	Wall	4:00	Irregular and in one area.	00:16	23 [0.38]	27 [0.45]
D	#4	Wall	1:00	Irregular and in one area.	02:06	XX	XX
	#5	Wall	6:00	Irregular and in one area.			
E	#6	Both ends of sleeve	12:00	Irregular and in one area.	05:55	14 [0.23]	17 [0.27]
F	#7	Wall	10:00	Linear; 3.6 inches long	03:10	7 [0.12]	8 [0.14]
	#8	Wall	12:00	Linear; 4 inches long			
	#9	Wall	1:00	Linear; 2 inches long			

Notes:
Following abbreviations are used: Flow rate was reported in standard cubic feet per hour (SCFH) and standard cubic feet per minute [SCFM].

All pressure decay measurements were made prior to air leak rate measurements. Measurements for the two methods were performed on separate days.

(XX) – indicates that during pressure run-up to 20 psig, in preparation for making flow measurements, a fragment fractured from the pipe leaving behind approximately a 0.3-inch diameter hole. Thus, the air leak rate (flow rate) that corresponded to actual conditions in the ground could not be recorded. However, for information purpose and future reference, the air leak rate for the pipe that contained the 0.3 inch diameter hole at 20 psig measured 180 SCFM [10,800 SCFH]. For natural gas, this would have been approximately 215 SCFM [12,900 SCFH].

N/A – not applicable to that section

[5] Method of converting volumetric gas flow (air to natural gas) is shown in Appendix B

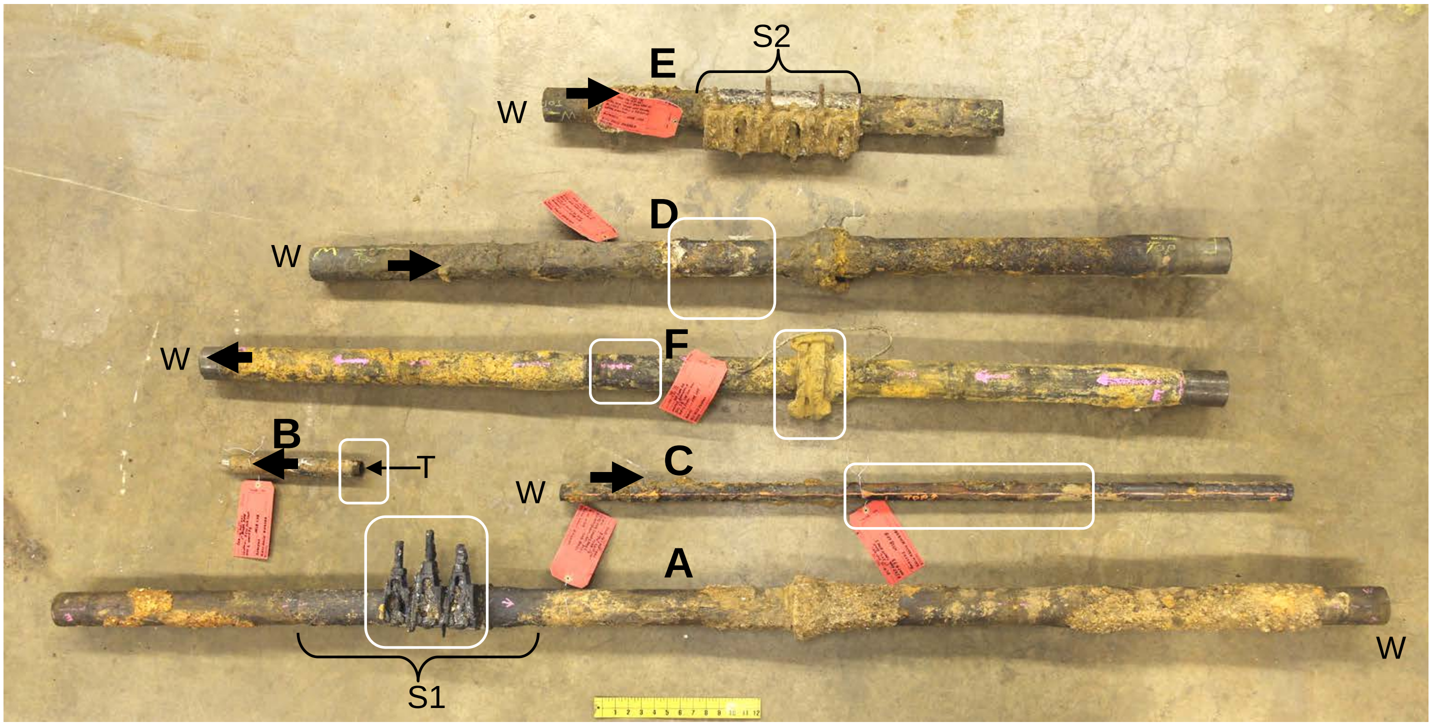


Figure 1. Photograph of the as-received pipe segments showing the top side. The pipe segments were arbitrarily labeled segments “A” through “F”.

SEGMENT “A”: 8-foot segment of cast iron main pipe from unit #80

SEGMENT “B”: 1-foot segment of steel meter riser from unit #72

SEGMENT “C”: 4-foot segment of steel pipe from unit #33

SEGMENT “D”: 6-foot segment of cast iron main pipe from unit #69

SEGMENT “E”: 3-foot segment of cast iron main pipe from unit #69

SEGMENT “F”: 6.6 foot (80-inch) segment of cast iron main pipe from unit #453

The west end of a pipe segment is indicated by the letter “W”. The direction of gas flow for each pipe is indicated by an unmarked arrow. Pipe segment labeled “A” reportedly was part of a two-way feed system, so the gas flow can be in either direction. The end indicated by arrow “T” is the threaded end of the steel pipe riser and was the end facing down. Alagasco representatives indicated that a gas leak was detected in several pipe segments following the accident on December 17, 2013 within the areas marked by a white box. The ends of each pipe were saw cut on site with the exception of the threaded end indicated by arrow “T”. Sleeve “S1” was installed over the pipe after excavation to cover a gas leak area. Sleeve “S2” was found installed on the pipe when it was uncovered (exposed) by excavation.

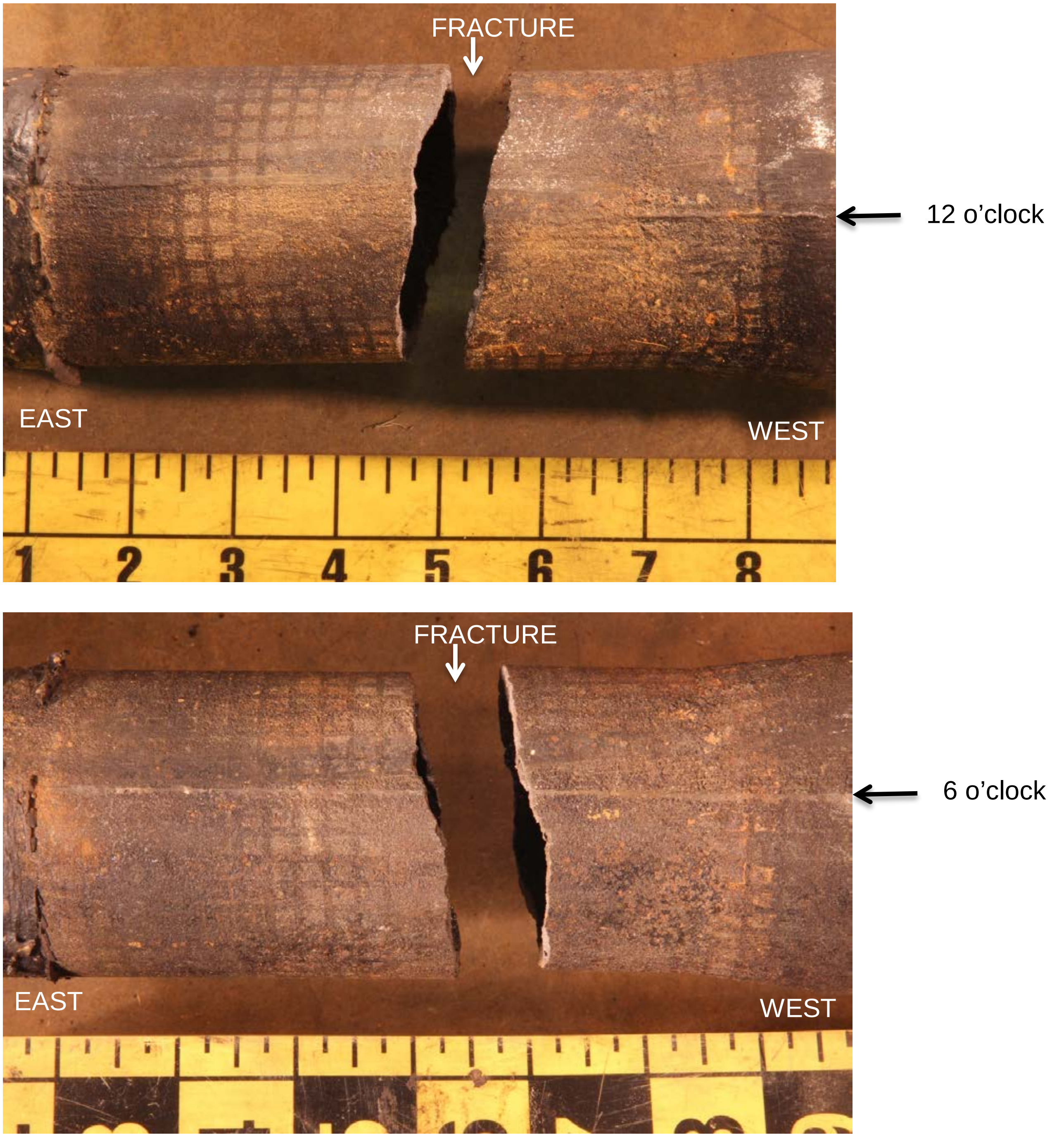


Figure 2. Photographs of pipe segment "A" showing the top and bottom sides of the pipe in the areas of the fracture (top and bottom of page, respectively). Casting mold parting lines that were oriented along the length of the pipe were located at the 12 and 6 o' clock positions.

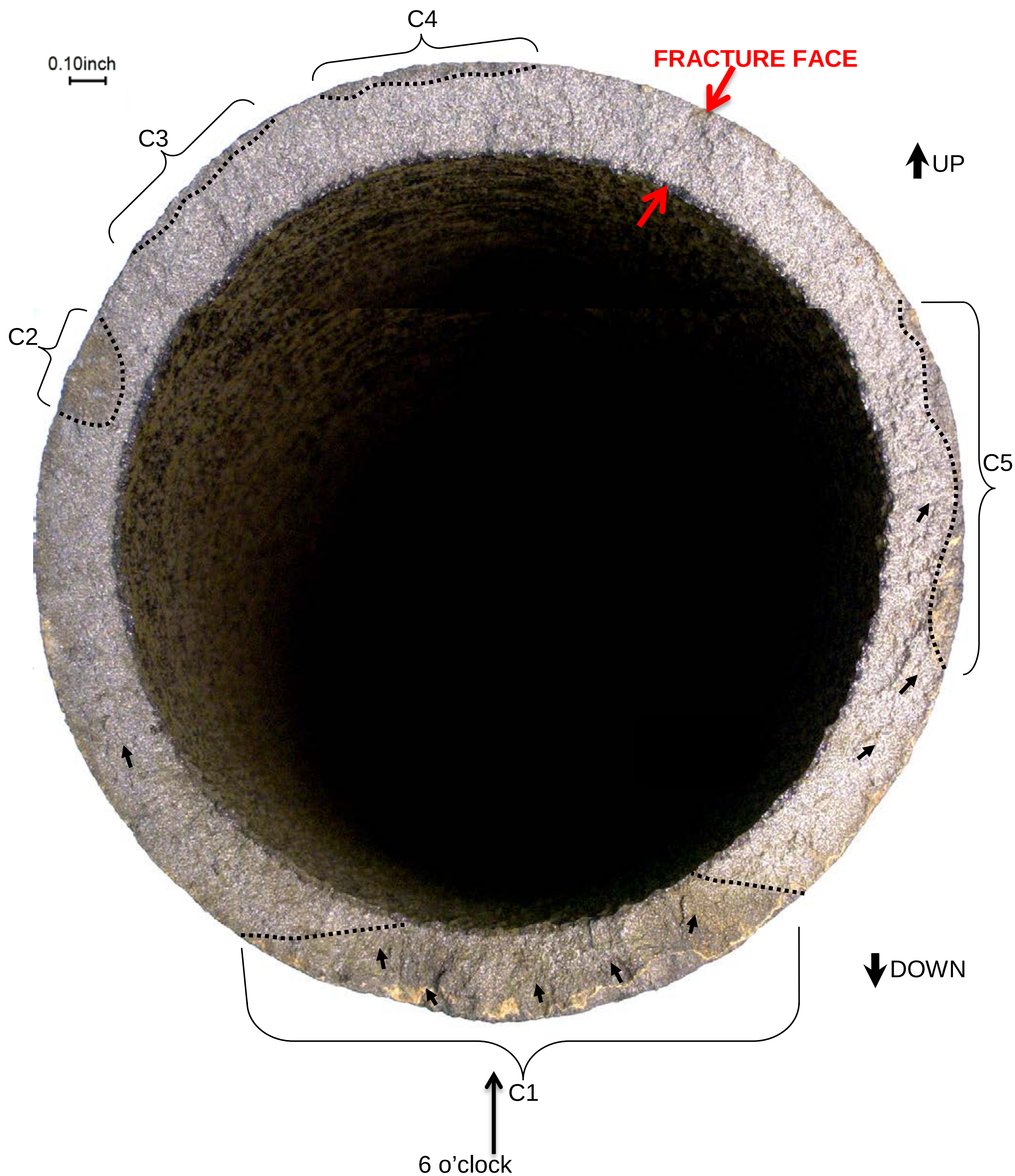


Figure 3. Composite photograph of the east face portion of the fracture from cast iron main pipe segment "A" in the as-received condition (prior to cleaning) showing five areas that contained dark regions. General direction of fracture propagation is indicated by unmarked arrows.

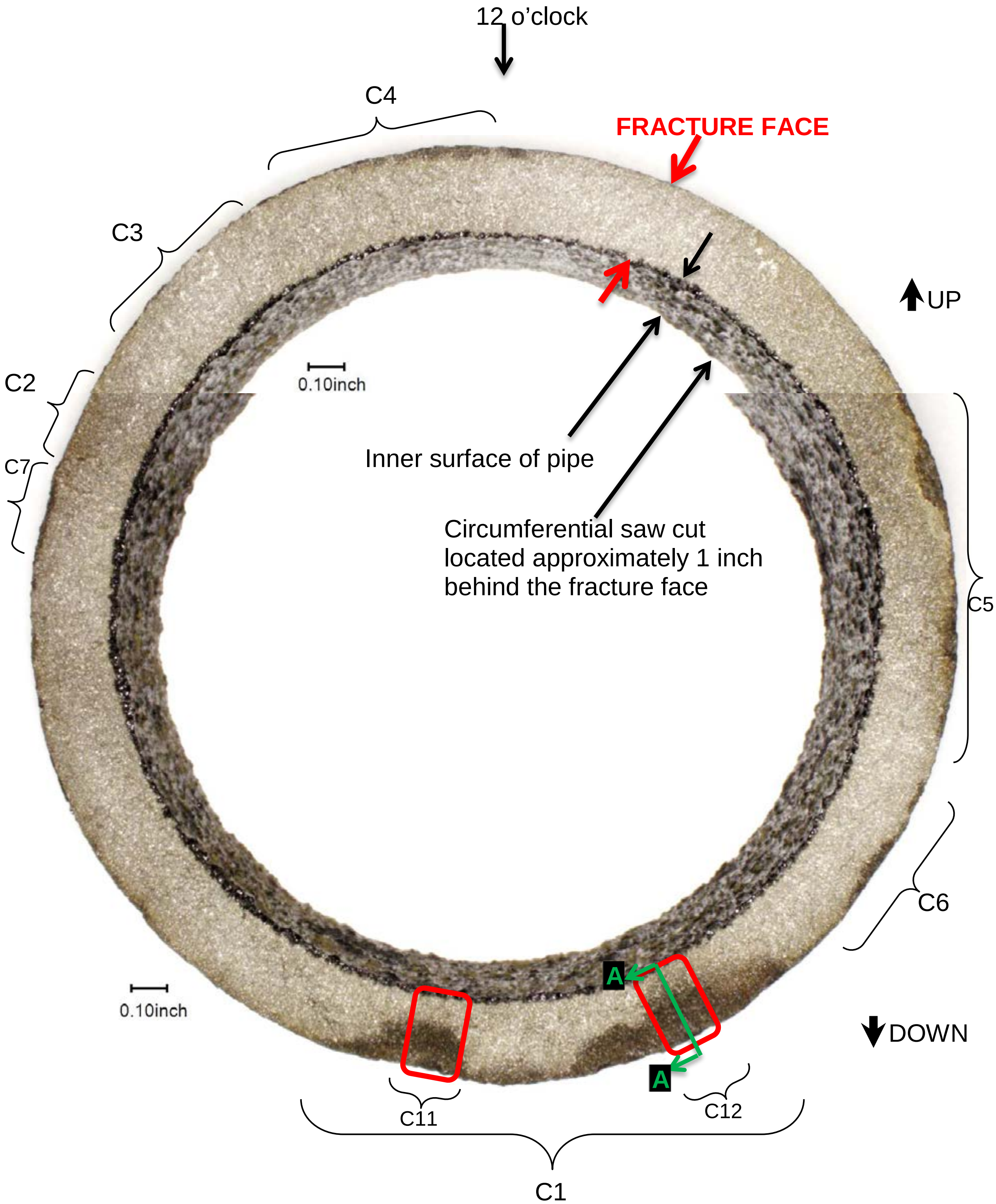
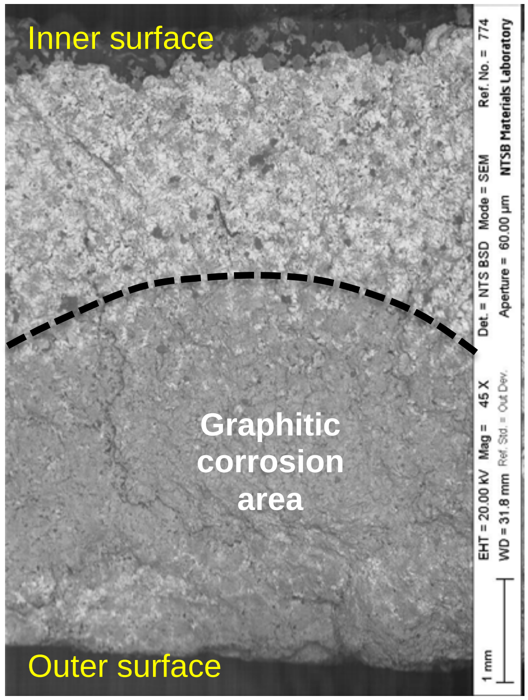


Figure 4. Composite photograph of the east face portion of the fracture from cast iron main pipe segment "A" looking down the length of the pipe segment after ultrasonic cleaning. Black areas on the fracture face and adjacent to the outer surface, in areas indicated by brackets "C1" through "C7", are consistent with graphitic corrosion in gray cast iron.



In this SEM electron backscatter image the graphitic corrosion area appears as dull gray.

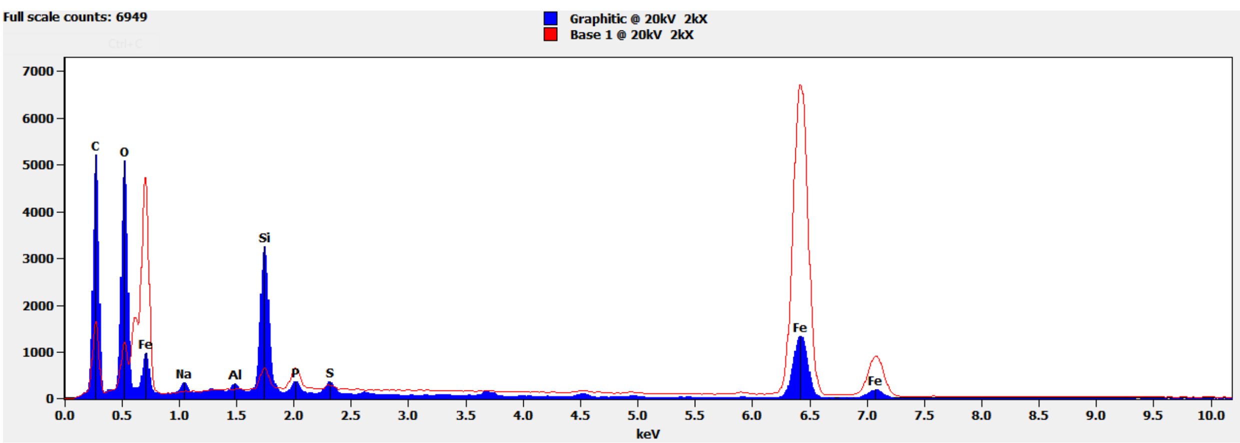


Figure 5. Scanning electron microscope (SEM) photograph in electron backscatter mode of a portion of the east face of the fracture from pipe segment “A” in the area located within box labeled “C11” in figure 4 showing graphitic corrosion that extended through approximately 60% of the wall (see top image). The dashed line indicates the border of the graphitic corrosion region. The bottom side of the page shows energy dispersive spectroscopy spectra of an area located outside of the graphitic corrosion region (red line) compared to an area located within the graphitic corrosion region (solid blue peaks).

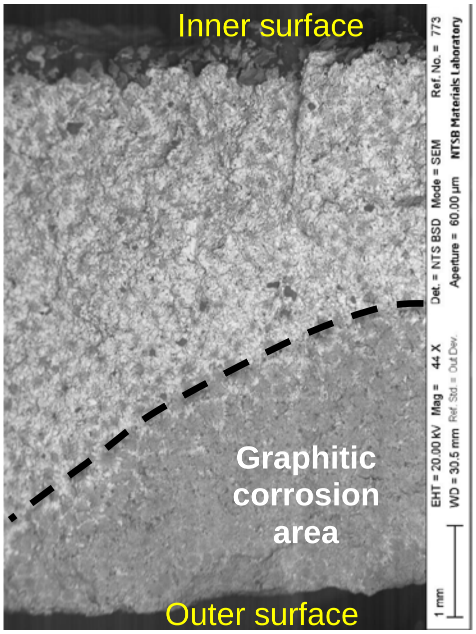


Figure 6. SEM electron backscatter image of a portion of the east face of the fracture of pipe segment "A" located within the box labeled "C12" in figure 4 showing graphitic corrosion that extended through approximately 50% of the wall.

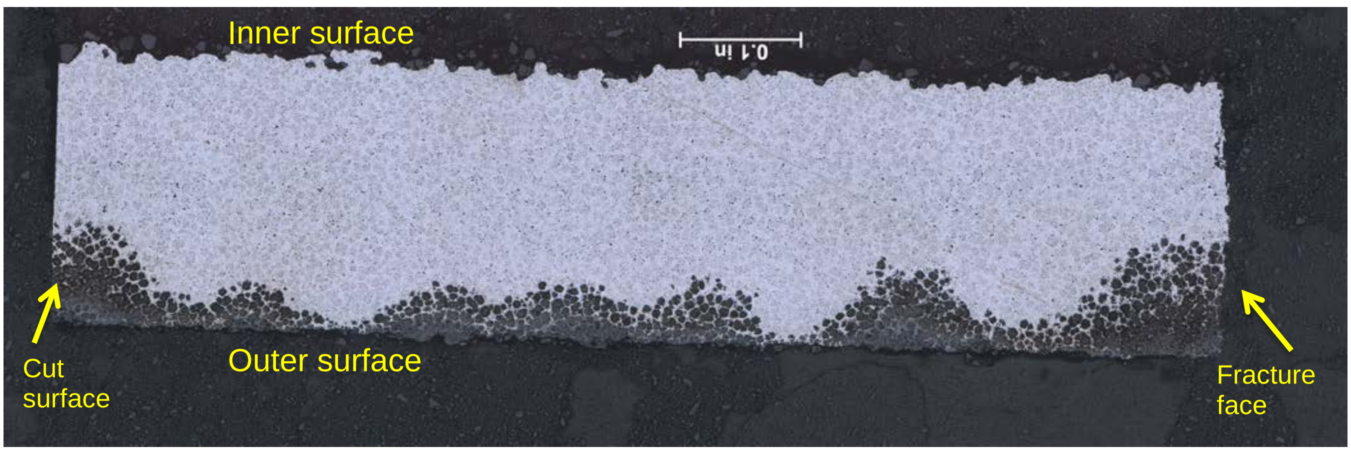


Figure 7. Longitudinal-radial metallurgical section that was through the fracture face of pipe segment "A" in the orientation indicated by section "A-A" in figure 4 showing graphitic corrosion (black areas) on the outer face of the pipe. Polished section.

Figure 8. Lower image shows a portion of pipe segment “D” prior to pressure testing with wall fragment indicated by arrow “DD” intact and attached to the pipe. Top left image shows fragment “DD” that fractured from the pipe during pressure testing at the NTSB Materials Laboratory (inner surface of the fragment is shown). Top right image shows an approximately 0.3-inch diameter hole in the wall after fragment “DD” fractured from the pipe.

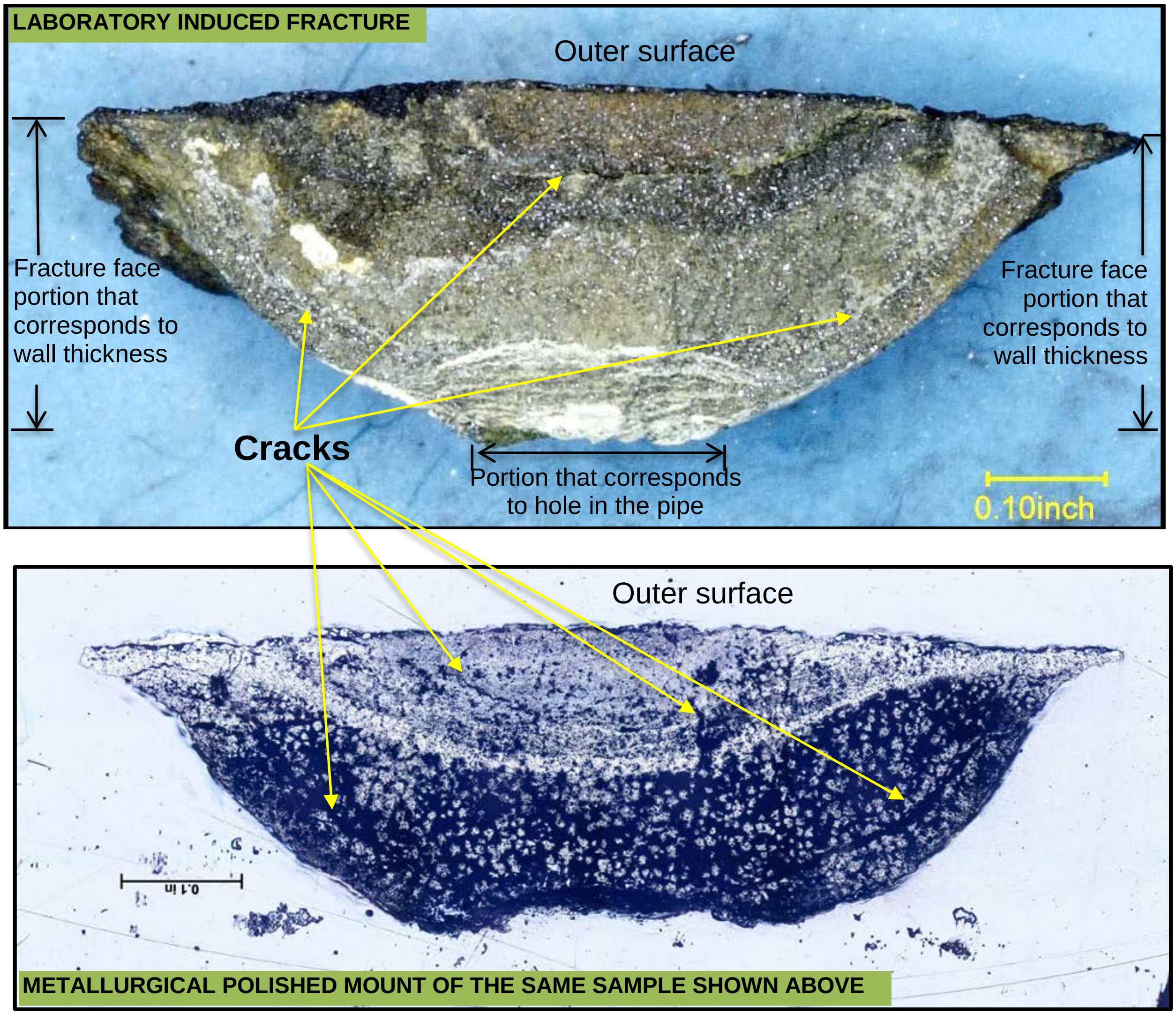


Figure 9. The Safety Board Materials Laboratory intentionally broke fragment “DD” shown in figure 8 in half to expose internal features. The upper photograph shows the laboratory induced fracture face (that was in the longitudinal-radial orientation) that contained internal cracks and discolored regions. The lower photograph shows the same sample after the fracture face was ground down with grit paper, encased in metallurgical mount, and polished to further reveal the internal structure of the fragment. The polished metallurgical mount (bottom of page) exhibits severe porosity and graphitic corrosion in all areas of the fragment.

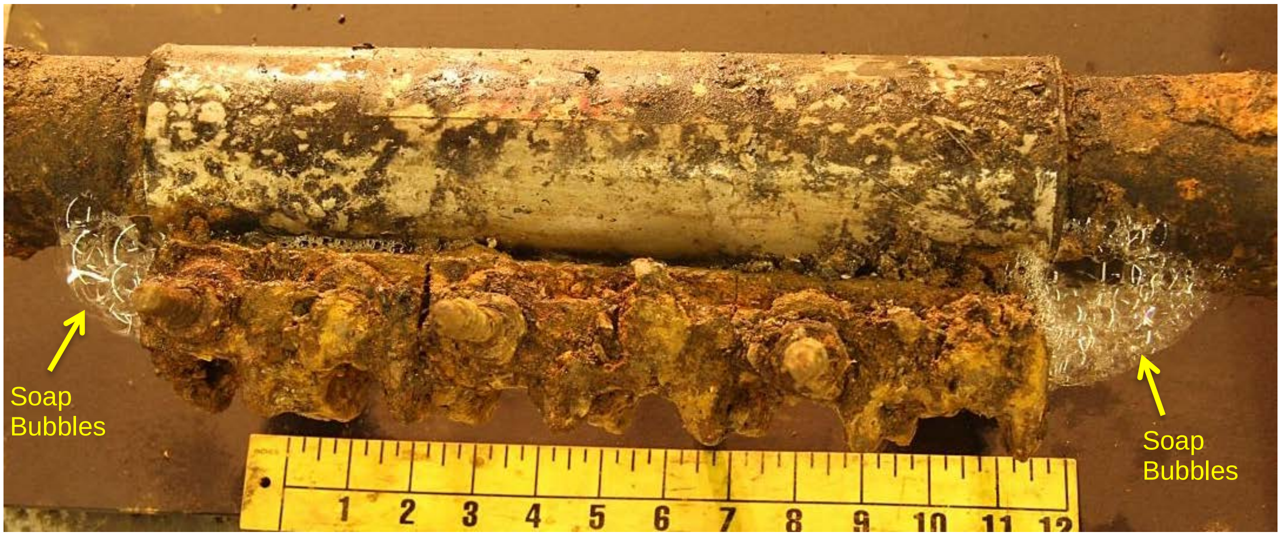


Figure 10. Photograph showing pipe segment “E” in area of the sleeve “S2” during pressure testing showing soap bubbles emitting from the ends of the sleeve. The soap bubbles show evidence of a leak.

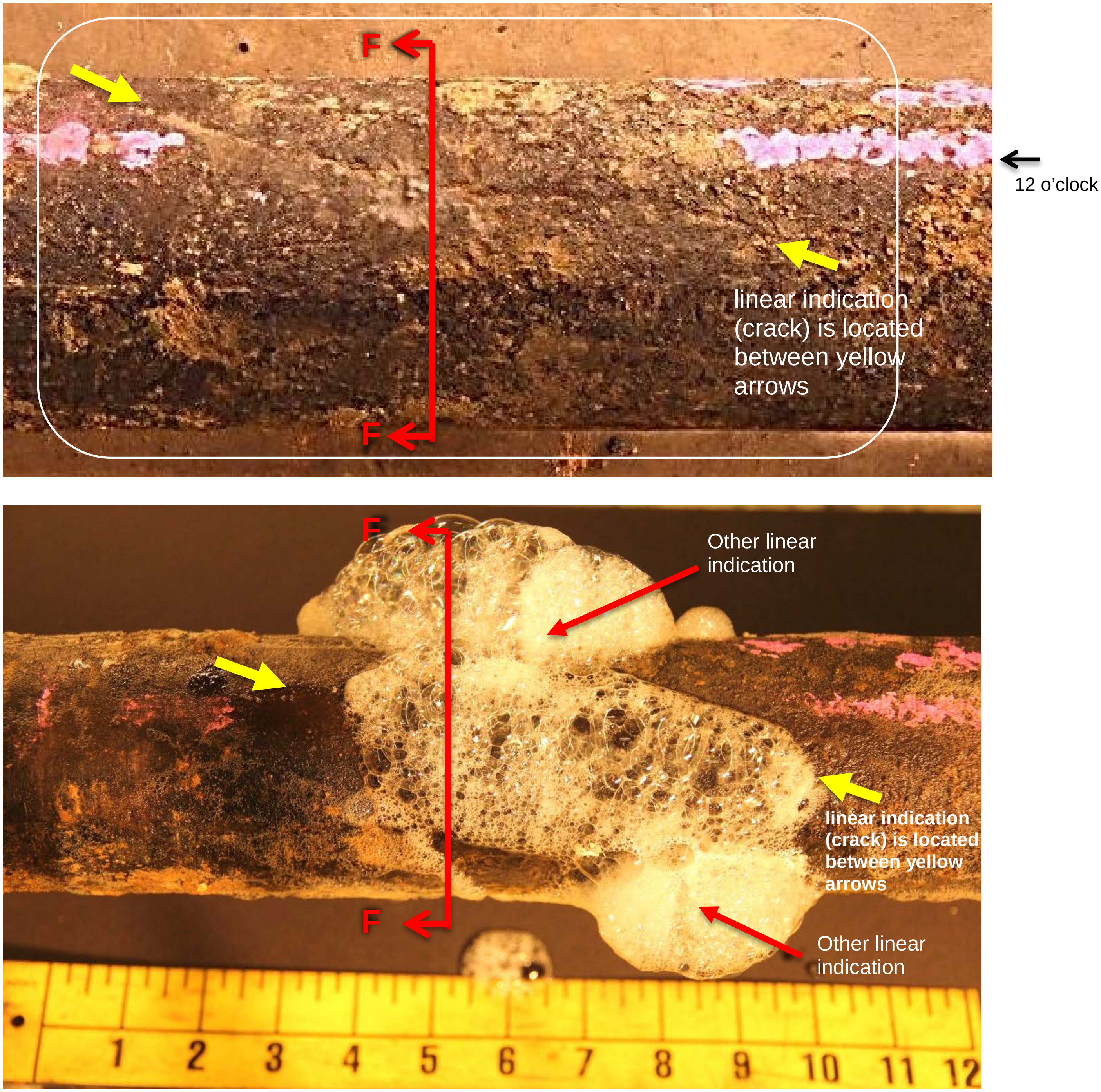


Figure 11. The upper photograph shows the top surface of a portion of pipe segment "F" in the area enclosed by the left white box in figure 1 before pressure testing and evidence of a linear indication (crack). The lower photograph shows the same area during pressure leak testing with soap bubbles emanating from the linear indication (crack) and another two linear indications.

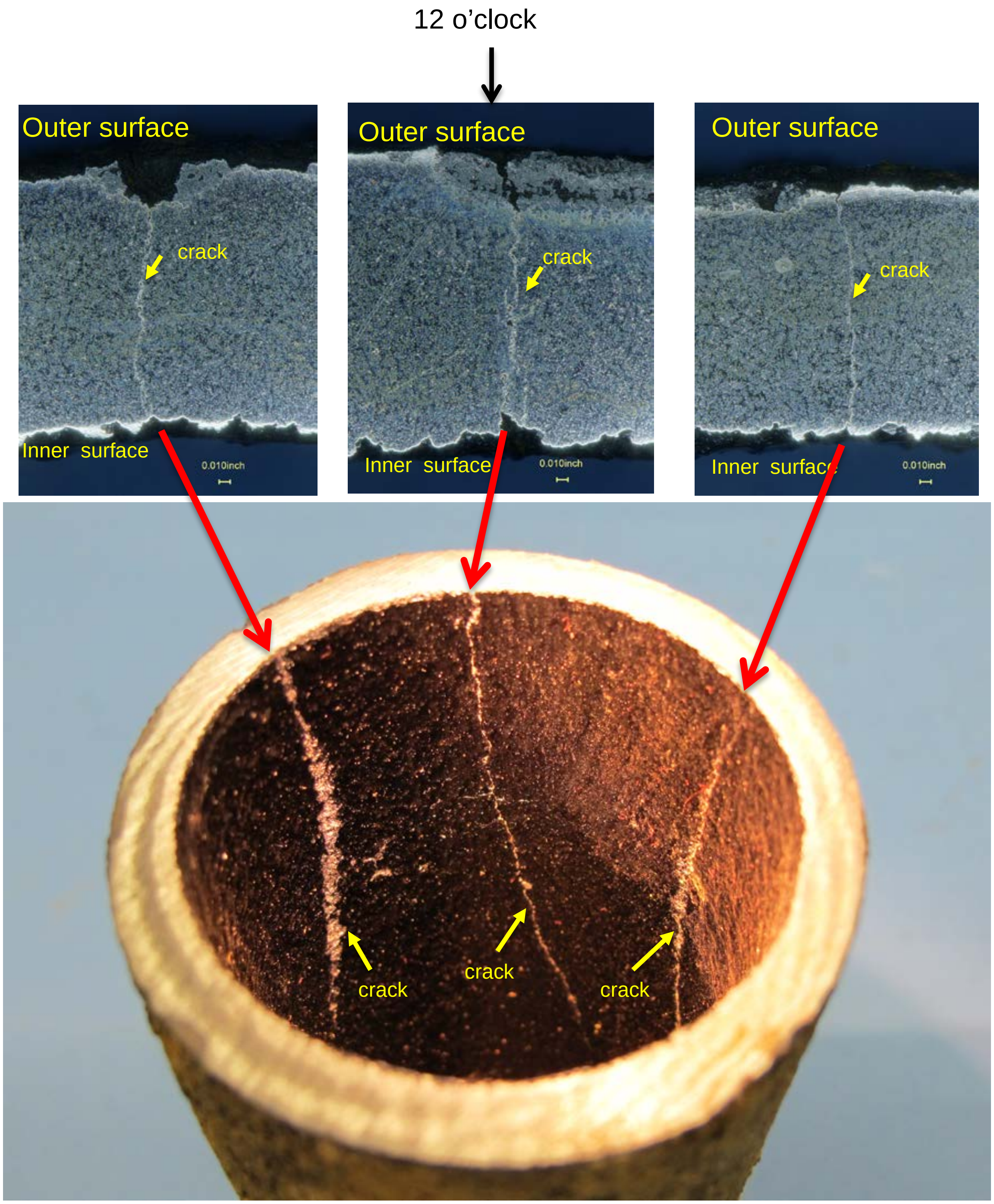
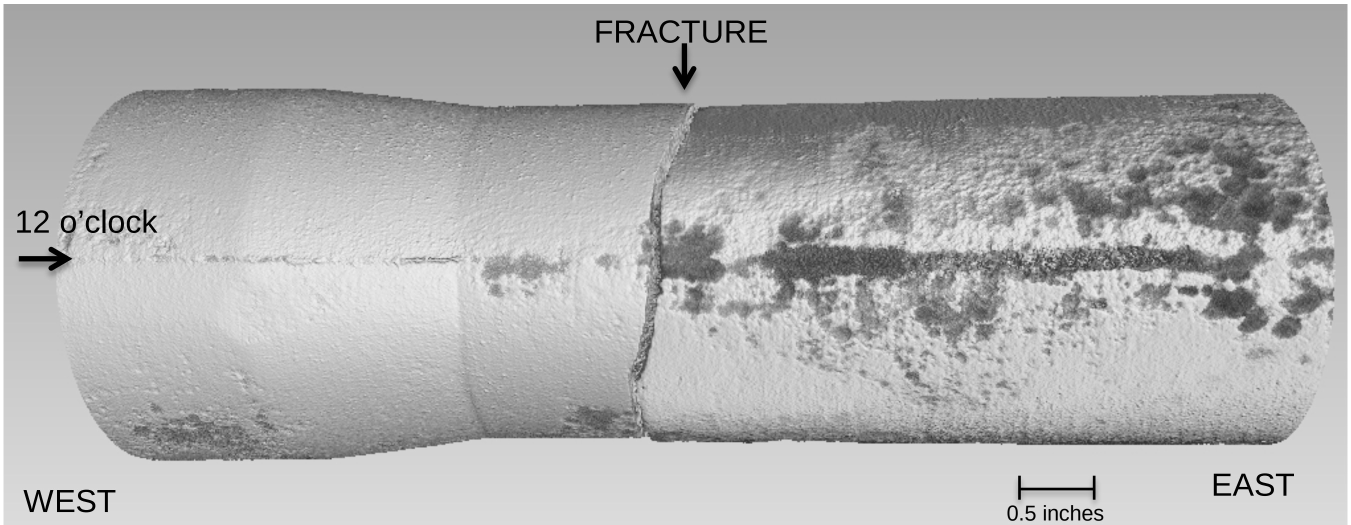
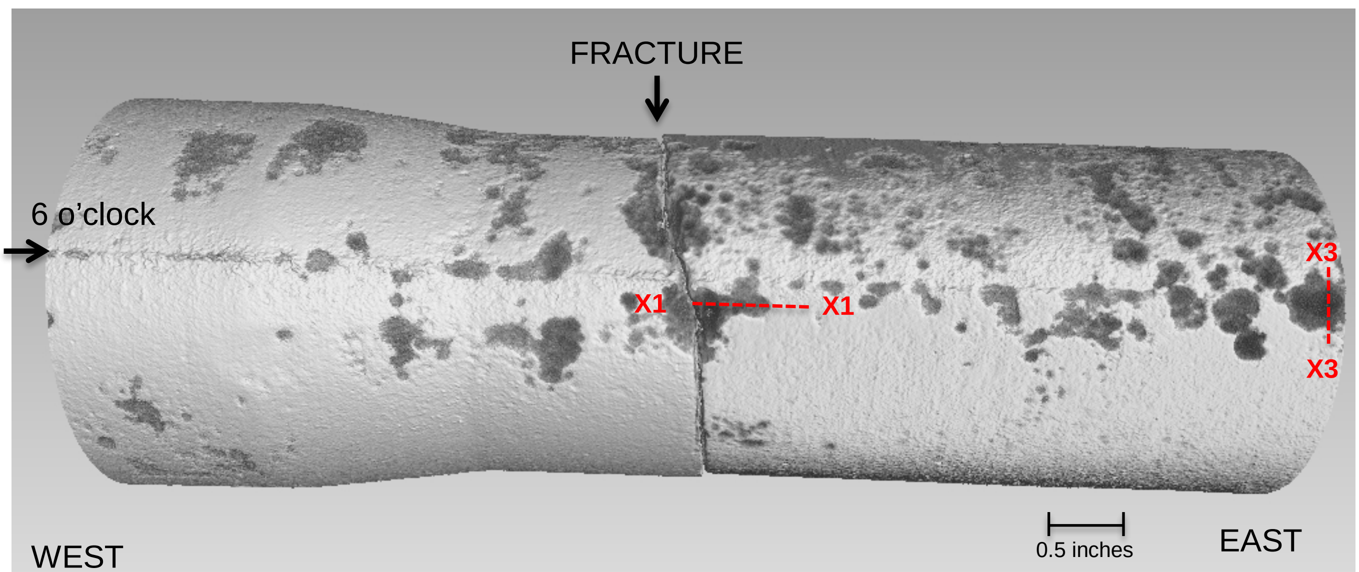


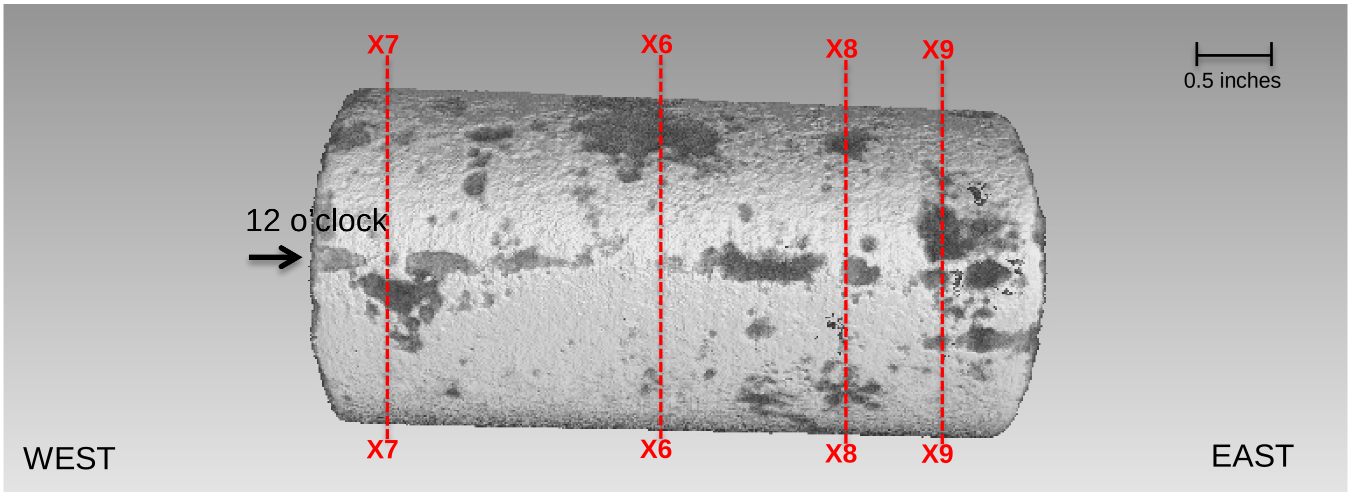
Figure 12. The lower photograph of section "F-F" that was made through pipe segment "F", looking west, showing three cracks on the inner surface of the pipe. The cut surface is shown prior to polishing the wall. The upper photographs on the top side of the page show the individual cracks after the saw cut surface was polished to expose cracks that penetrated the wall.

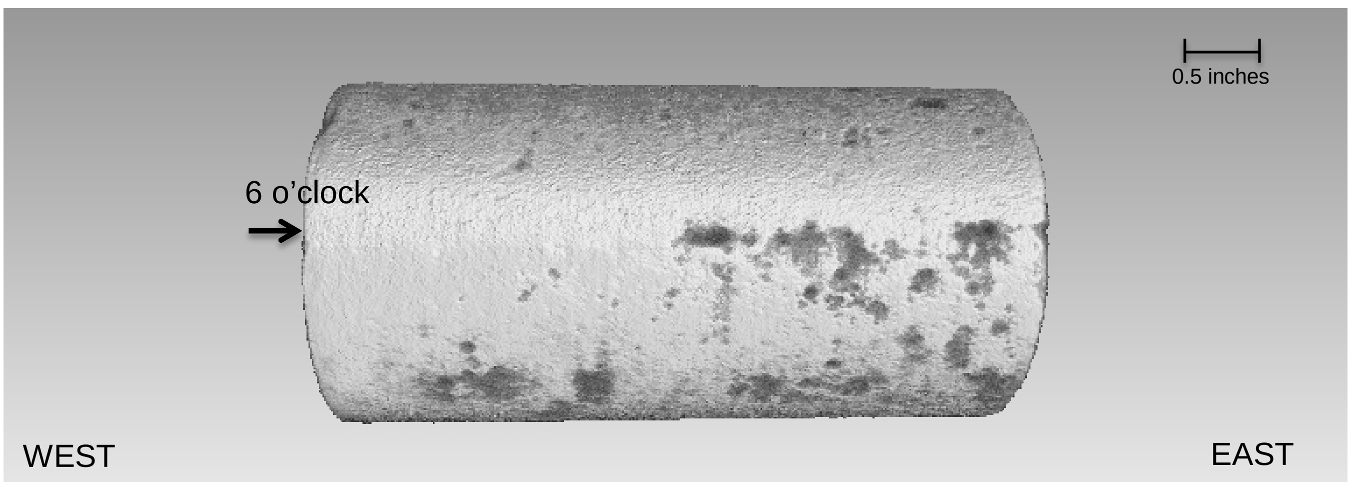
APPENDIX A
Series of X-Ray CT Images from Pipe Segment “A”



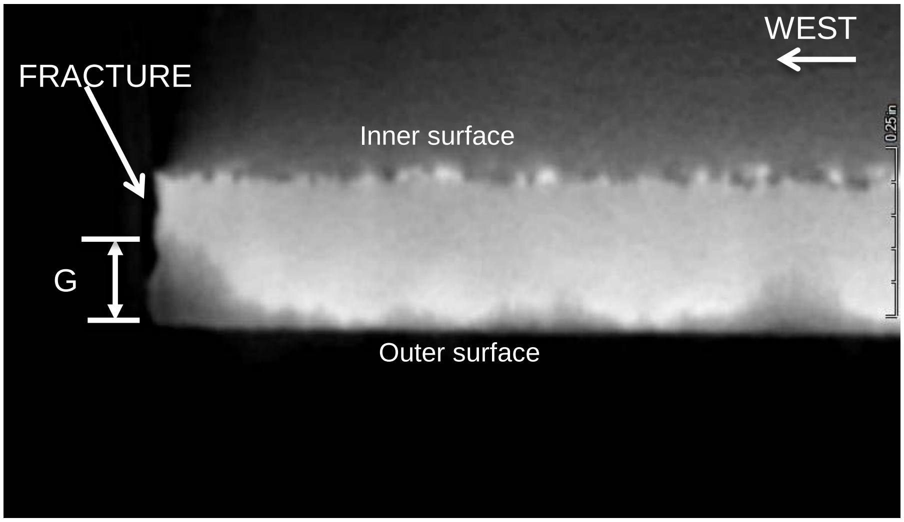


APPENDIX A1: X-ray CT reconstructed images of pipe segment "A" in the area of fracture showing the top side (upper image) and bottom side (lower image). Dark isolated areas are graphitic corrosion areas. These images were reconstructed so that the mating fracture faces are facing each other.

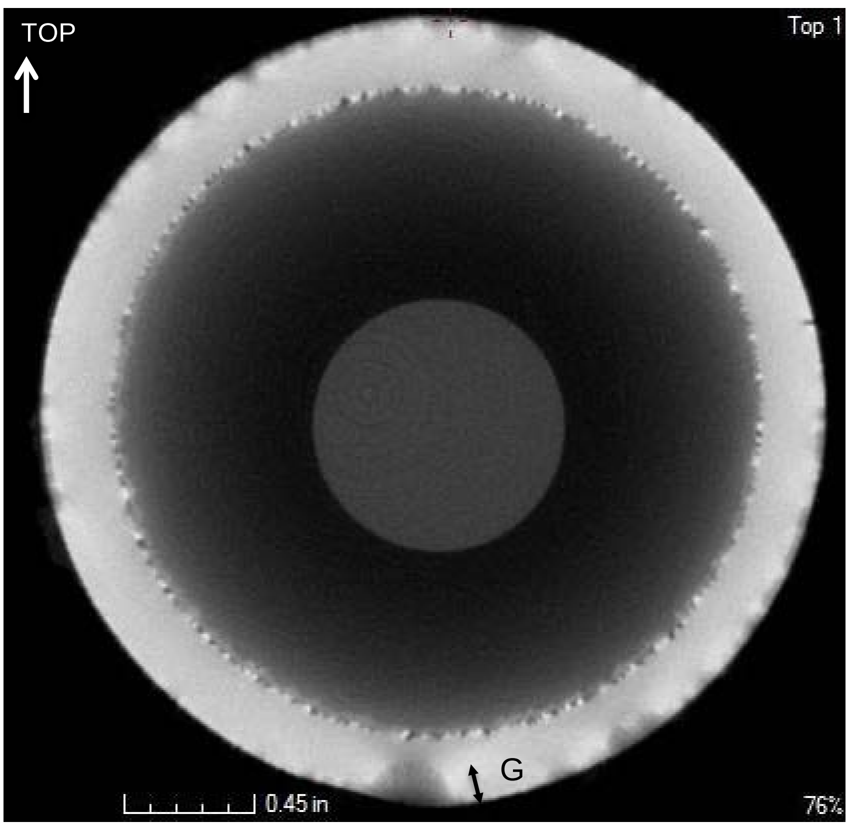




APPENDIX A2. X-ray CT images from pipe segment "A" in the area located between 1 foot and 1.5 feet west of the fracture showing the top side (upper image) and bottom side (lower image).

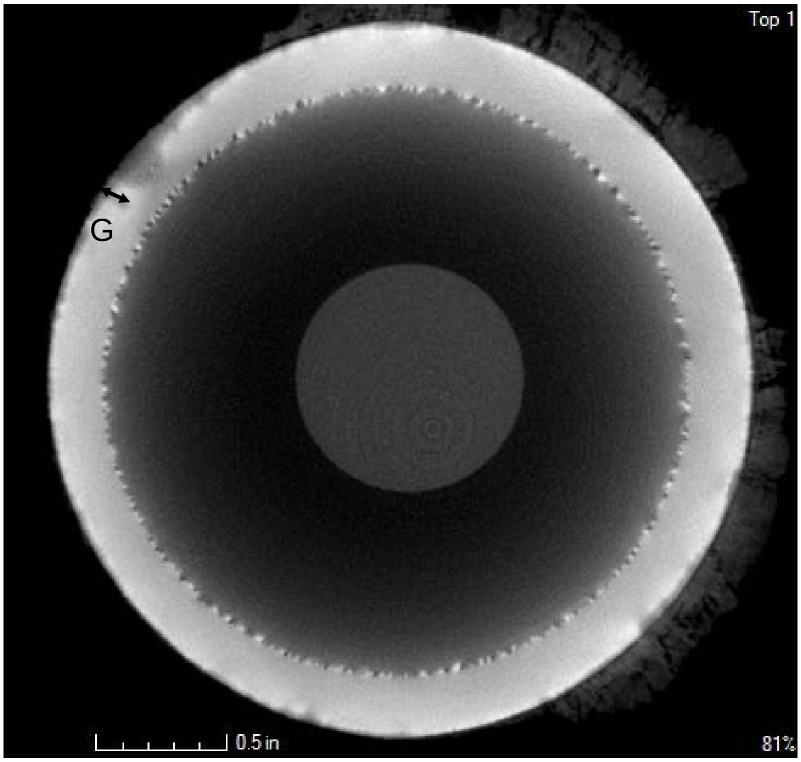


Appendix A3. X-ray CT scan of the bottom wall portion of pipe segment A showing a longitudinal-radial cross section in the area indicated by dashed line "X1-X1" in Appendix A1. Dark areas on the outer surface are graphitic corrosion. "G" indicates deepest extent of graphitic corrosion on the fracture face.

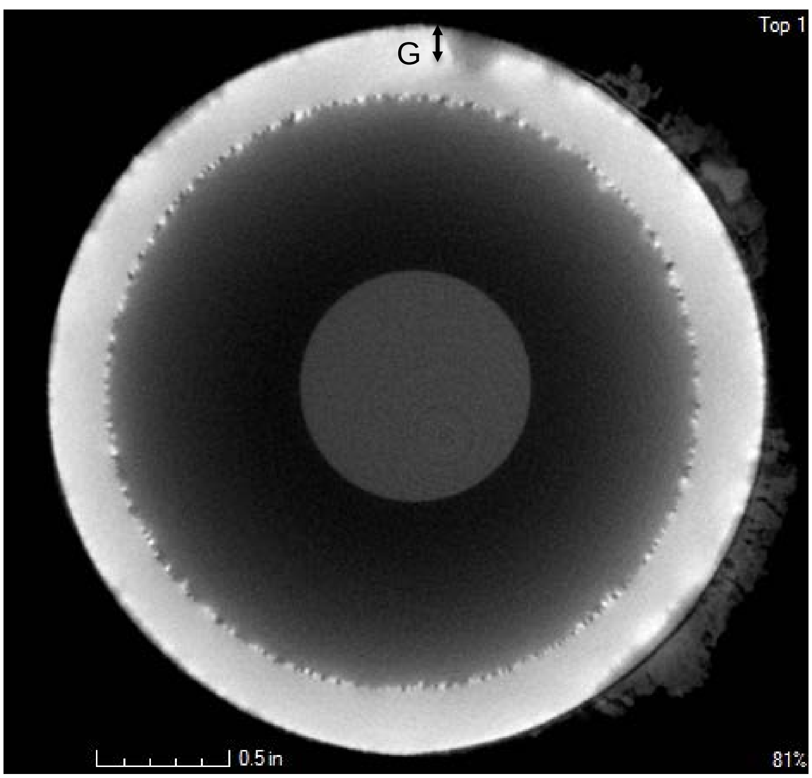


The light gray circle and similar irregular shapes at the center of the pipe on the inside diameter in Appendices A4 through A8 in this report are structural foam columns that were used to hold the pipe segment in place during X-ray CT inspection.

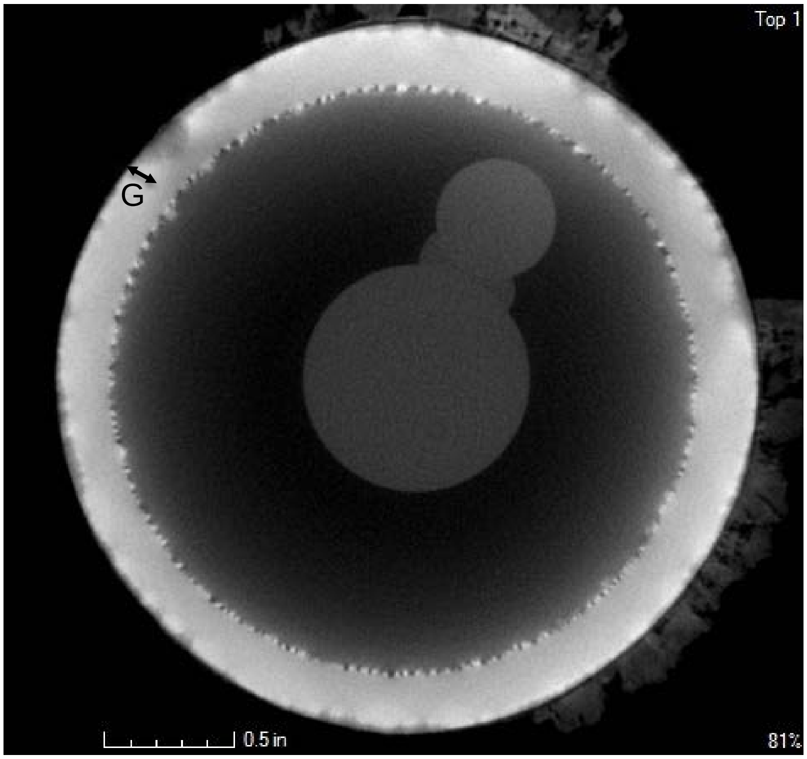
Appendix A4. X-ray CT scan of pipe segment A showing circumferential-radial cross section in the area indicated by dashed line "X3-X3" in Appendix A1, looking east. "G" indicates deepest extent of graphitic corrosion.



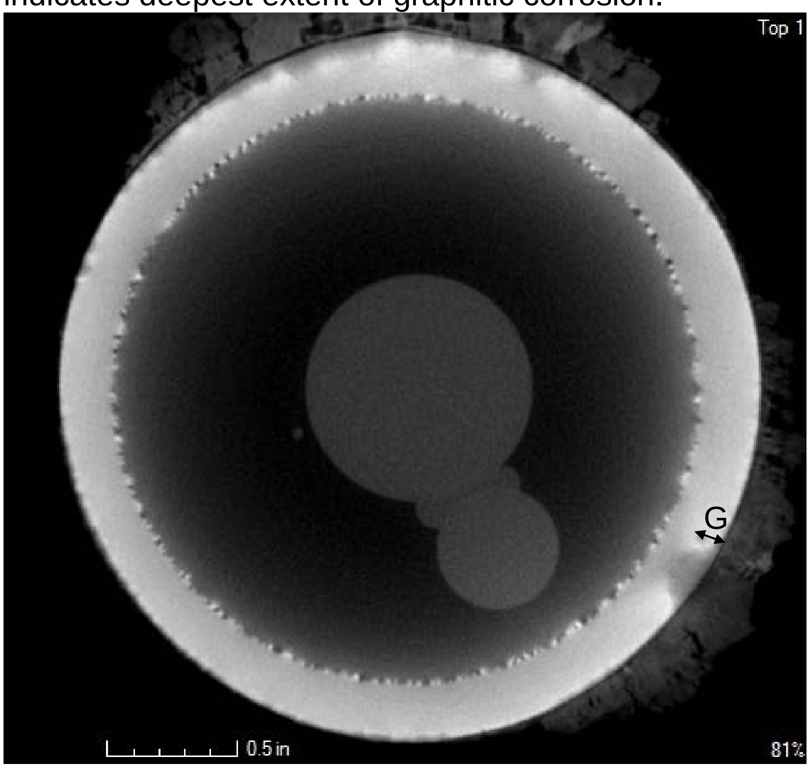
Appendix A5. X-ray CT scan of pipe segment A showing a circumferential-radial cross section in the area indicated by dashed line "X6-X6" in Appendix A2, looking east. "G" indicates deepest extent of graphitic corrosion.



Appendix A6. X-ray CT scan of pipe segment A showing a circumferential-radial cross section in the area indicated by dashed line "X7-X7" in Appendix A2, looking east. "G" indicates deepest extent of graphitic corrosion.



Appendix A7. X-ray CT scan of pipe segment A showing a circumferential-radial cross section in the area indicated by dashed line “X8-X8” in Appendix A2, looking east. “G” indicates deepest extent of graphitic corrosion.



Appendix A8. X-ray CT scan of pipe segment A showing a circumferential-radial cross section in the area indicated by dashed line “X9-X9” in Appendix A2, looking east. “G” indicates deepest extent of graphitic corrosion.

APPENDIX B

Formula and Calculations for Converting Flow Rate (Air to Natural Gas)
Three Step Process

STEP 1:

Convert the air flow to standard conditions and then calculate the equivalent gas flow. [6]

To correct to standard flow rate, Q_s, correct the flowing temperature T_a and pressure P_a to standard T - P conditions using the combined gas laws:

$$P_sQ_s/T_sZ_s = P_aQ_a/T_aZ_a$$

where the subscript **a** refers to actual conditions and the subscript **s** refers to standard conditions, Z is the compressibility.

Solving for Q_S and noting that Z_S=1 for P_s << 100 psia

$$Q_s = T_s\ P_aQ_a/T_aZ_a\ P_s$$

Use the simple valve equation to calculate the gas and air standard flow rates.

$$Q_{s\text{-}gas} = C_v \sqrt{[\ (P_a\Delta P)/\ (T_aG_{gas}\ Z_{gas})]}$$

$$Q_{s\text{-}air} = C_v \sqrt{[\ (P_a\Delta P)/\ (T_aG_{air}\ Z_{air})]}$$

C_v, P_a, ΔP, and T_a cancel out when you take the ratio $Q_{s\text{-}gas}$ / $Q_{s\text{-}air}$. Also note that the flow is assumed to be turbulent so that viscosity does not come into play.

$$Q_{s\text{-}gas} / Q_{s\text{-}air} = \sqrt{[1/(G_{gas}\ Z_{gas})]} / \sqrt{[1/(G_{air}\ Z_{air})]}$$

$$Q_{s\text{-}gas} / Q_{s\text{-}air} = \sqrt{[(G_{air}\ Z_{air})/(G_{gas}\ Z_{gas})]}$$

G_{air}=1 by definition. If P_a << 100 psia then Z_{air} and Z_{gas} can be taken as 1.0 and

$$Q_{s\text{-}gas} = Q_{s\text{-}air} \sqrt{[1/G_{gas}]}$$

[6] Derivation from www.eng-tips.com,

Nomenclature:
Q_s = Volumetric flow rate at standard conditions.
P_s = Standard pressure.
T_s = Standard temperature.
Z_s = Compressibility at standard conditions.
Q_a = Volumetric flow rate at actual conditions.
P_a = Actual pressure.
T_a = Actual temperature.
Z_a = Compressibility at actual conditions.
Z_{air} = Compressibility of air at actual conditions.
Z_{gas} = Compressibility of gas at actual conditions.
$Q_{s\text{-}gas}$ = Volumetric flow rate of gas at standard conditions.
$Q_{s\text{-}air}$ = Volumetric flow rate of air at standard conditions.
$Q_{a\text{-}gas}$ = Volumetric flow rate of gas at actual conditions.
$Q_{a\text{-}air}$ = Volumetric flow rate of air at actual conditions.
C_v = Valve constant
ΔP = Pressure drop across the component.
G_{gas} = Specific gravity of gas (density gas/density air).
G_{air} = Specific gravity of air (density air/density air = 1.0).

STEP 2:

Specific Gravity (Relative Density) of Natural Gas[7]

The following procedure can be used to calculate the specific gravity of a gas relative to that of air (1.00 at standard temperature and pressure). The example used is for natural gas (ng) of a fixed composition with no distillates.

Molecular weight of air

To find the molecular weight of air, make the following assumptions and calculations:

79% nitrogen (molecular weight = 28) in air: 0.79 x 28 = 22.1

21% oxygen (molecular weight = 32) in air: 0.21 x 32 = 6.7

Therefore, the molecular weight of air, MW a , is 22.1 + 6.7 = 28.8 *****

Molecular weight of natural gas

To find the molecular weight of natural gas (ng), make the following assumptions and calculations:

90% methane (molecular weight = 16) in natural gas: 0.90 x 16 = 14.4

5% ethane (molecular weight = 30) in natural gas: 0.05 x 30 = 1.5

5% nitrogen (molecular weight = 28) in natural gas: 0.05 x 28 = 1.4
Therefore, the molecular weight of natural gas, MW ng , is 14.4 + 1.5 + 1.4 = 17.3

Specific gravity of natural gas

The specific gravity of natural gas compared with that of air is thus MW ng /MW a = 17.3/28.8 = 0.60 ******

*Note: Ideal molecular weight of air = 28.9644

** Note: Published values of the specific gravity of natural gas range from about 0.554 to about 0.87. Variation in natural gas composition by location accounts for the different values.

[7] Reference from www.inelindia.com, a website by Inel Gas Controls Private Limited.

STEP 3:

$$\mathbf{Q_{s\text{-}gas} = Q_{s\text{-}air}\ \sqrt{[1/G_{gas}]}}$$ -------- recall formula from STEP 1

$Q_{s\text{-}gas}$ = Volumetric flow rate of gas at standard conditions
$Q_{s\text{-}air}$ = Volumetric flow rate of air at standard conditions
G_{gas} = Specific gravity of gas (density gas/density air)

For natural gas, assume specific gravity of $\mathbf{G_{gas}}$ = 0.7

$$Q_{s\text{-}gas} = Q_{s\text{-}air}\ \sqrt{[1/0.7]}$$

$$Q_{s\text{-}gas} = Q_{s\text{-}air}\ \sqrt{[1.428]}$$

$$Q_{s\text{-}gas} = Q_{s\text{-}air}\ (1.195)$$

In this report, the measured air flow $\mathbf{Q_{s\text{-}air}}$ (as read on the air flow meter) was inserted into the equation to solve for $\mathbf{Q_{s\text{-}gas}}$. This formula was used in Table 5 to convert the volumetric leak rate in air to a volumetric leak rate at standard conditions as if the pipe segment was tested with natural gas.