Docket No. SA-534

Exhibit No. 3-A

NATIONAL TRANSPORTATION SAFETY BOARD

Washington, D.C.

Metallurgical Group Chairman
Factual Report

(77 Pages)

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

January 21, 2011

MATERIALS LABORATORY FACTUAL REPORT Report No. 10-119

A. ACCIDENT

Place : San Bruno, CA
Date : September 9, 2010
Vehicle : Natural Gas Transmission Pipeline
NTSB No. : DCA10MP008
Investigator : Ravi Chhatre, RPH-20

B. COMPONENTS EXAMINED

Three pieces of 30 inch diameter pipe.

C. DETAILS OF THE EXAMINATION

From September 30, 2010 through October 8, 2010, a Metallurgical Group was convened at a facility in Ashburn, VA for the purpose of documenting and examining the ruptured pipeline pieces and determining which portions of the pipe should be removed for further examination at the Materials Laboratory in Washington, DC. Members of the group included:

1) Donald Kramer, Ph.D., Materials Engineer, NTSB
2) Ravindra Chhatre, Investigator in Charge, NTSB
3) Robert Fassett, Director – Integrity Management & Technical Services, PG&E
4) Joshua Johnson, P.E., Materials Engineer, PHMSA Office of Pipeline Safety
5) Sunil Shori, Utilities Engineer, State of California Public Utilities Commission
6) Paul Tibbals, P.E., Sr. Materials Technology Engineer, PG&E

C.1. DOCUMENTATION OF AS-RECEIVED CONDITION

The as-received pipe was comprised of eight lengths of pipe in three separate sections as illustrated by the schematic in figure 1 and the photographs in figures 2-5. The pipeline had a north alignment at this location and the flow of gas was to the north under typical conditions. The southern section of pipe measured 12 foot – 4 inch at its longest point and was comprised of a single piece of long pipe (commonly referred to as a joint[i]) as shown in figure 2. The center section was 27 foot – 8 inch at its longest point and was

[i] A joint is a single length of pipe, typically 20 feet or greater in length.

comprised of the same long joint continuing from the southern section as well as four shorter lengths of pipe (pups) as shown in figures 3 and 4. The northern section of pipe measured 15 foot – 9 inch and was comprised of two pups and a long joint as shown in figure 5. For convenience the pups were numbered 1 through 6 in the south to north direction. The circumferential welds (i.e. girth welds) that joined the pups were numbered sequentially from south to north as C1, C2, and so on through C7.

The center section had circumferential fractures at both ends. One fracture was through the long joint to the south of pup 1 as shown in figure 4. The other fracture was at the girth weld between pup 4 and pup 5 (girth weld C5 in figure 1) as shown in figures 3 and 6. There was a longitudinal fracture in pup 1 that continued in the long joint south of pup 1 to the circumferential fracture at the south end of the center section, visible in figure 3. There were circumferential fractures in girth weld C2 between pup 1 and pup 2 on both sides of the pup 1 longitudinal fracture as shown in figures 7a and b. In the counterclockwise direction, the circumferential fracture measured 27 inch (Note: Clockwise and counterclockwise directions are assigned as a rotation about the longitudinal axis of the pipeline looking north). At the end of the fracture there was a 10 inch diameter circular depression in the pipe. In the clockwise direction, the circumferential fracture measured 6.25 inch, at which point it intersected with a longitudinal fracture in pup 2 as shown in figure 7b. The longitudinal fracture in pup 2 extended 29.25 inch from girth weld C2 at which point it branched in two, visible in figure 7a and 7c. One branch continued in the longitudinal direction to within 3 inch of girth weld C3 (Note: This was only visible after removal of the coating as shown in figure 7c). The other branch was angled 66° to the longitudinal direction and measured 18 inch. The circumferential fracture at the north end of the center section deviated from girth weld C5 along a 3.5 inch circumferential length up to 1 inch longitudinally in pup 4 at the location shown in figure 6.

The southern section had a helical fracture at its north end as shown in figure 2c. Out of plane bending was observed along a 5 inch length along the top of the pipe, consistent with the point of final fracture. The bending deformation started at the longitudinal seam as shown in figures 2b and 8 and continued north and clockwise from this point. The fracture ran along the west side of the seam for approximately 1.5 inch, transitioned across the seam and continued on the east side of the seam. A circumferential crack was observed from the inside of the pipe where the main fracture intersected the seam. The crack propagated through the seam and continued for approximately 1.25 inch along the east side of the seam.

There was a 10° deformation bend in the pipe in the vicinity of pup 2 that caused the section to lie partly on its western side as shown in figure 4. The pipe showed continuously varying ovalization from pup 2 through pup 4, visible in figure 6. The minor radius, measured from inner wall to inner wall varied from 16.0 inch at the south end of pup 2 to 26.2 inch at the north end of pup 4. By comparison, the inner radius of an undeformed nominal 30 inch diameter 0.375 inch wall pipe is 29.2 inch. The southern and northern sections each had a fractured end that mated with one of the fractures on the center section. The true top of the center section was located by mating fracture features and longitudinal seams on the center section with features on the northern and southern sections that had their true tops labeled prior to removal from the pipeline.

The long joint south of pup 1, pup 6, and the long joint north of pup 6 all had longitudinal seams with visible weld beads on the outside of the pipe as shown in figures 2a and 5c. There were no visible weld beads on the outside of pups 1 – 5. A gap was observed along the longitudinal direction on the inside wall of pup 3 at the circumferential position indicated in figure 6 and shown in greater detail in figure 9. The gap ran along the entire length of the pup. Longitudinal weld beads were observed on the inside of pup 4 and pup 5. The weld bead on the inside of pup 4 is labeled in figure 6. An example of the weld bead on the inside of pup 5 is shown on a cut section of pipe in figure 10a. The weld was 0.312 inch wide and had a rippled surface consistent with a manual fusion welding process. Each weld spanned the entire length of the pup. A longitudinal weld was observed on the inside of pup 6 as shown on a cut section of pipe in figure 10b. The weld bead was 0.625 inch wide and had a smooth appearance consistent with an automated submerged arc welding process. The circumferential distance from the top of the pipe of the seams on the long joints, the seams on pups 3 – 6, and the longitudinal fractures (along seam welds as shown below) along pup 1 and pup 2 from the top of the pipe are listed in Table 1.

The appearance of the pipe coating was consistent with hot applied asphalt, parts of which had been exposed to elevated temperatures. Examples of the coating condition on the southern sections are shown in figures 2 and 11. No coating was observed on the bottom half of the pipe starting 3 foot – 4 inch from the cut end and continuing to the fractured end. The visible pipe surface was an orange color. The coating on the top half of the pipe close to the fracture exhibited features consistent with drips, sags, and charring as shown in figure 11a. The coating flow patterns were complex with longitudinal and circumferential flow occurring in different regions. Close to the cut end, the coating features were more consistent with as-applied asphalt as shown in figure 11b. No coating was observed on much of the sides and bottom of the northern section as shown in figure 5c. Much of the visible pipe surface was an orange color. Along the top close to the fracture (pup 5) the surface was black and had a slight gloss as shown in figure 12a. Moving away from the fracture, drip marks were observed along the top of pup 6 (not shown). Toward the cut end, the sides and bottom showed little to no indications of heat exposure as shown in figure 12b. The coating on the top and sides of the center section (in its resting position and not as installed) had either a charred or glossy appearance in various locations as shown in figure 13. In some locations, the coating appeared to be comingled with soil. On the underside of the pipe (in its resting position) between pup 1 and pup 2 there was a partially attached piece of coating approximately 32 inch in length, the start of which is indicated by an arrow in figure 13a. There was also an approximately 18 inch wide strip of coating attached to the underside running from pup 1 and continuing south to within 6 foot of the southern fracture, the start of which is also indicated in figure 13a. There were also regions on the underside where no coating was observed and the pipe surface was visible. One region on pup 4 near the girth weld fracture is shown in figure 14a. The region was approximately 12.5 inch at its longest and 6 inch at its widest. The visible pipe surface had an orange/brown appearance. A second region from the underside of the long joint south of pup 1 is shown in figure 14b. No coating was observed over a cluster of small patches each approximately 2 inch in diameter. The visible pipe surface had an orange/brown appearance. Similar areas of no coating were observed on the undersides of pups 1, 2, and 3.

C.2. REMOVAL OF ASPHALT COATING AND VISUAL EXAMINATION

In preparation for non-destructive testing, the asphalt coating was removed from the pipe. The bulk of the coating was carefully chipped off by hand using brass hammers and flexible metal putty knives. The fracture surfaces were taped and covered by a split rubber hose and then each pipe section was grit blast using olivine blast media. The areas on either side of the girth welds were blasted to white (SSPC – SP5 / NACE No. 1) while the rest of the surface was blasted to near white (SSPC – SP10 / NACE No. 2). The southern section was grit blast over an approximately 1 foot wide by 7 foot long strip centered about the longitudinal seam as shown in figure 15. On the center section, the entire exterior of pups 1 – 4 was grit blast as was an approximately 18 inch length of the outer diameter surface on the long joint south of pup 1 as shown in figure 16. On the northern section, the entire exterior of pup 5 and pup 6 was grit blast as well as 18 inch of the long joint to the north of pup 6 as shown in figure 17.

The cleaned pipe was examined visually. There were no visible areas of general external corrosion on the grit blast surfaces nor were there any visible areas of corrosion on the inner diameter surface of the pipe. Upon close inspection, round-bottom pits ranging in depth from 0.004 inch to 0.019 inch were occasionally observed on the outer diameter surface as shown for pup 2 in figure 18. On pups 3, 4, and 5, the appearance of the outer diameter surface longitudinal seams were consistent with mechanical removal of a weld bead (pups 1 – 2 were inconclusive due to masking of the surface). Pipe markings were found on pup 4 approximately 4.5 inch from girth weld C5 and 90° clockwise of the longitudinal seam as shown in figures 19a and b. The markings included the number “30”, two instances of a backwards “P”, five lines arranged in a “zigzag”, and two stamps similar in appearance to a circle-with-a-half-moon.

The longitudinal weld beads on the long joint south of pup 1 (south joint) and the long joint north of pup 6 (north joint) were visually examined near their butt welded ends (near girth welds C1 and C7). The outer weld beads for the south and north long joints are shown in figures 20a and b, respectively. The outer weld bead on the south joint had a uniform appearance up to the girth weld. The weld bead on the north joint by contrast showed widening and variation in width approaching girth weld C7, consistent with a “squirt” weld[ii]. The inner weld beads on the south and north long joints are shown in figures 21a and b, respectively. The inner weld bead on the south joint was ground starting 1.75 inch from girth weld C1. The inner weld bead on the north joint was ground starting approximately 12 inch from girth weld C7.

[ii] Automatic welding units in use at Consolidated Western at least as late as 1949 had a tendency to produce pipe with cracked seams 5 to 8 inch from the ends. The ends were chipped out and repaired using a semi-automatic “squirt” weld unit to complete the longitudinal weld at each end[1].

A number was painted on the inside wall of the long joint south of pup 1 near girth weld C1. The paint had faded and the numbers were partly obscured by dirt, rust, and oxidation. The numbers are shown in figure 22 where the contrast of the photo has been altered. The best estimate of the number was 1299(?) – 12-(?). The number and number format was consistent with 0.375 inch wall thickness X52 pipe purchased in 1949[2,3].

A length of welding rod was found fused to the C2 girth weld on the inside of pup 2 as shown in figure 23. The location was approximately 90° counterclockwise of the longitudinal fracture in pup 2.

C.3. CHORD LENGTH AND WALL THICKNESS MEASUREMENTS

The pup chord lengths and wall thicknesses were measured by tape measure and ultrasound, respectively. The chord lengths were measured at four locations at 90° intervals starting at the top of the pipe. The data are listed in table 2. The chord length for pup 2 at the 6 o'clock position could not be measured due to deformation to the pipe. The length of pups 1 – 5 (taken along the top of the pipe) varied between 43 inch and 46.75 inch. Pup 6 measured 54.25 inch along its top. The ultrasonic thickness measurements were taken at 30° intervals starting at the top of the pipe, taking care to stay a minimum of 1 inch from the longitudinal seams. The mean, minimum, and maximum values are listed in table 3. All of the thickness measurements can be found in Appendix A, table A1. The pipe within this pipeline segment was reported as 0.375 inch nominal wall thickness pipe[4]. The measured mean wall thickness values varied between 0.359 inch and 0.381 inch from pup 2 to pup 4, respectively. PG&E and API specifications in the 1948 to 1954 time frame allowed a -10% tolerance on wall thickness[3,5,6]. The thickness values were consistent with nominal 0.375 inch wall thickness pipe. The variation in wall thickness for an individual piece of pipe varied between 1.1 and 2.8 percent, consistent with pipe that was formed from a rolled plate.

The wall thicknesses of the long joint south of pup 1 and the long joint north of pup 6 were checked by micrometer and a series of wall thickness measurements on the bottom of the southern section were made by ultrasound. The wall thickness of the long joint south of pup 1 was 0.371 inch, consistent with nominal 0.375 inch wall thickness pipe. The wall thickness of the long joint north of pup 6 was 0.315 inch, consistent with nominal 0.3125 inch wall thickness pipe. The ultrasound wall thickness measurements on the long joint south of pup 1 were taken starting 3 inch from the cut end of the southern section continuing every 3 inch through the 45-inch mark. The measurements were taken along a longitudinal line at the 6 o'clock position and along longitudinal lines 12 inch on either side. The mean, minimum, and maximum wall thickness values are shown in table 4. The complete data set can be found in Appendix A, table A2. The mean wall thickness for the three longitudinal lines varied between 0.381 inch and 0.382 inch. The minimum wall thickness varied between 0.377 inch and 0.378 inch.

C.4. RADIOGRAPHY, MAGNETIC PARTICLE, AND WELD INSPECTION

The longitudinal seams on all pups and all intact circumferential girth welds (C1 – C4 and C6 – C7) were examined by radiography using an iridium 192 isotope recorded on Fuji type 80 film that measured 4.5 inch x 17 inch. The long joint south of pup 1 was examined by radiography along the center section and along the grit blast area shown in figure 15 on the southern section. The long joint north of pup 6 was examined by radiography over a 24 inch length north of pup 6. The radiographs were interpreted by an American Society for Nondestructive Testing (ASNT) certified Level III[iii] inspector in accordance with the current API specification[7]. The discontinuity definitions, the acceptance criteria for the current API specification, and the acceptance criteria for the 1956 edition[8] can be found in Appendix B. A discontinuity is defined as an interruption of the typical structure of a material. A defect is defined as, "a discontinuity or discontinuities that by nature or accumulated effect render the weld unable to meet minimum applicable acceptance standards or specifications"[9]. There were no records indicating radiography was performed as part of the project in 1956. ASA B31.1.8-1955 (predecessor to ASME B31.8) left the use of radiography, the number, and the location of welds examined to the discretion of the operating company[10]. Adherence to API 1104 was not a code requirement until January 17, 1961 when it became incorporated into CPUC General Order 112[11].

The longitudinal seams showed various defects including lack of penetration, incomplete fusion, slag inclusion, porosity, and undercutting. No defects were detected along the longitudinal seam of the long joint south of pup 1. Porosity was observed along a 12 inch length adjacent to pup 1 that was within the acceptance criteria of API 1104[7]. The longitudinal seams of pup 1 and pup 2 could not be examined by radiography as they were fractured. The longitudinal seam on pup 3, of which 1.5 inch is visible in figure 24, exhibited a lack of penetration defect along its entire length[iv]. The longitudinal seam on pup 4 exhibited incomplete fusion, porosity, and undercutting defects on all radiographs along its length. A slag inclusion defect was observed between 12 inch and 36 inch from girth weld C4. The longitudinal seam on pup 5 exhibited a lack of penetration defect along its entire length. The first 15 inch of the longitudinal seam along pup 5 is shown in figure 25. The longitudinal seam on pup 6 exhibited porosity discontinuities on all radiographs along its length. The porosity in the region 0 – 12 inch from girth weld C6 was within the acceptance criteria of API 1104 while the porosity elsewhere did not meet the acceptance criteria. See Appendix B for the complete list of indications on the longitudinal seams.

The girth welds exhibited various defects including lack of penetration, incomplete fusion, burn through, slag inclusion, crack, porosity, undercutting, and excess reinforcement. All girth welds exhibited incomplete fusion, slag inclusion, and porosity defects on at least one radiograph. Lack of penetration defects were exhibited on all intact

[iii] Level III inspectors have been certified by ASNT as qualifying to common examinations developed and administered by an independent third party.
[iv] The term "lack of penetration" is used in this document to indicate an observed lack of weld filler metal in the through-thickness direction of the weld joint.

girth welds except C1 and C6. Undercutting defects were exhibited on all intact girth welds except C2 and C3. Four plug welds were observed on pup 4 adjacent to girth weld C4. An example radiograph of girth weld C3 is shown in figure 24. See Appendix B for the complete list of indications on the girth welds.

Magnetic particle inspection was conducted on the intact longitudinal seams, girth welds, the outside surface of pup 1, the inside surface of pup 1, and the accessible inside surfaces of pup 2 using the wet fluorescent method. Results were interpreted by an ASNT Level III certified inspector. Three locations on pup 5 showed indications using the magnetic particle method shown in figure 26a. The features were consistent with a lack of fusion. One region, shown in figure 26b, was centered 5.5 inch north of the C5 girth weld. The other two regions were approximately 26 inch north of the C5 girth weld and were 0.5 inch to 1.0 inch in length. No other indications were observed on the pipe.

A visual weld inspection was conducted by an American Welding Society certified inspector. The appearance of the longitudinal weld in the long joint south of pup 1 and the long joint north of pup 6 was consistent with a submerged arc welding process. No imperfections were found on the longitudinal welds except for pups 1 – 3 for which lack of weld penetration along the ID surface was observed. Also noted, no evidence of an external weld bead was observed on pups 1 – 5[v]. The longitudinal weld bead on pup 5 had been visibly ground. The appearance of the girth welds was consistent with a shielded metal arc welding process. Arc strike and undercut imperfections were observed on the outside diameter of girth weld C1 as shown in figure 27a. Plug welds were observed on pup 4 near C4 and C5 at 90° intervals around the circumference. Undercut and a 1/16" gouge were observed on the outside diameter of girth weld C6. Visual inspection of the inside diameters was consistent with a back welding process rather than welding from the outside diameter. The welds had a poor weld profile consistent with low welding amperage and exhibited various features including cold lap, incomplete fusion between the weld metal and the base metal, slag, under fill along the weld joint, and lack of penetration. An example is shown for a portion of girth weld C2 on the inner diameter shown in figure 27b. The imperfections observed on the girth welds can be found in Table 5.

C.5. FRACTOGRAPHY

Before cutting samples from the pipe pieces, the geometry of the three sections of pipe was analyzed using a three-dimensional digital laser scanner to record the overall dimensions of the pipe pieces. Then the following fracture surfaces were cut from the pipe using a plasma cutter and transported to the NTSB Materials Laboratory in Washington, DC where the Metallurgical Group conducted a laboratory examination from October 12, 2010 through October 22, 2010.

1) 52 inch-long section containing the pup 1 counterclockwise fracture face starting 8 inch upstream of girth weld C1 continuing to fractured girth weld C2 (Figure

[v] There is no known prohibition against removing the weld bead on the outer diameter surface in API 5LX or PG&E material specifications, as long as the resultant pipe meets mechanical testing requirements.

28a) (Note: Clockwise and counterclockwise directions are assigned as a rotation about the longitudinal axis of the pipeline looking north.);
2) 85 inch-long section containing the pup 1 and pup 2 clockwise fracture faces starting 8 inch upstream of girth weld C1 continuing to where the cut intersected the fracture in pup 2 angled at 66° to the longitudinal seam (Figure 28b);
3) 8 inch-long section of pup 2 counterclockwise fracture face including the mating fracture face of girth weld C2 included in item number 1 above (Figure 28c);
4) 6 inch ring from pup 4 containing the fracture at girth weld C5 (Figure 28d).

The fracture surfaces were cleaned with alternating applications of mild detergent/rinse water and toluene using a nylon bristle brush. Well adhered dirt and surface rust were removed using acetate replicating tape softened with acetone, pressed onto the fracture surface, allowed to dry, and the tape peeled off.

C.5.a. Fractography of Longitudinal Fracture

The features on the fracture surface of the long joint south of pup 1 were consistent with overstress fracture with the crack propagating from pup 1. Over the first 3.5 inch adjacent to girth weld C1 (see figure 1), the fracture surface had 45° shear lips along the inner and outer third of the wall and a flat region in the middle third as indicated in figure 29. Moving further away from pup 1 the fracture profile transitioned to a 90° flat fracture consistent with an accelerating fracture. Partial chevron[vi] features pointing in the direction of pup 1 were observed consistent with overstress fracture.

At the other end of the longitudinal fracture, there were features along the pup 2 longitudinal seam consistent with overstress in out-of-plane shear propagating from girth weld C2. The counterclockwise half of the longitudinal seam adjacent to C2 is shown in figure 30. The inner half of the seam had a color and texture similar to the inner wall of the pipe, consistent with lack of weld penetration. The outer half of the seam showed a shear lip and a smeared fracture surface consistent with out of plane shear. The pipe wall on the clockwise half of the fracture exhibited outward bending deformation as shown in figure 31. The bending curvature was greatest adjacent to girth weld C2 and decreased continuously approaching the mid length of pup 2. There was no outward bending deformation on the counterclockwise side of the longitudinal seam on pup 2. The fracture surface and bending deformation were consistent with a crack propagating from girth weld C2.

There were fracture features on girth weld C2 consistent with overstress in mixed tension and shear consistent with a crack propagating from the pup 1 longitudinal seam. Approaching the pup 2 longitudinal seam, a shear lip was visible along the girth weld as shown in figure 32a consistent with out of plane shear. At the location where the pup 1 longitudinal seam met the girth weld (see figure 28c), a longitudinal crack was visible in the weld cap as shown in figure 32b. The crack did not continue through the wall of the pipe

[vi] Chevron marks are “V” shaped features with the tip of the V pointing opposite the direction of propagation.

underneath the cap. The fracture features were consistent with a crack originating in the longitudinal seam of pup 1.

The crack initiation site was found along the pup 1 longitudinal seam at the location shown in figure 33a. The counterclockwise half of the longitudinal seam at the initiation site is shown in figure 33b. The inner half of the seam had a color and texture similar to the inner diameter surface of the pipe, consistent with a lack of weld penetration. The outer half of the seam had a rough texture consistent with a tensile overstress fracture.

The lack of penetration was seen along the entire length of the fractured pup 1 longitudinal seam. The lack of penetration depth and total wall thickness were measured at 10 locations starting 4.25 inch downstream (south) of girth weld C1 and spaced at 4 inch intervals along the pup 1 longitudinal seam from calibrated digital images taken on an optical microscope (measured after the conclusion of the group examination). The data are included in Appendix C. The average lack of penetration depth was 0.140 inch ± 0.021 inch (1 standard deviation). The average wall thickness on the counterclockwise side of the seam was reduced from 0.367 inch measured in the rest of the pipe to 0.312 inch ± 0.015 inch. The average percent weld penetration was 55% ± 7%. Specifications for pipe purchased by PG&E in 1948 and 1949 defined an injurious defect to be one that reduced the wall thickness to less than 90 per cent of the specified wall thickness. The defect was considered repairable if the depth did not exceed 33 – 1/3 per cent of the specified wall thickness and provided the length of the defect was not greater than a length equivalent to one diameter of the pipe (30 inch)[3,6]. An API 5LX Standard on High-Test Line Pipe from 1954 considered all cracks, sweats, leaks, or other defects in welds to be injurious[5].

An apparent crack arrest mark was observed using a stereomicroscope between 20.3 inch and 22.7 inch north (downstream) of the C1 girth weld and was identified as the initiation site. The location of the initiation site is indicated in figure 33a. The arrest mark is indicated in figure 33b and in figure 34 by a yellow dotted line labeled “2”. The lack of penetration depth at the initiation site was 0.150 inch. The wall thickness was reduced to 0.332 inch. The percent weld penetration was 55%. The fracture surface in the area labeled zone “1” in figure 34 had a slightly darker tint than the fracture surface in the area labeled zone “3”. Porosity was observed at the root of the weld as indicated in figure 35. The crack arrest mark was 2.4 inch at its widest and was within 0.057 inch of the outer diameter surface at the 21.4 inch mark, its deepest point, also shown in figure 35. In contrast to the rough texture observed over most of the fracture surface, a thin band of flat fracture was seen along the crack arrest mark starting at the 22 inch mark and continuing to the north extent of the crack arrest mark at 22.7 inch. Interpretation of the fracture morphology at the crack arrest mark between the 20.3 inch and 22 inch marks was inconclusive. A micrograph of the fracture surface at the 22.7 inch mark is shown in figure 36. A higher magnification optical micrograph was taken in the region indicated by the black rectangle and is shown without annotations in figure 37a and with annotations in figure 37b. Two dotted yellow lines are superimposed on the micrograph in figure 37b. The area in zone 2 between the dotted yellow lines had a flat morphology compared to the rough morphology in zones 1 and 3 consistent with progressive fracture. The band was 0.005 inch wide where indicated in the figure and widened as it approached the end of the initiation site.

Scanning electron microscopy (SEM) of the fracture initiation site indicated three regions with different fracture morphologies. Referring to figure 34, dimples were observed on the rough fracture surface in zone 1 as illustrated by the SEM micrograph in figure 38, consistent with ductile fracture originating from the root of the weld. The fracture surface along zone 2 was oxidized and largely devoid of features except for a few locations between the 22 and 22.7 inch marks that had been protected by asphalt that had flowed onto the fracture surface. Those regions showed occasional feathery features and, in a few instances, striated features aligned with the crack arrest mark as shown in the SEM micrograph in figure 39. The fracture surface in zone 3 was smooth with hackle marks propagating across the surface as shown in the SEM micrograph in figure 40, consistent with quasicleavage fracture. An inhibited acid solution (ASTM G1 Solution C.3.5)[12] was used to remove rust on the fracture surface to see if it would reveal additional fracture features, however no additional features were observed.

In summary, the fracture features in the center section of pipe were consistent with a crack that initiated in the pup 1 longitudinal seam between 20.3 inch and 22.7 inch north of the C1 girth weld as shown in figure 41. The direction of crack propagation consistent with the fracture features is indicated by the white arrows in the figure. The crack initiated in a manner consistent with ductile overstress from the root of the weld. At the boundary of the ductile overstress region, features consistent with progressive crack growth were observed. Moving toward the outer diameter surface, quasicleavage features were observed consistent with overstress and final rupture. The fracture features were consistent with one branch of the crack propagating south into the long joint south of pup 1 and toward the point of final fracture. The fracture features were consistent with the other branch propagating north until it intersected the C2 girth weld. The fracture features were then consistent with the crack propagating in the counterclockwise and clockwise directions along the C2 girth weld. The counterclockwise branch propagated 27 inch toward the true top of the pipe and arrested. The clockwise branch propagate 6.25 inch where it intersected the pup 2 longitudinal seam. The out of plane bending and shear on the pup 2 longitudinal seam fracture surface were consistent with the crack continuing to propagate north along the pup 2 longitudinal seam where it arrested.

C.5.b. Fractography of Circumferential Girth Weld Fracture

Examination of much of the circumferential fracture at girth weld C5 was inconclusive as the fracture features that might indicate direction of propagation could not be conclusively discriminated from the microstructure of the weld. However, there were several spots indicated by yellow arrows in figure 42 where features similar to chevron or radial lines could be discriminated that enabled a partial determination of the direction of crack propagation. An example macrophotograph is shown in figure 43. The examination indicated that the girth weld fracture likely originated along the east side of the pipe with at least one branch crack propagating across the bottom of the pipe and around the west side. No signs of corrosion or perforations in the weld were observed.

C.5. METALLOGRAPHY

The microstructure of the longitudinal seam welds on all pieces of pipe was examined by cross section metallography (Note: Metallographic cross sections were evaluated after the conclusion of the group examination). Samples were mounted and polished according to standard laboratory protocols[13] and microetched with a 2% Nital solution[14].

The microstructure of the seam weld in the long joint south of pup 1 was consistent with a double submerged arc welding process as shown in figure 44. The microstructure of the weld was consistent with the first pass along the outer diameter surface and the second pass along the inner diameter surface. The weld pool from the outer pass was 0.659 inch wide at the outer diameter, the weld pool from the inner pass was 0.723 inch wide at the inner diameter, and the two passes overlapped in the middle of the weld by 0.10 inch. The outer diameter weld cap was 0.095 inch proud of the outer diameter surface. The inner diameter weld cap was 0.123 inch proud of the inner diameter surface. There was a 5° angle between the tangent lines to the inner diameter surface on either side of the seam. The heat affected zone had an hourglass shape. It was 0.77 inch wide at the outer diameter, decreased to a width of 0.61 inch in the center of the wall, and increased to a width of 0.81 inch at the inner diameter.

The weld microstructure for pup 1 was consistent with a fusion welding process with filler metal laid down into the weld joint along the outer diameter surface of the seam and a ground down weld cap. A typical cross section 9 inch north of girth weld C1 is shown in figure 45. The two sides of the seam were matched up in the longitudinal direction, and glued together for mounting and polishing. The two sides of the seam are within 0.005 inch or less of one another in the longitudinal direction. The point of deepest weld penetration was 0.185 inch and was off center of the seam by 0.084 inch. The wall thickness on the counterclockwise side of the seam had been reduced to 0.315 inch by grinding. At its widest, the weld was 0.662 inch. There was a 0.030 inch radial offset between the mating edges of the plate and a 15° angle between the tangent lines to the inner diameter surface on either side of the seam. The heat affected zone decreased in width continuously from 0.88 inch wide near the outer diameter surface to 0.72 inch near the inner diameter surface.

The plane of fracture was not in line with the longitudinal seam, but rather started offset 0.070 inch from the seam as shown in figure 46 before displacing back toward the seam as it propagated toward the outer diameter surface to an offset of 0.017 inch. A 45° bevel was observed on the clockwise side of the seam that did not match up with the seam profile on the counterclockwise side. There was a visible reduction in grain coarsening along the bevel. The weld penetration depth changed abruptly at the edge of the counterclockwise face by 0.020 inch consistent with a gap present at the edge due to the presence of the bevel on the clockwise side. The distance from the end of the bevel to the outer diameter surface was 0.159 inch.

The weld microstructure for the pup 2 and pup 3 longitudinal seams was similarly consistent with a fusion welding process with filler metal laid down into the weld joint along the outer diameter surface of the seam and a ground down weld cap. Example weld microstructures for pup 2 taken 9 inch south of girth weld C3 and pup 3 taken 10 inch north of girth weld C3 are shown in figures 47 and 48, respectively. The maximum depth of weld penetration for pup 2 was 0.202 inch in line with the seam. There was no measureable reduction in wall thickness or angle between tangent points on opposite sides of the seam. The weld at its widest point measured 0.722 inch across. The heat affected zone decreased in width continuously from 0.84 inch at the outer diameter surface to 0.66 inch at the inner diameter surface.

The plane of fracture started offset 0.041 inch from the seam as shown in figure 45 before displacing back in line with the seam as it propagated toward the outer diameter surface. A 30° bevel was observed on the counterclockwise side of the seam and a 28° bevel was observed on the clockwise side of the seam. The distance from the end of the 30° bevel to the outer diameter surface was 0.173 inch.

The maximum depth of weld penetration for pup 3 was 0.165 inch and was off center by 0.029 inch. There was a 0.022 inch radial offset between mating edges of the plate. The heat affected zone decreased in width continuously from 0.91 inch at the outer diameter surface to 0.73 inch at the inner diameter surface. The crack through the weld started in line with the seam.

The weld microstructure for pup 4 and pup 5 was consistent with a fusion welding process with filler metal laid down into the weld joint along the outer diameter and inner diameter of the seam and grinding of the outer diameter weld cap. Example microstructures for pup 4 taken 8 inch south of girth weld C5 and pup 5 taken 5.5 inch north of girth weld C5 are shown in figures 49 and 50, respectively. For pup 4, the weld penetrated through the wall thickness except for a region of lack of penetration at 0.222 inch below the outer diameter surface and a 0.067 inch long teardrop-shaped root crack at the base of the inner diameter weld. The weld along the outer diameter appeared to have been completed in two passes as illustrated in figure 48. The first pass achieved a depth of penetration of 0.222 inch at its deepest. The second pass achieved a depth of penetration of 0.104 inch. The number of passes along the inner diameter was indeterminate but achieved a depth of penetration of 0.113 inch measured from the inner diameter surface. The widest weld width along the outer diameter was 0.597 inch. The widest weld width along the inner diameter was 0.460 inch. There was apparent grinding on the outer diameter surface on the left side of the seam as depicted in the micrograph which reduced the wall thickness from 0.380 inch to 0.360 inch. There was a 13° angle between the tangent lines to the inner diameter surface on either side of the seam. The heat affected zone had an hourglass shape. It measured 0.75 inch at the outer diameter, decreasing to 0.44 inch and increasing to 0.50 inch at the inner diameter.

For pup 5, the maximum depth of weld penetration on the outer diameter surface was 0.073 inch and the maximum depth of weld penetration on the inner diameter surface was 0.072 inch. The weld bead on the inner diameter surface was raised 0.044 inch at its highest. The inner diameter surface was undercut by 0.018 inch as indicated in figure 49. The widest weld width along the outer diameter was 0.356 inch. The widest weld width along the inner diameter was 0.413 inch. There was a 0.041 inch radial offset between the mating edges of the plate and a 5° angle between the tangent lines to the inner diameter surface on either side of the seam. The heat affected zone for the outer and inner diameter welds were semi-circle shaped and did not meet. The heat affected zone of the weld on the outer diameter measured 0.45 inch at its widest and 0.15 inch at its deepest. The heat affected zone on the inner diameter measured 0.47 inch at its widest and 0.20 inch at its deepest.

The weld microstructure for pup 6 was consistent with a double submerged arc welding process as shown in figure 51. The microstructure of the weld was consistent with the first pass along the outer diameter surface and the second pass along the inner diameter surface. The weld pool from the outer pass was 0.631 inch wide at the outer diameter, the weld pool from the inner pass was 0.660 inch wide at the inner diameter, and the two passes overlapped in the middle of the weld by 0.18 inch. The outer diameter weld cap was 0.110 inch proud of the outer diameter surface. The inner diameter weld cap was 0.115 inch proud of the inner diameter surface. There was a 5° angle between the tangent lines to the inner diameter surface on either side of the seam. The heat affected zone had an hourglass shape. It was 0.74 inch wide at the outer diameter, decreased to a width of 0.60 inch in the center of the wall, and increased to a width of 0.76 inch at the inner diameter.

The weld microstructure of the seam weld in the long joint north of pup 6 was consistent with a double submerged arc welding process as shown in figure 52. The microstructure of the weld was consistent with the first pass along the outer diameter surface and the second pass along the inner diameter surface. The weld pool from the outer pass was 0.554 inch wide at the outer diameter, the weld pool from the inner pass was 0.675 inch wide at the inner diameter, and the two passes overlapped in the middle of the weld by 0.13 inch. The outer diameter weld cap was 0.113 inch proud of the outer diameter surface. The inner diameter weld cap was 0.102 inch proud of the inner diameter surface. There was a 5° angle between the tangent lines to the inner diameter surface on either side of the seam. The heat affected zone had an hourglass shape. It was 0.58 inch wide at the outer diameter, decreased to a width of 0.60 inch in the center of the wall, and increased to a width of 0.74 inch at the inner diameter.

D. REFERENCES

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14. "ASTM E407 – 99 Standard Practice for Microetching Metals and Alloys," ASTM International, West Conshohocken, PA, 2004.

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Table 1: Circumferential distance of longitudinal seams and longitudinal fractures measured from the top of the pipe.

Pipe Piece / Feature	Circumferential Distance from Top of Pipe, inch
Long Joint South of Pup 1 – DSAW Seam	2.88 inch – Clockwise
Pup 1 – Longitudinal Fracture	18.50 inch - Clockwise
Pup 2 – Longitudinal Fracture	24.75 inch - Clockwise
Pup 3 – Longitudinal Seam	27.25 inch – Counterclockwise
Pup 4 – Longitudinal Seam	15.25 inch – Clockwise
Pup 5 – Longitudinal Seam	34.25 inch – Counterclockwise
Pup 6 – DSAW Seam	0.38 inch – Counterclockwise
Long Joint North of Pup 6 – DSAW Seam	11.50 inch – Counterclockwise

Table 2: Chord length measurements for pups 1 – 6 measured along the top of the pipe and at 90˚ intervals.

Pipe Piece	12 o'clock Chord Length, inch	3 o'clock Chord Length, inch	6 o'clock Chord Length, inch	9 o'clock Chord Length, inch
Pup 1	44.50	44.50	44.62	44.38
Pup 2	45.25	45.38	N/A	45.12
Pup 3	46.12	45.50	46.00	46.25
Pup 4	46.75	46.88	47.00	46.75
Pup 5	43.00	43.00	42.75	43.00
Pup 6	54.25	54.88	55.88	55.00

Table 3: Mean, minimum, and maximum wall thickness data for pups 1 – 6. Percent wall thickness variation is the difference between the maximum and minimum wall thickness values divided by the mean wall thickness.

Pup	Mean Wall Thickness, inch	Min. Wall Thickness, inch	Max. Wall Thickness, inch	Percent Wall Thickness Variation
Pup 1	0.367	0.365	0.369	1.1
Pup 2	0.359	0.353	0.363	2.8
Pup 3	0.364	0.360	0.368	2.2
Pup 4	0.381	0.377	0.385	2.1
Pup 5	0.366	0.363	0.369	1.6
Pup 6	0.363	0.361	0.366	1.4

Table 4: Mean, minimum, and maximum wall thickness data along the bottom of the southern section as measured by ultrasound. The wall thickness was measured every 3 inch through the 45 inch mark along a longitudinal line at the 6 o'clock position and 12 inch on either side.

Position	Mean Wall Thickness, inch	Min. Wall Thickness, inch	Max. Wall Thickness, inch
6 o'clock	0.381	0.378	0.384
12 inch CCW of 6 o'clock	0.382	0.377	0.389
12 inch CW Of 6 o'clock	0.381	0.377	0.383

Table 5: Weld imperfections observed during visual weld inspection.

Girth Weld	Inside Diameter	Outside Diameter
C1	Cold Lap, Excess Weld Cap, Icicles, Over Lap	Undercut, Arc Strikes
C2	Cold Lap, Lack of Fusion, Under Fill, Lack of Penetration	N/A
C3	Undercut, Burn Through, Weld Concavity	N/A
C4	Undercut, Excess Weld Cap, Cold Lap, Misalignment	None. Plug welds noted
C5 - Fractured	Undercut, Under Fill, Lack of Penetration	None. Plug welds noted
C6	Weld Concavity, Excessive Cap	Undercut, 1/16 inch gouge
C7	Lack of Penetration, Weld Concavity, Misalignment	N/A

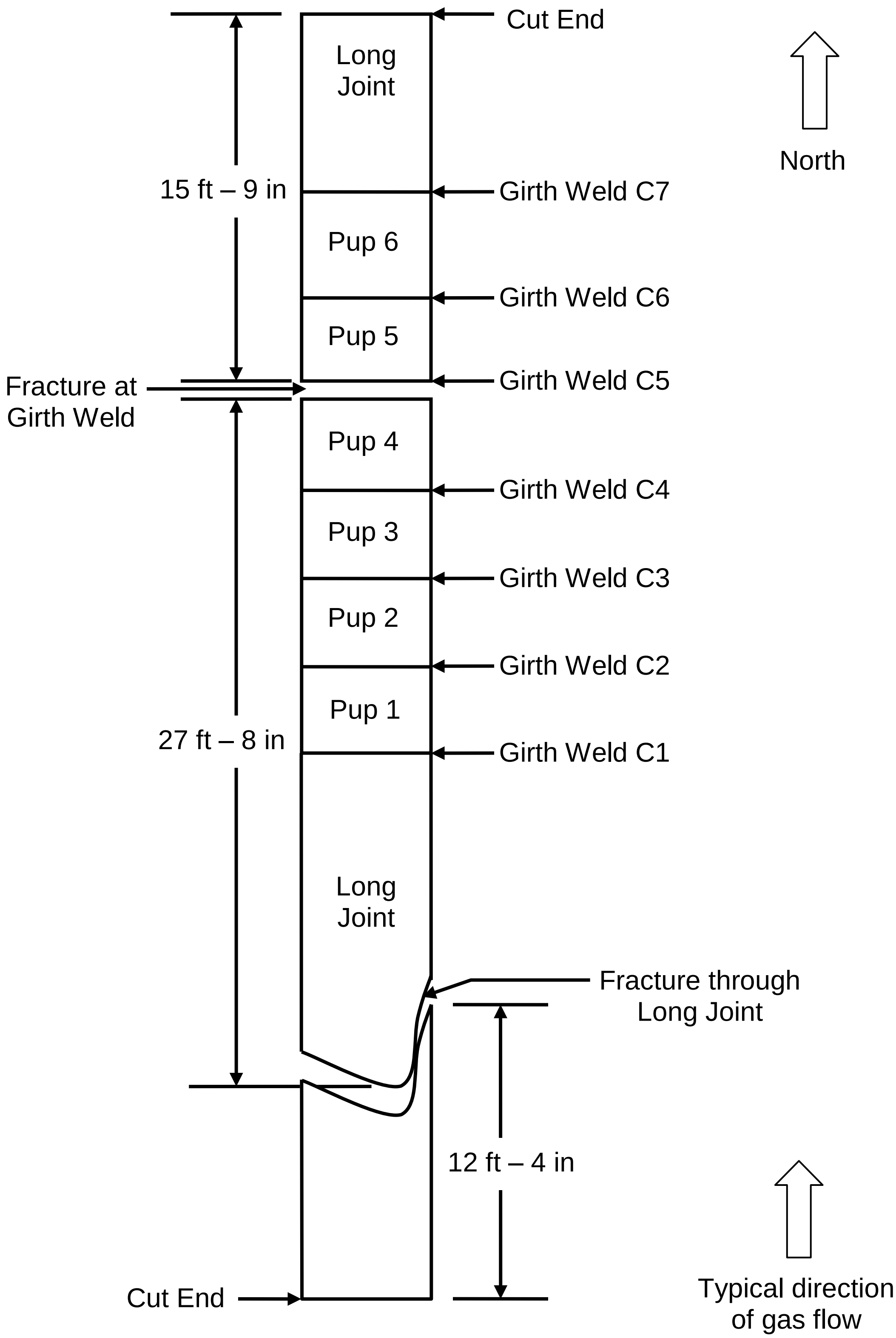


Figure 1: Schematic of pipe showing location of girth welds and fractures. Longitudinal fracture not depicted.

a)
b)
c)

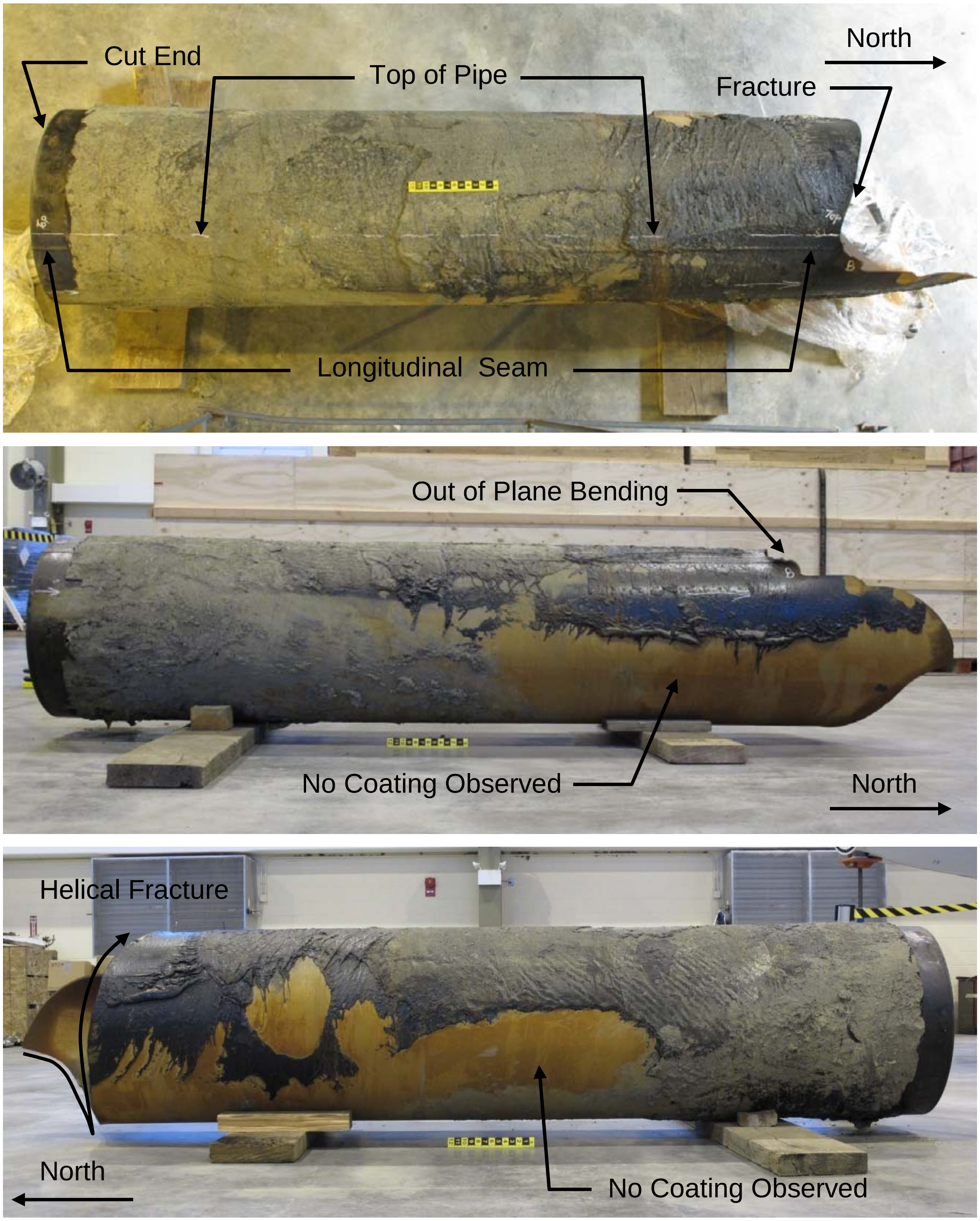


Figure 2: Southern section of pipe as received; a) Top side of pipe; b) East side of pipe; c) West side of pipe.

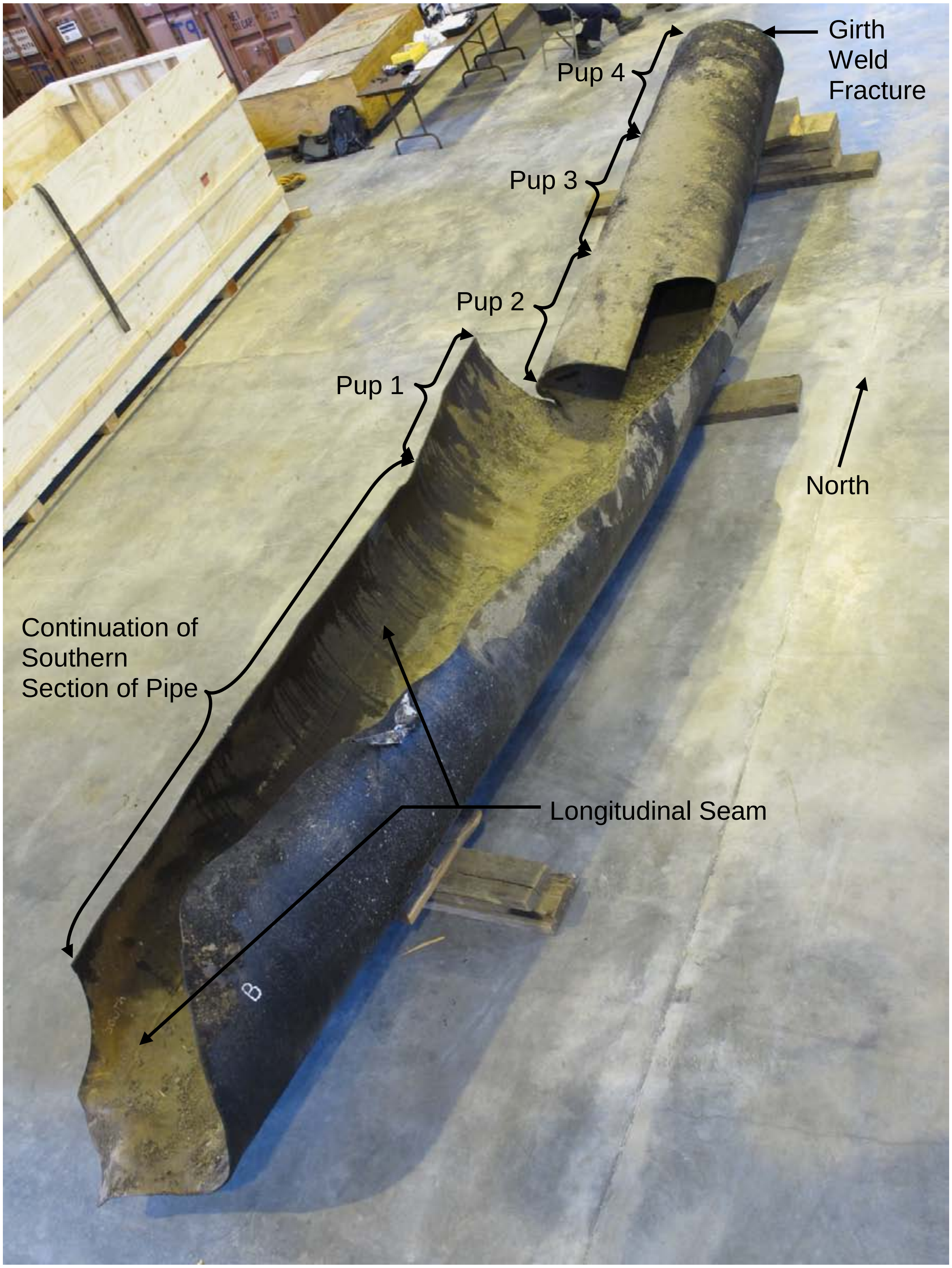
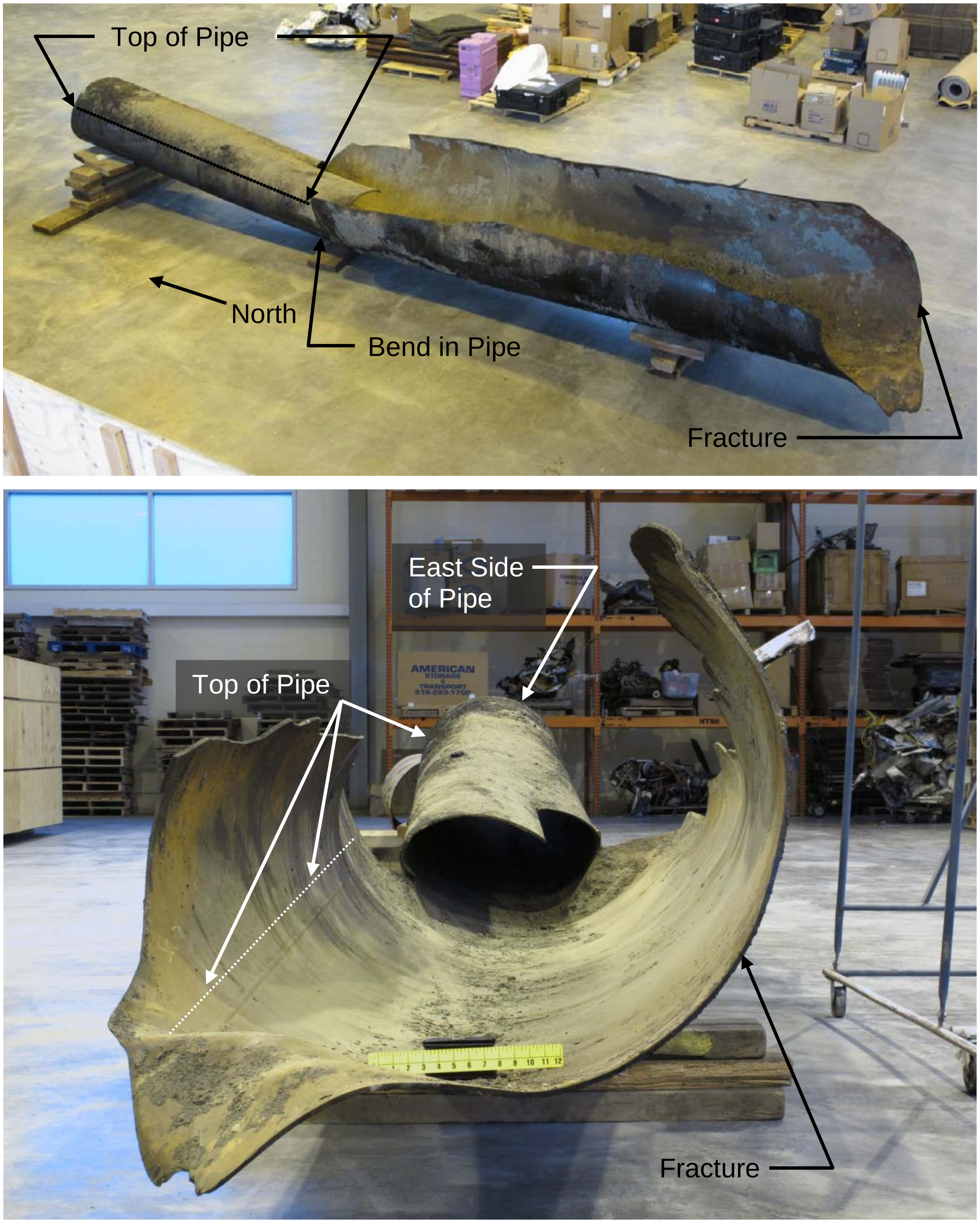


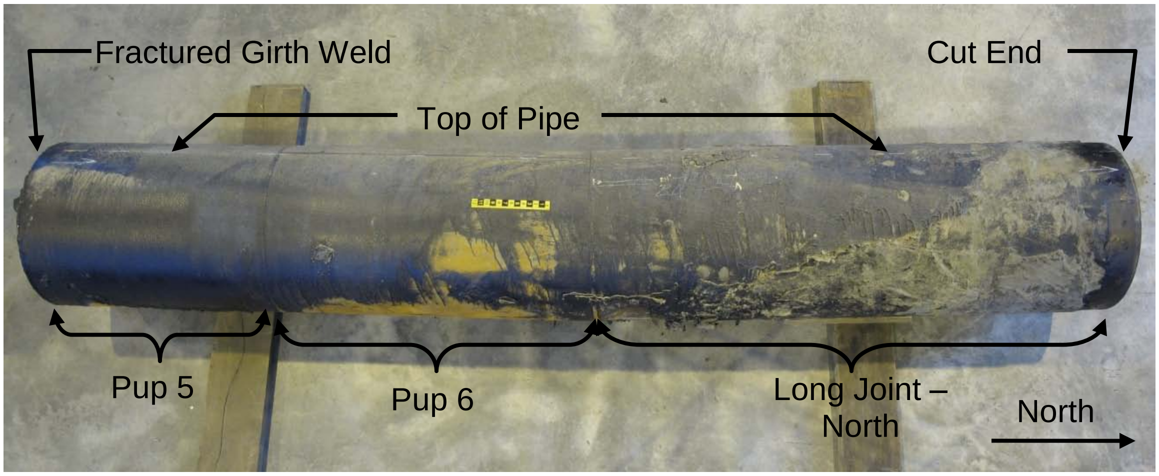
Figure 3: Center section of pipe.



a)

b)

Figure 4: Center section of pipe; a) Orientation of the "true" top of the pipe at the north end; b) Orientation of the true top of the pipe and the east side of the pipe viewed along an axial direction.

a)


b)

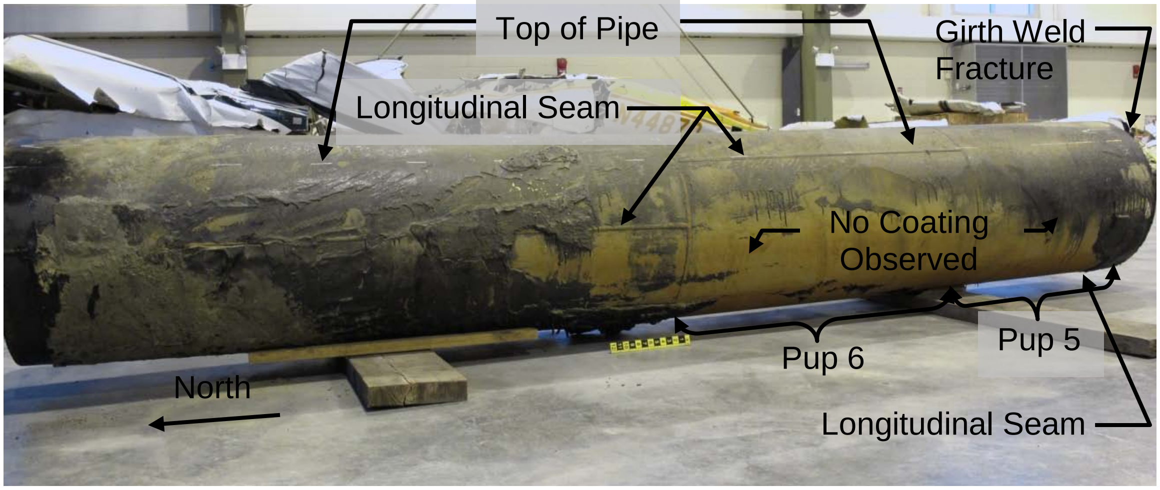

c)


Figure 5: Northern section of pipe as received; a) Top side of pipe; b) East side of pipe; c) West side of pipe.

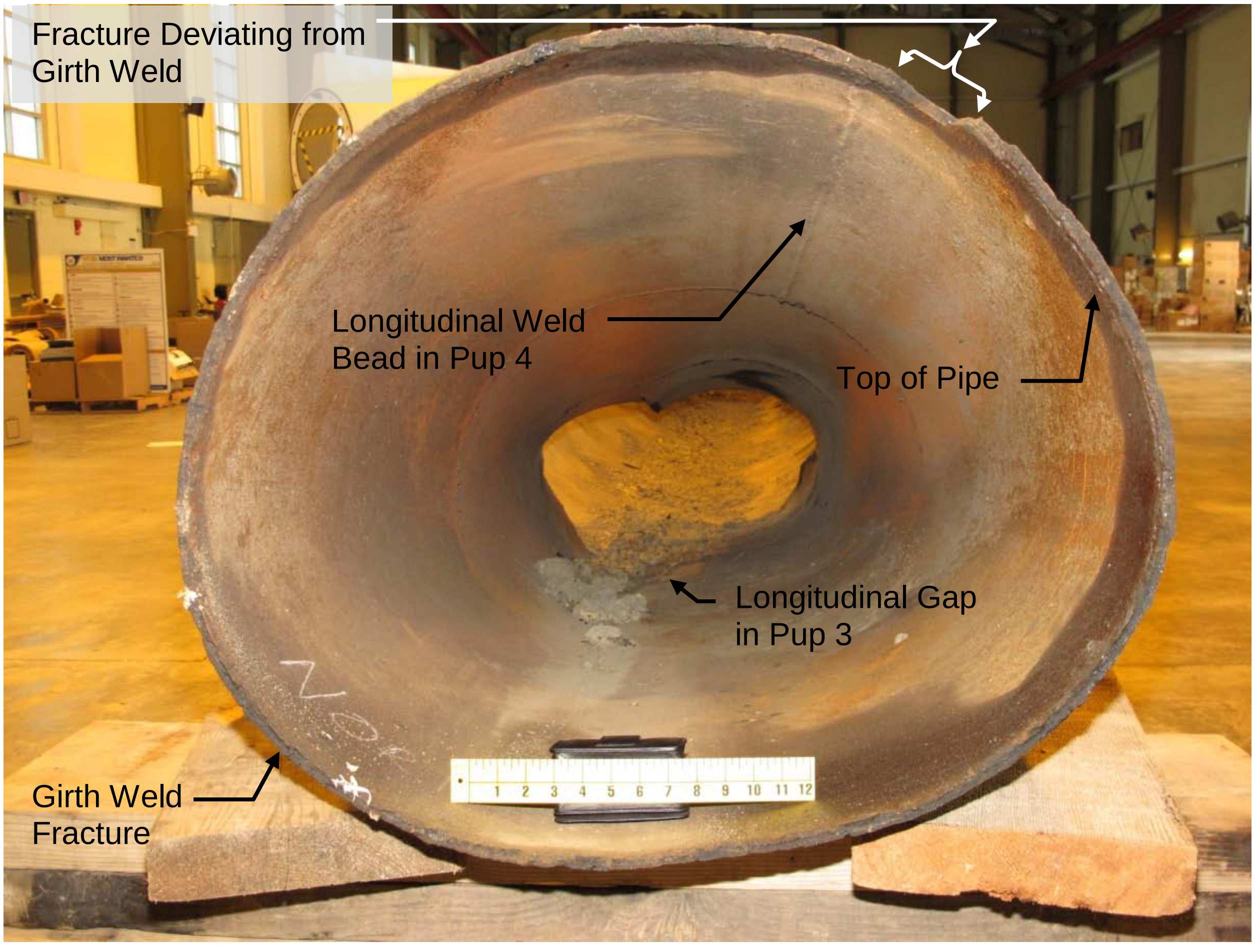
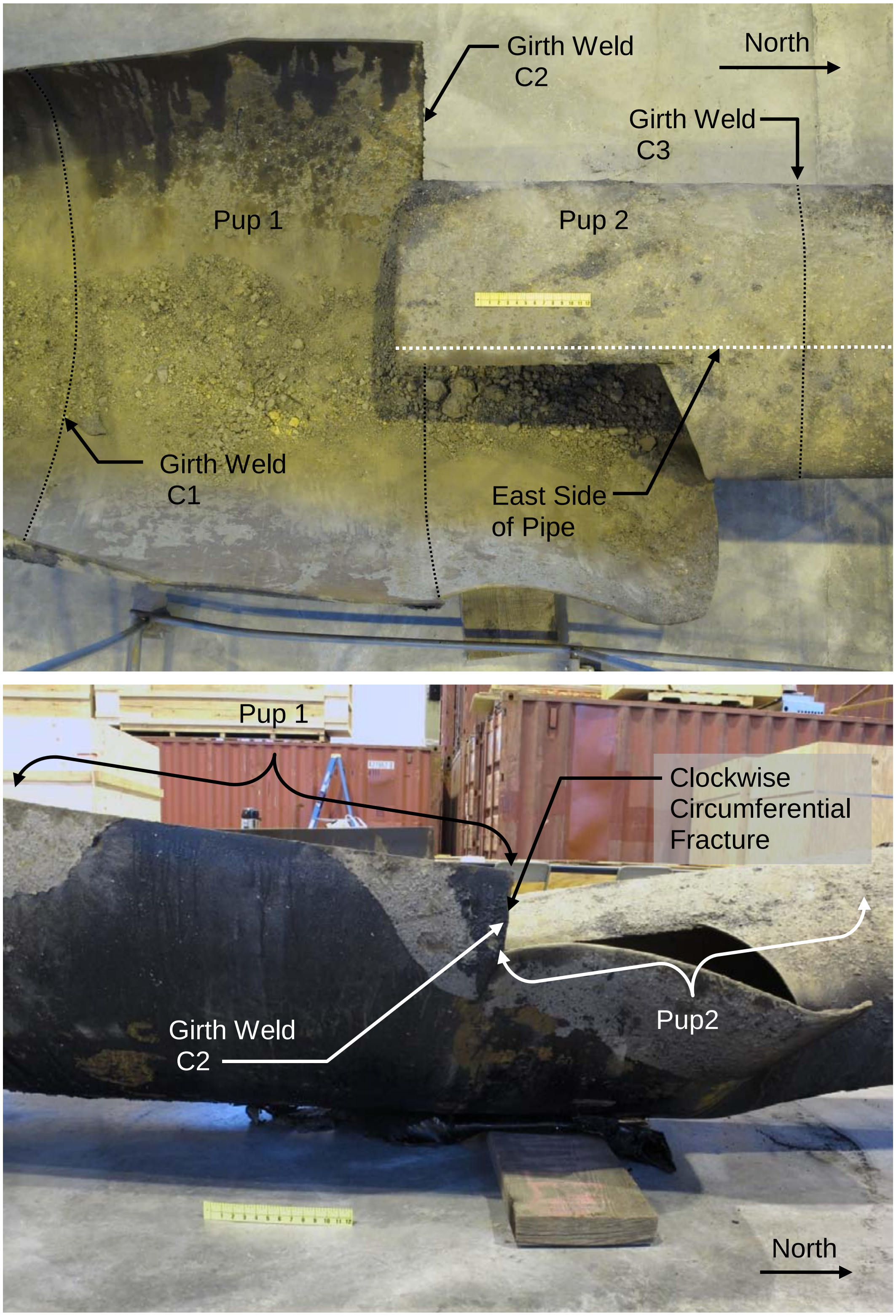


Figure 6: Fracture through the girth weld between pup 4 and pup 5 at the north end of the center section. The view is looking south. Pup 3 and pup 2 are also visible.

a)



b)

Figure 7: The longitudinal and circumferential fractures in pup 1 and pup 2; a) overhead view of the east side of the pipe; b) side view of east and bottom sides of the pipe.

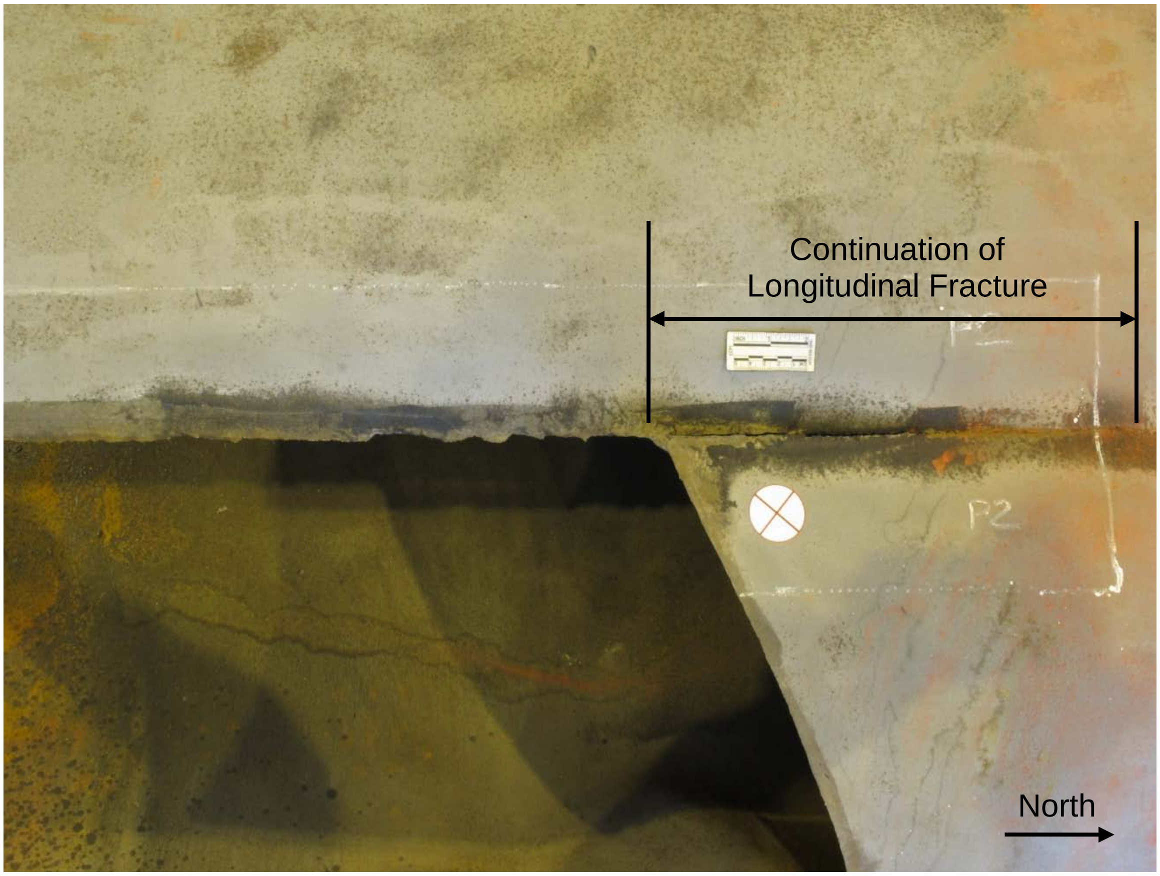


Figure 7 (cont.): c) Continuation of the longitudinal fracture in pup 2 past the branching point was visible after removal of the coating.

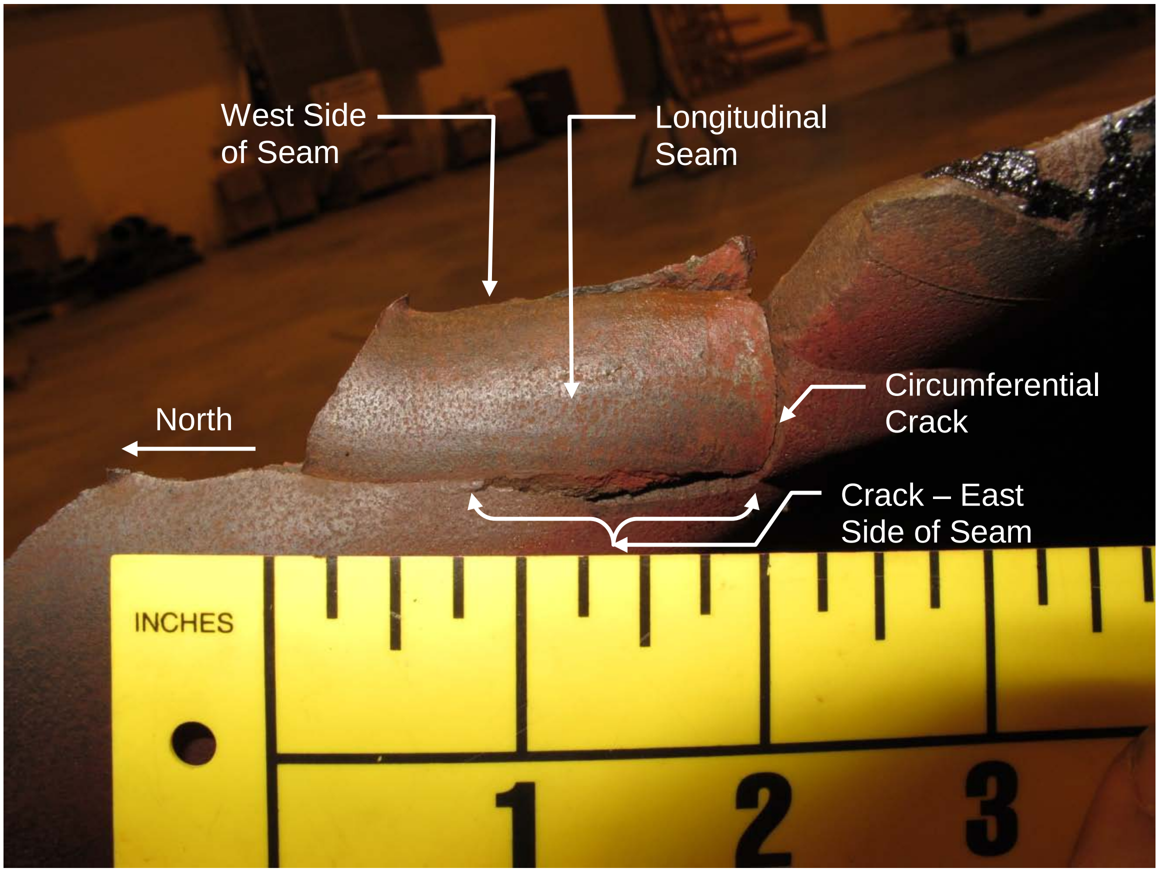


Figure 8: Fracture, a crack, and out of plane bending at a longitudinal seam on the southern section.

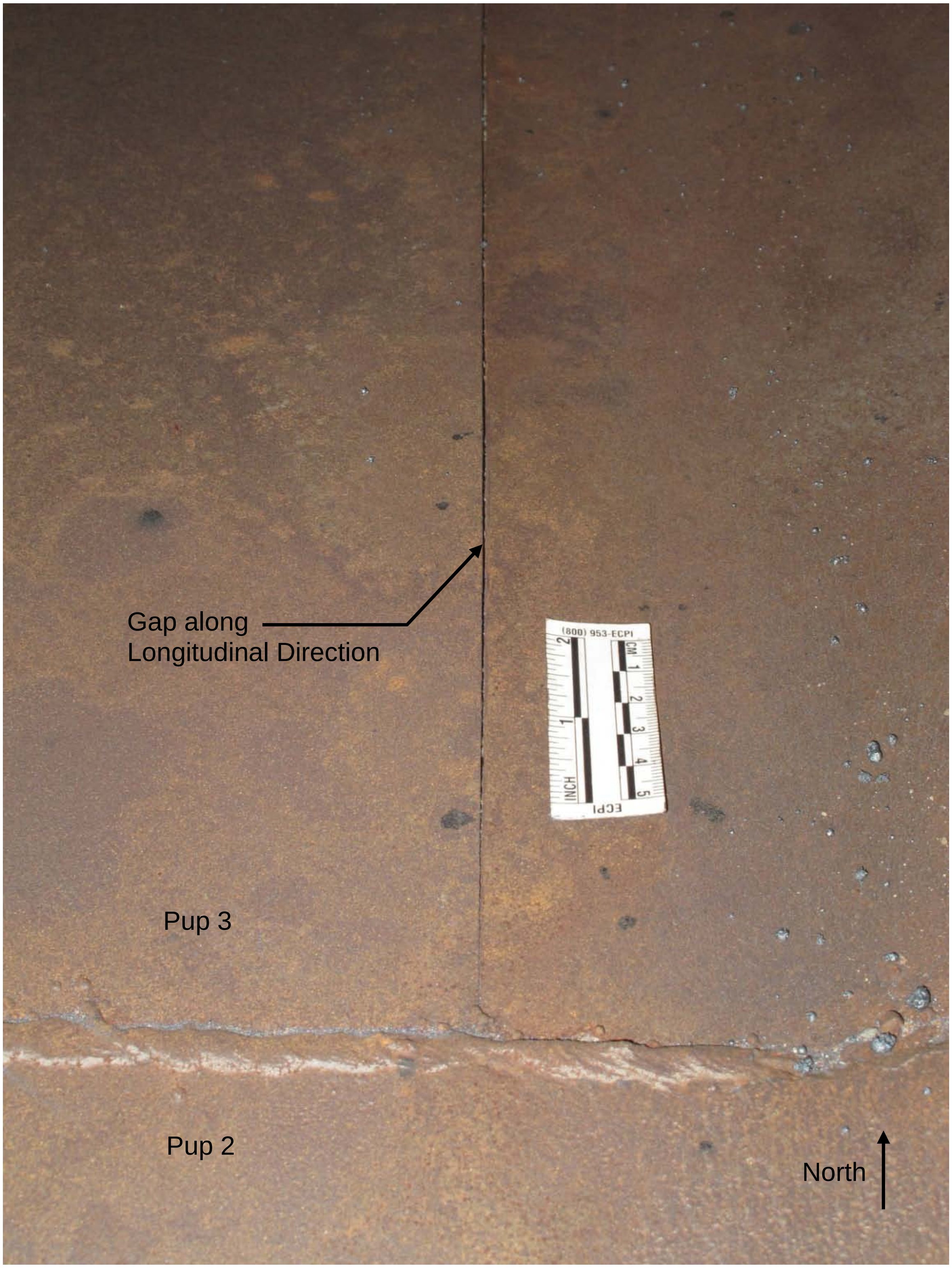
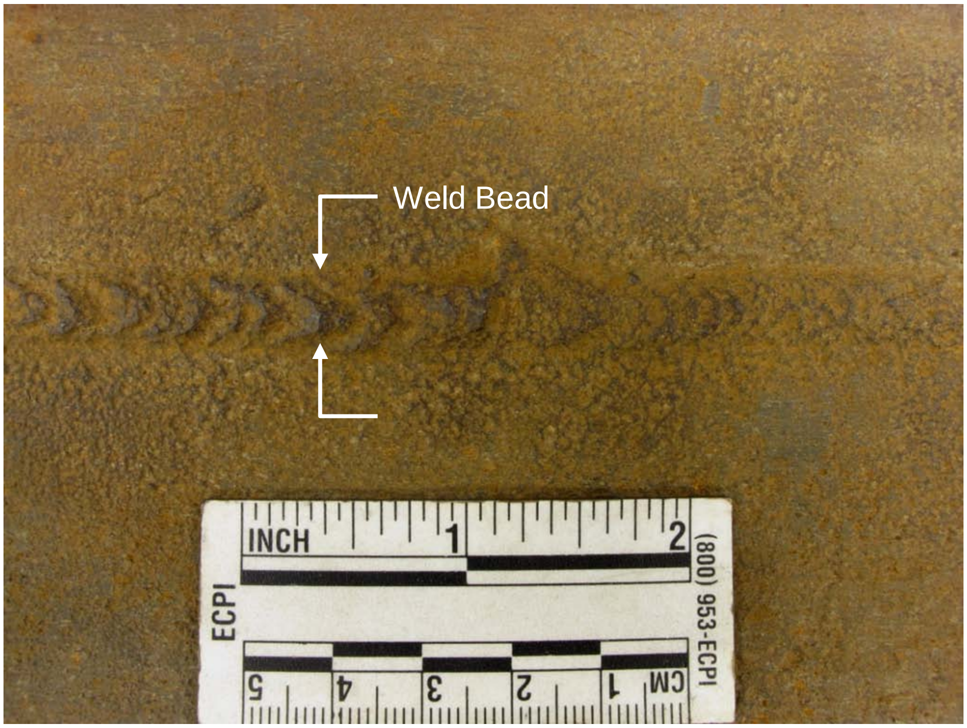
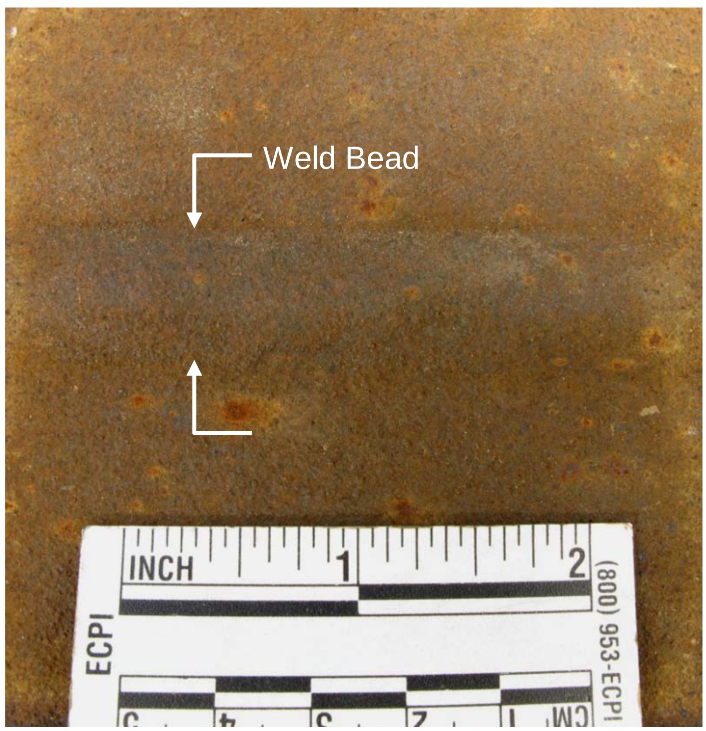


Figure 9: Inside wall of pup 3 showing a longitudinal gap that extended the length of the pup.

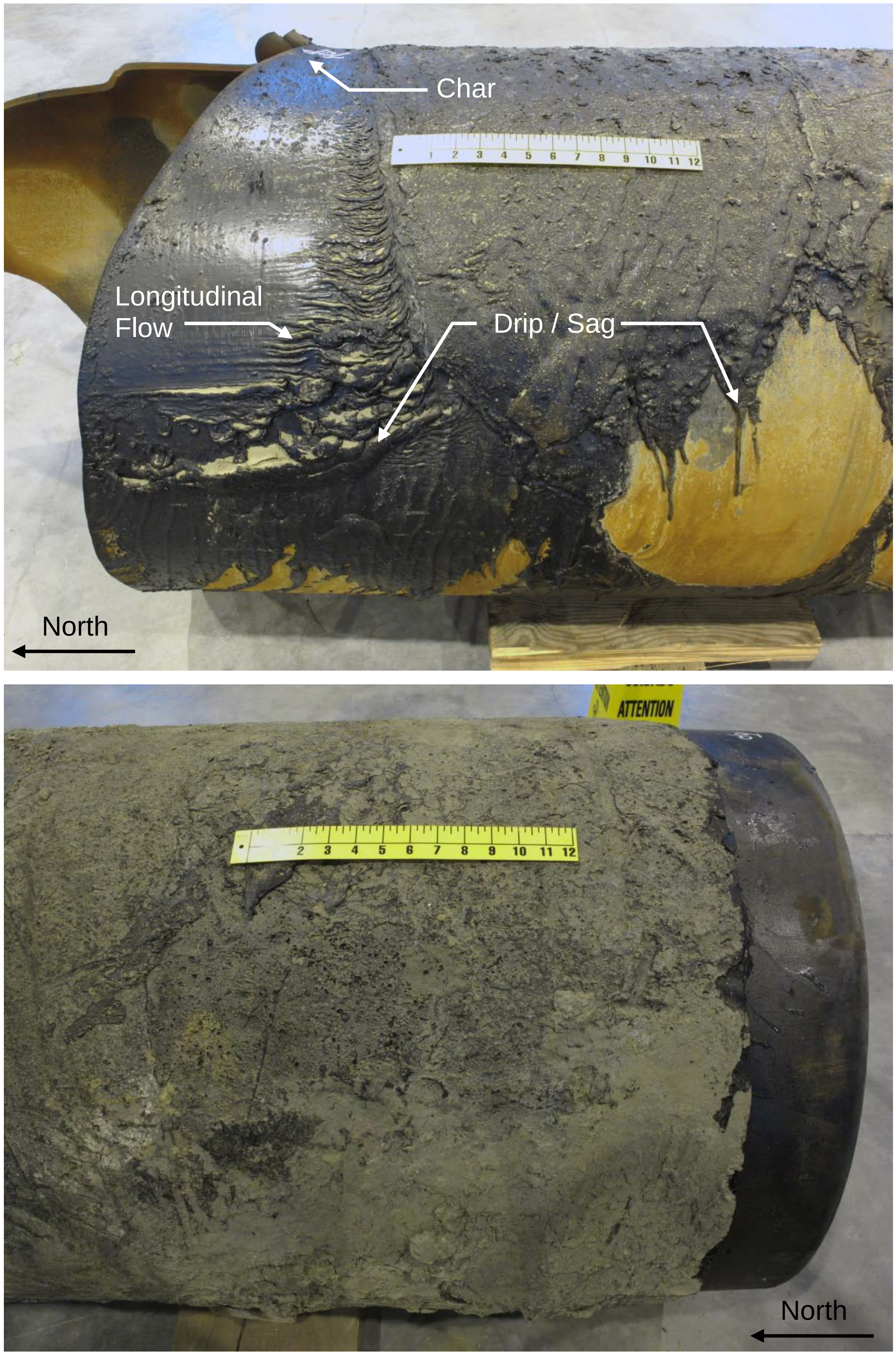


a)



b)

Figure 10: a) Longitudinal weld bead observed on the inside of pup 5; b) Longitudinal weld bead observed on the inside of pup 6.

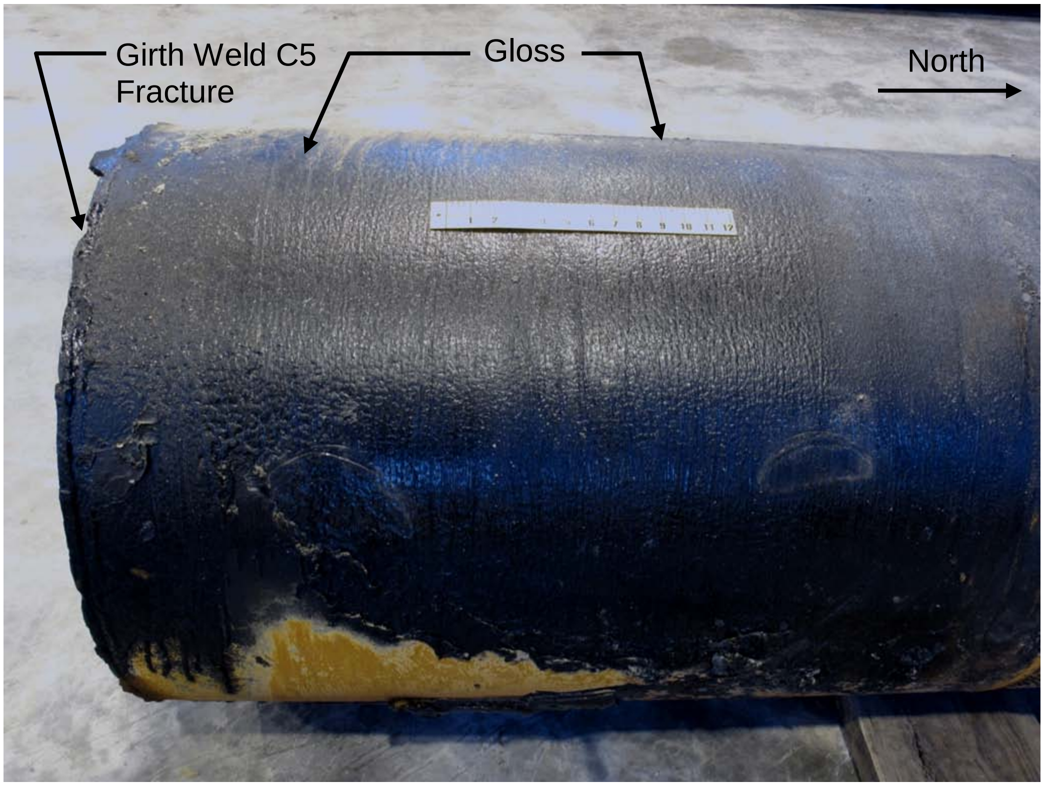


a)

b)

Figure 11: Condition of the asphalt coating on the southern section; a) Adjacent to the circumferential fracture; b) Away from the fracture close to the cut end.

a)



b)

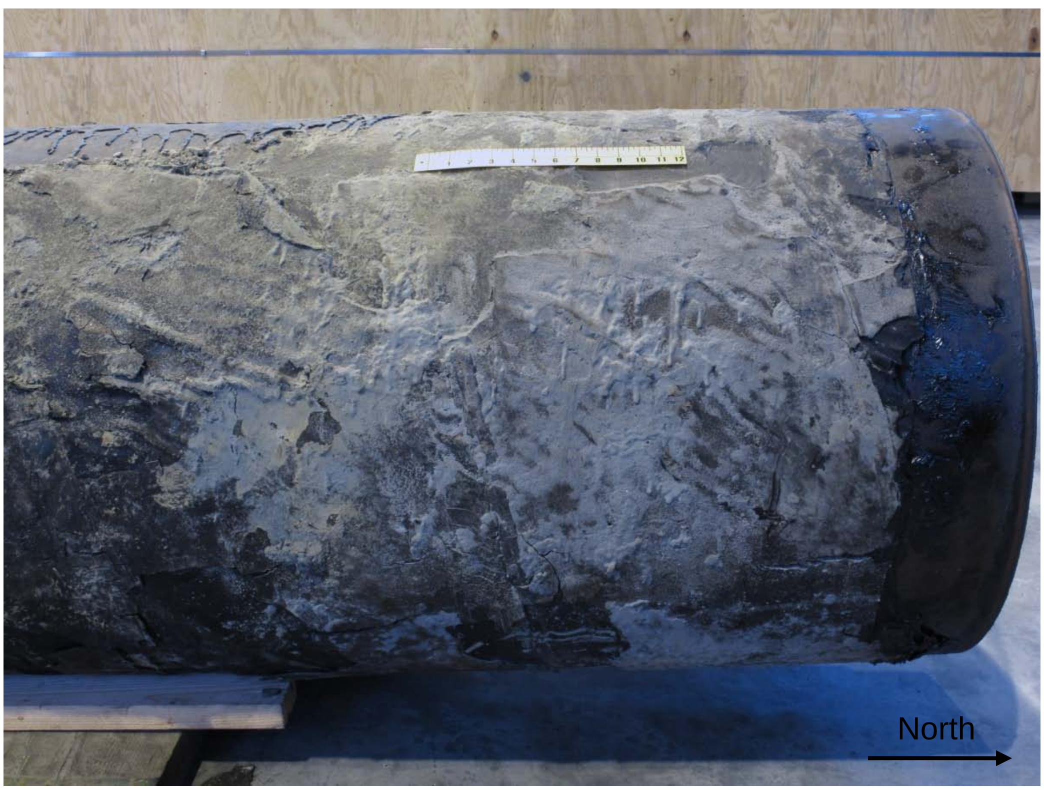
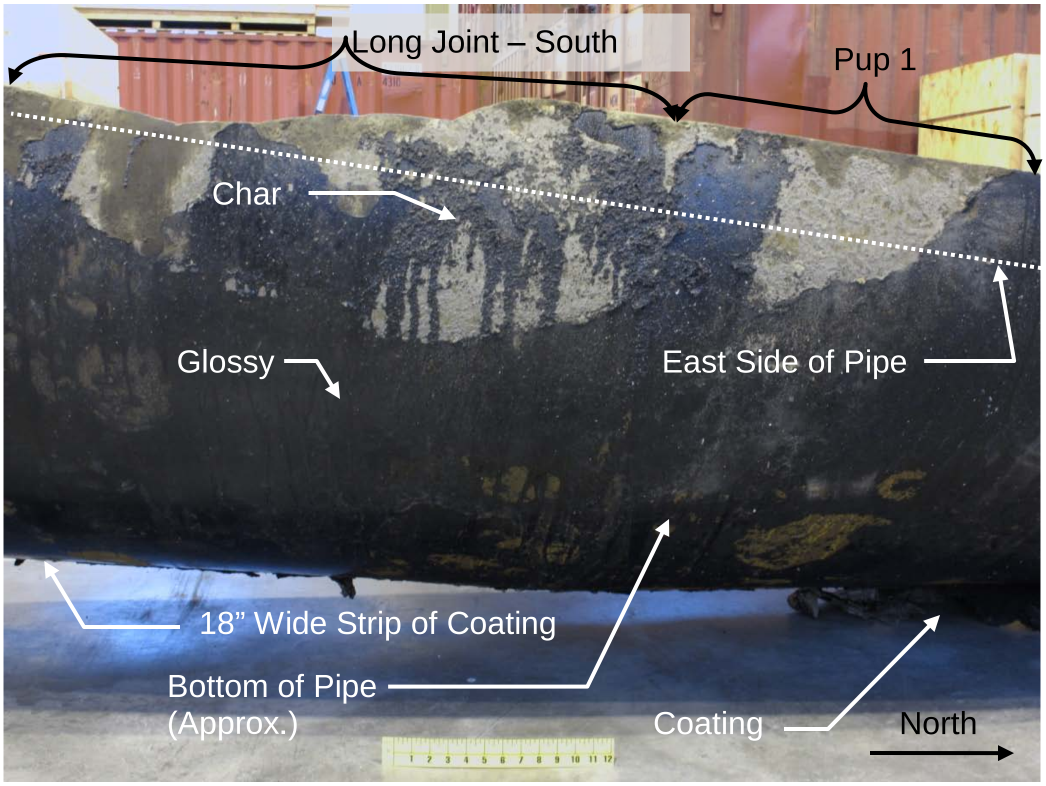
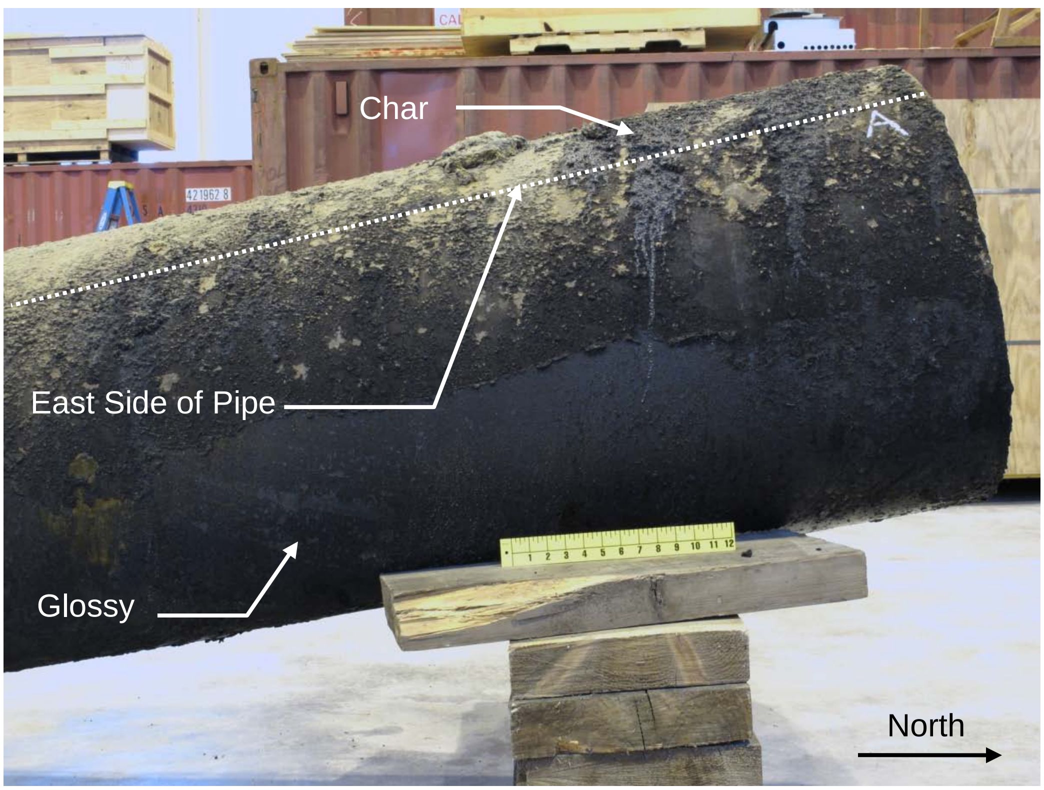


Figure 12: Condition of the asphalt coating on the northern section; a) Top of pup 5 adjacent to the girth weld fracture; b) Away from the fracture close to the cut end.



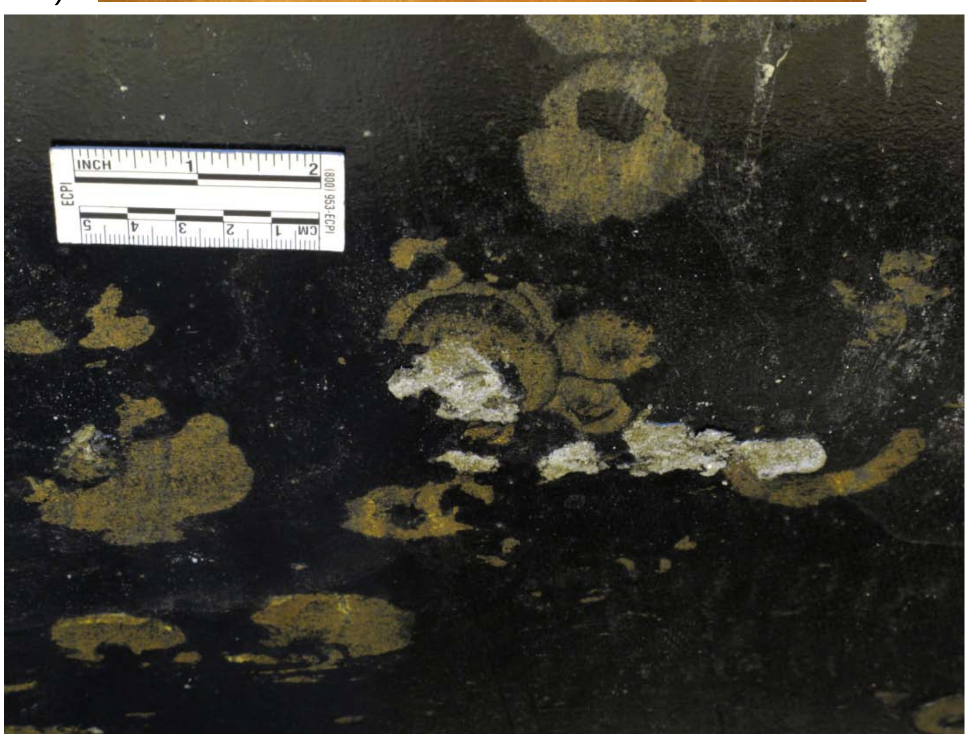
a)



b)

Figure 13: Condition of the asphalt coating on the center section; a) East side / bottom of long joint and pup 1; b) East side / bottom of pup 4 adjacent to girth weld fracture.

a)



b)

Figure 14: Examples on the underside of the center section where no coating was observed; a) Underside of pup 4 near the girth weld fracture; b) Underside of long joint to the south of pup 1.

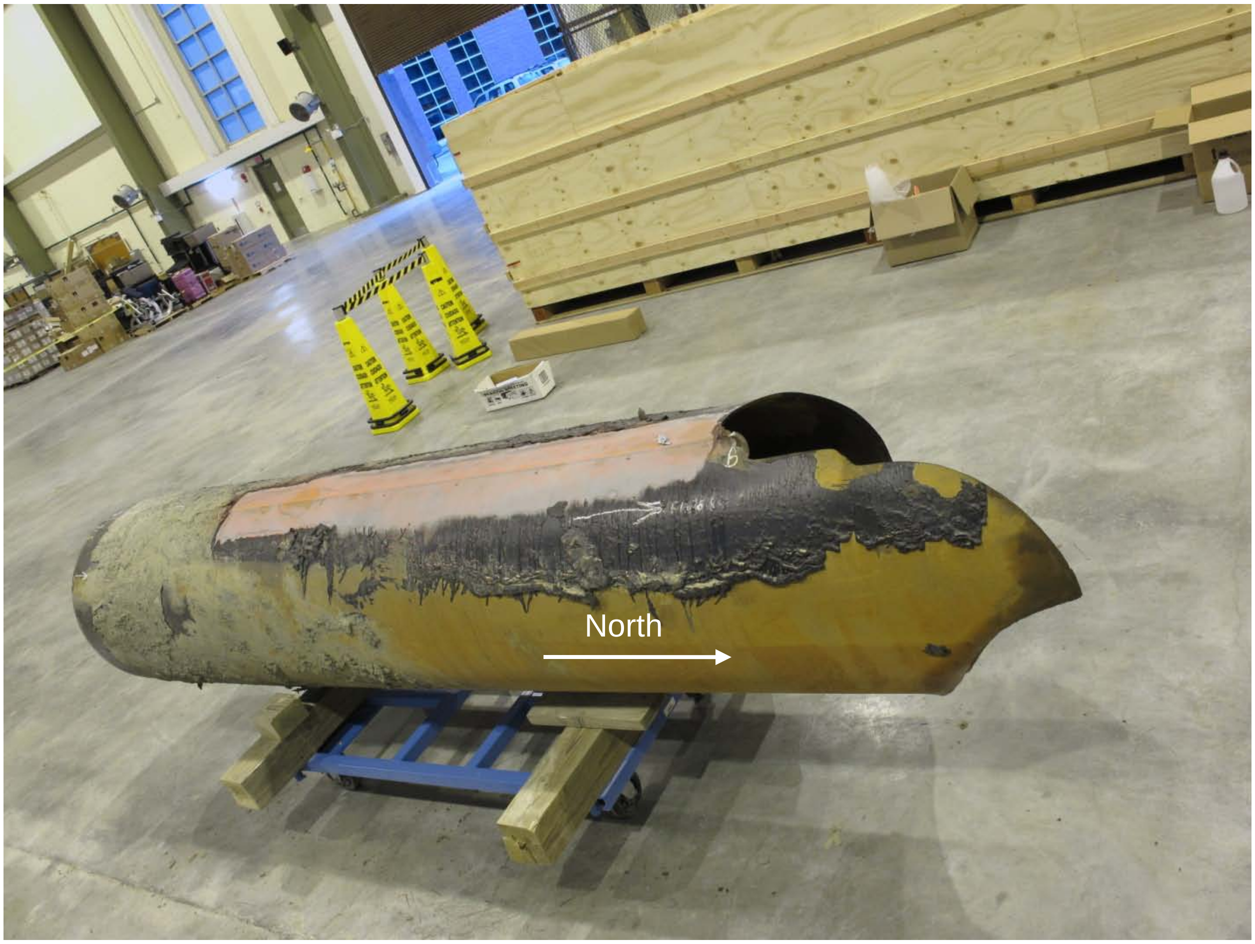


Figure 15: Condition of the southern section of pipe after grit blasting and magnetic particle inspection.

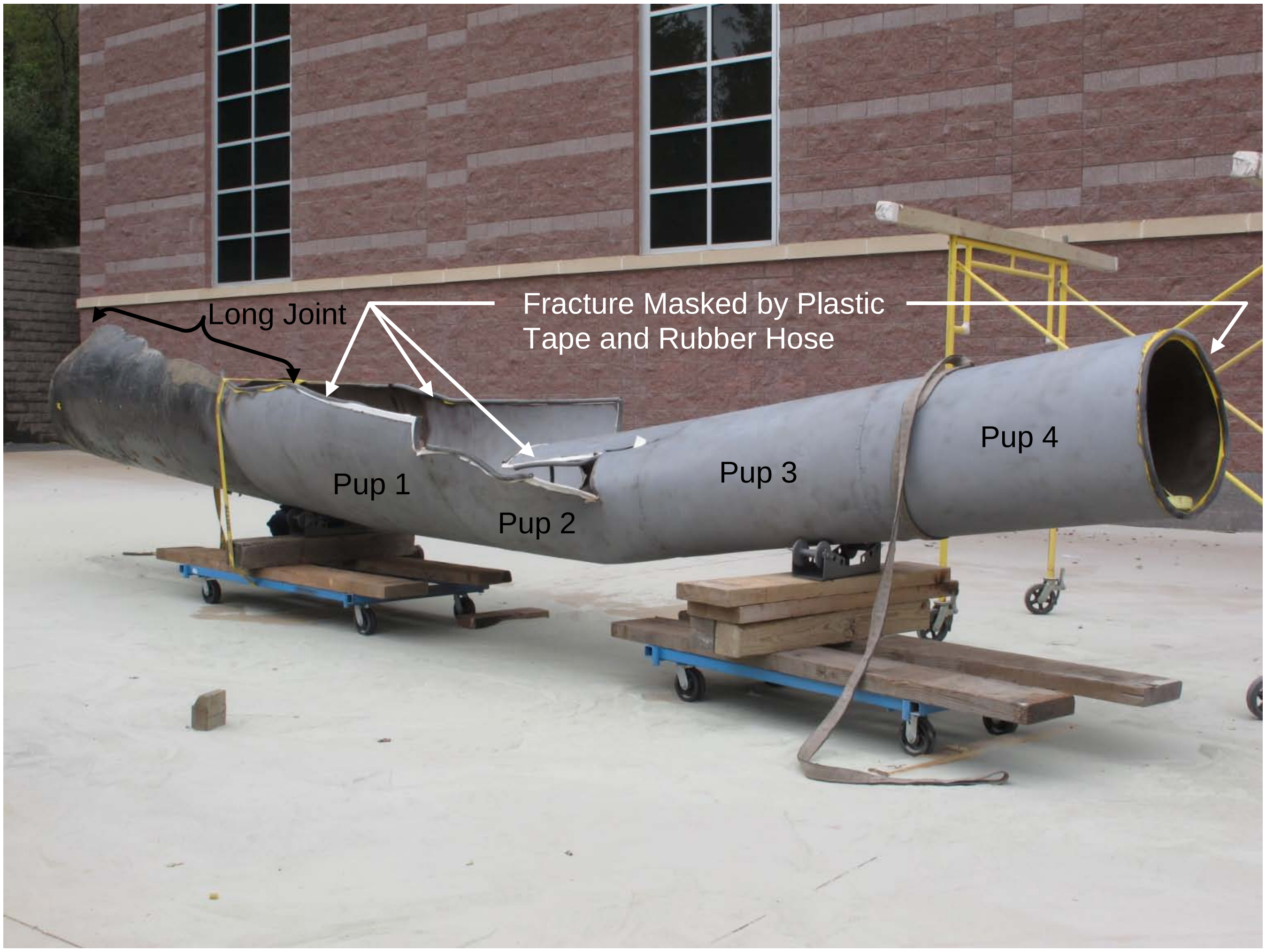


Figure 16: Condition of the center section of pipe after grit blasting.

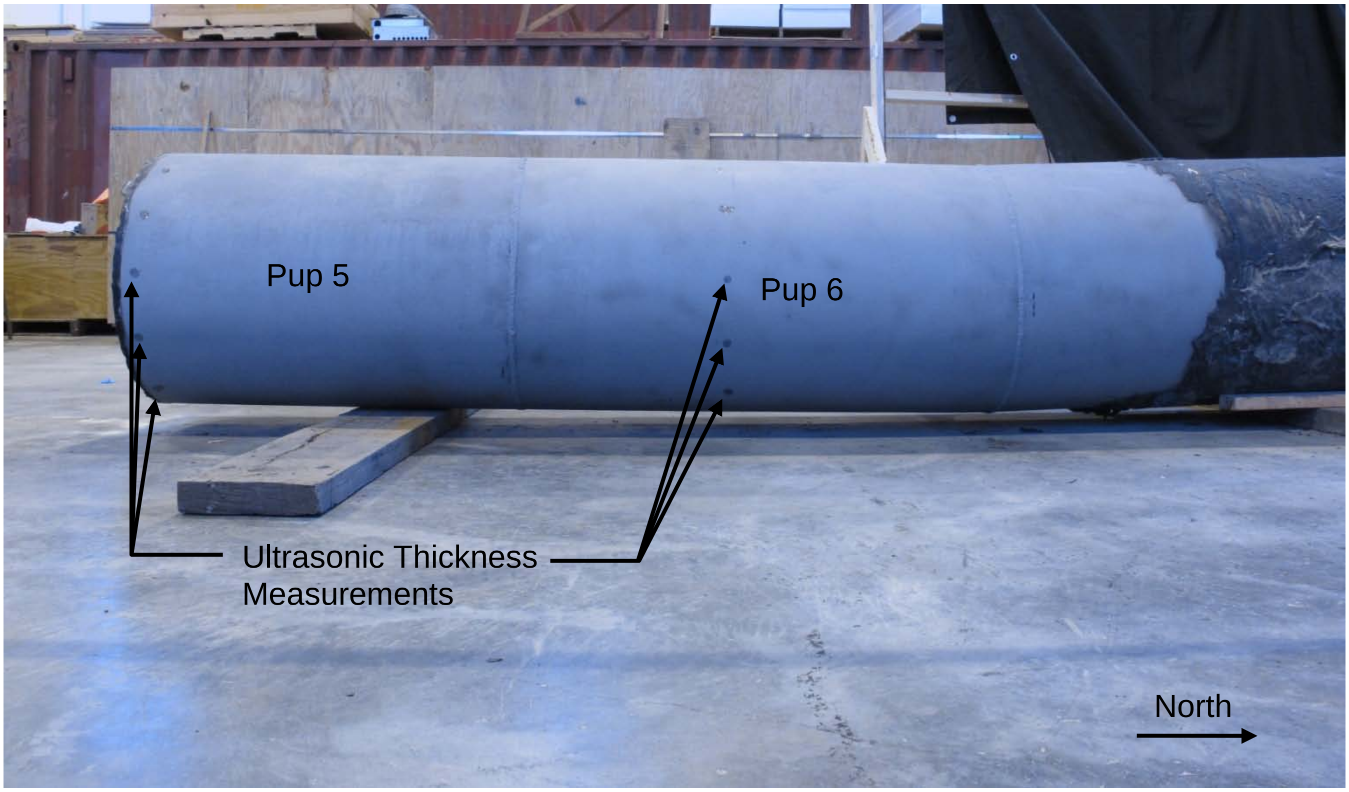


Figure 17: Condition of the northern section of pipe after grit blasting. Dots of gel from the ultrasonic thickness measurements are visible on pup 5 and pup 6.

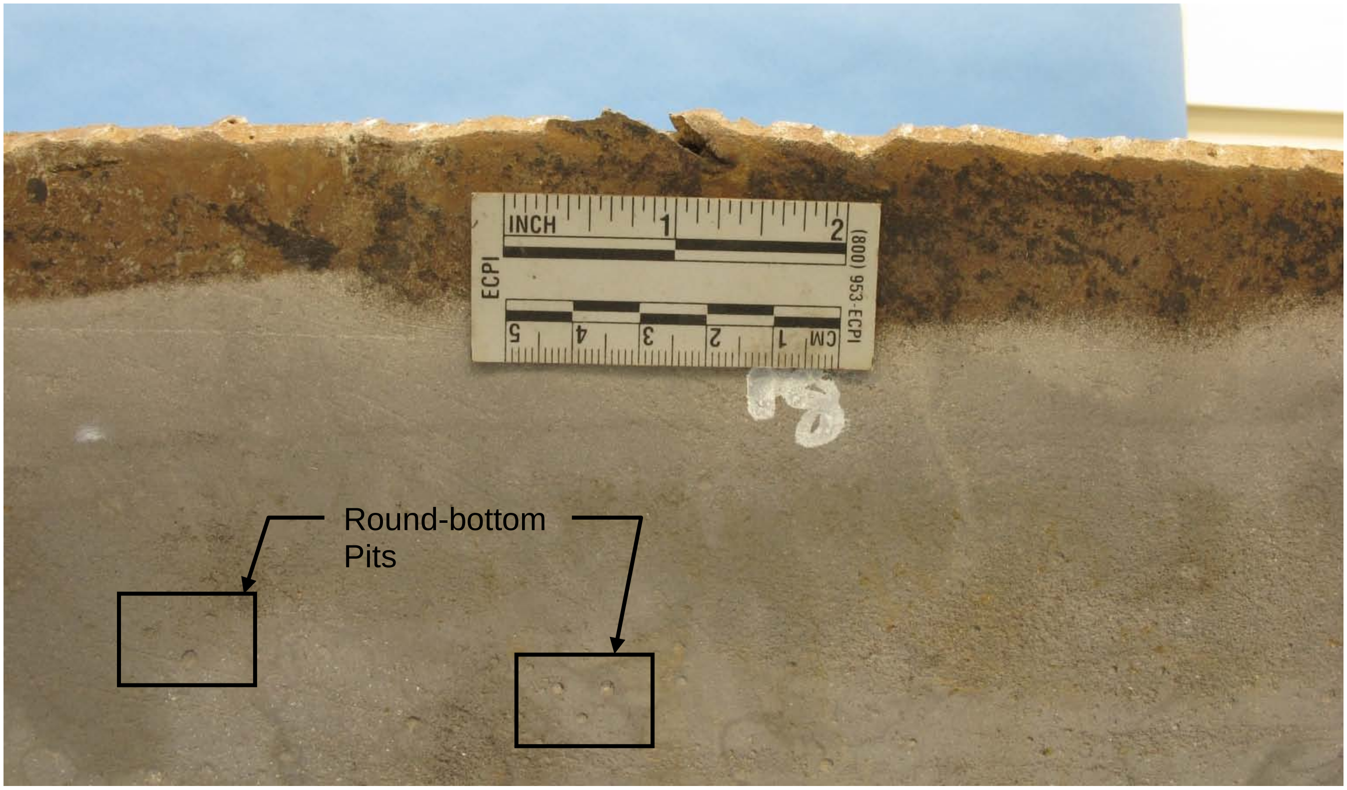
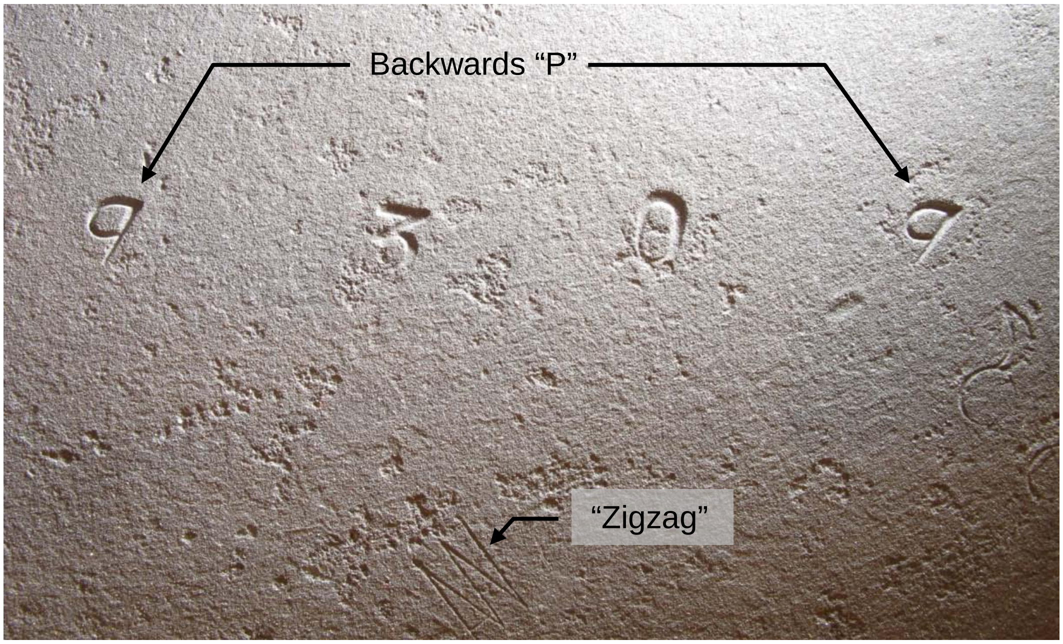
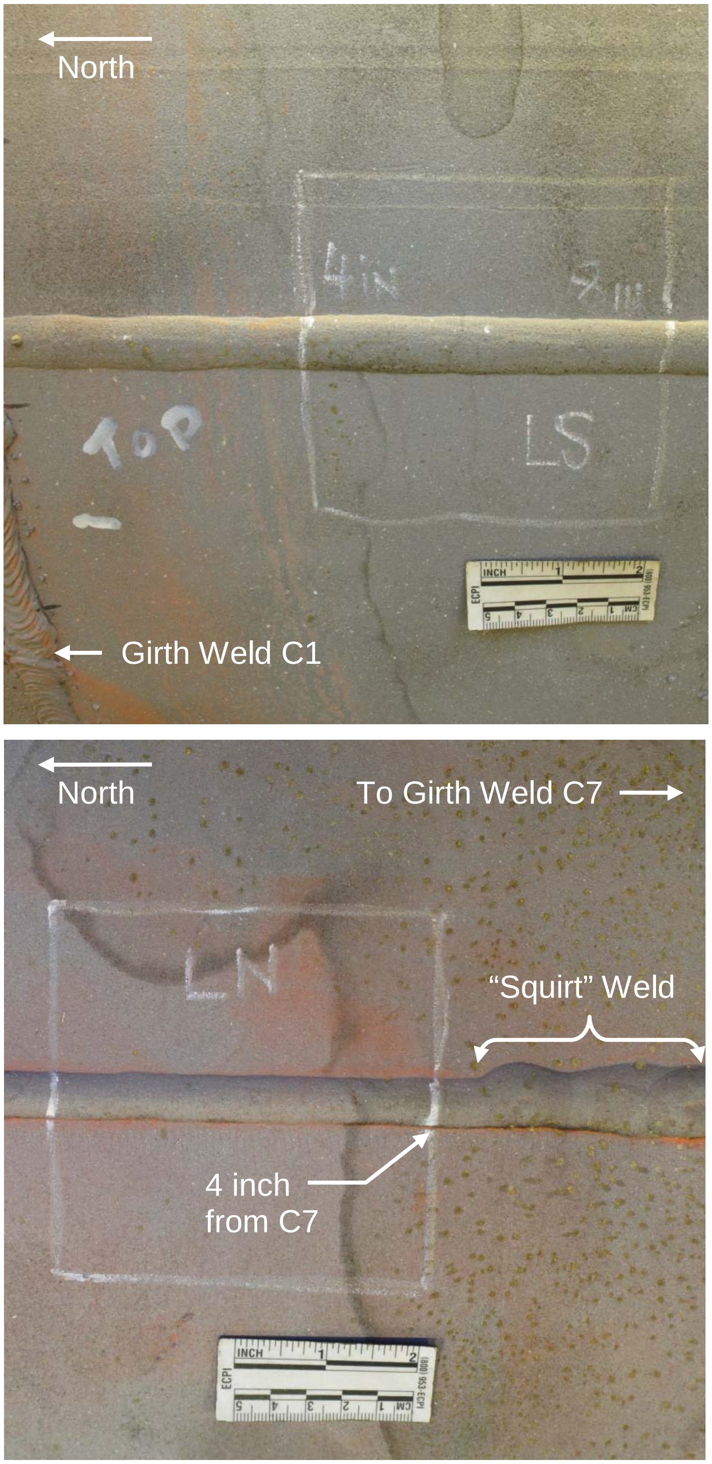


Figure 18: Photograph of pup 2 on the outer diameter adjacent to the longitudinal fracture after grit blasting, magnetic particle inspection, and manual laboratory cleaning of the surface.

a) 

b) 

Figure 19: Pipe markings found on pup 4; a) The number “30”, backwards “P” and five lines forming a “Zigzag”; b) Marking forming a circle and half-moon.



a) b)

Figure 20: a) Outer weld bead on the long joint south of pup 1. There was no apparent "squirt" weld adjacent to girth weld C1; b) Outer weld bead on the long joint north of pup 6. There was an apparent "squirt" weld adjacent to girth weld C7. The photographs are taken after grit blasting and magnetic particle inspection and prior to sample removal for cross-section metallography.

a)
b)

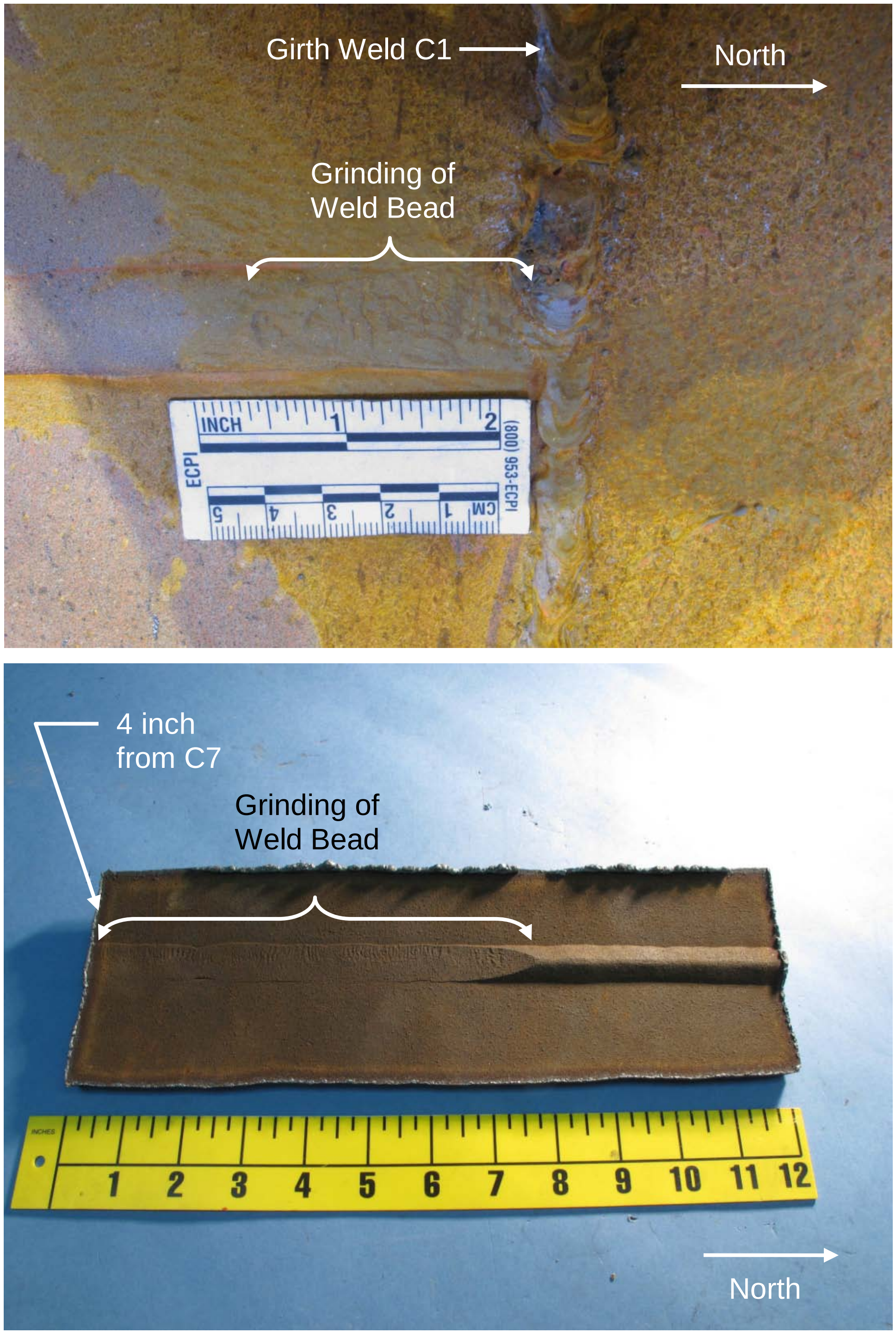
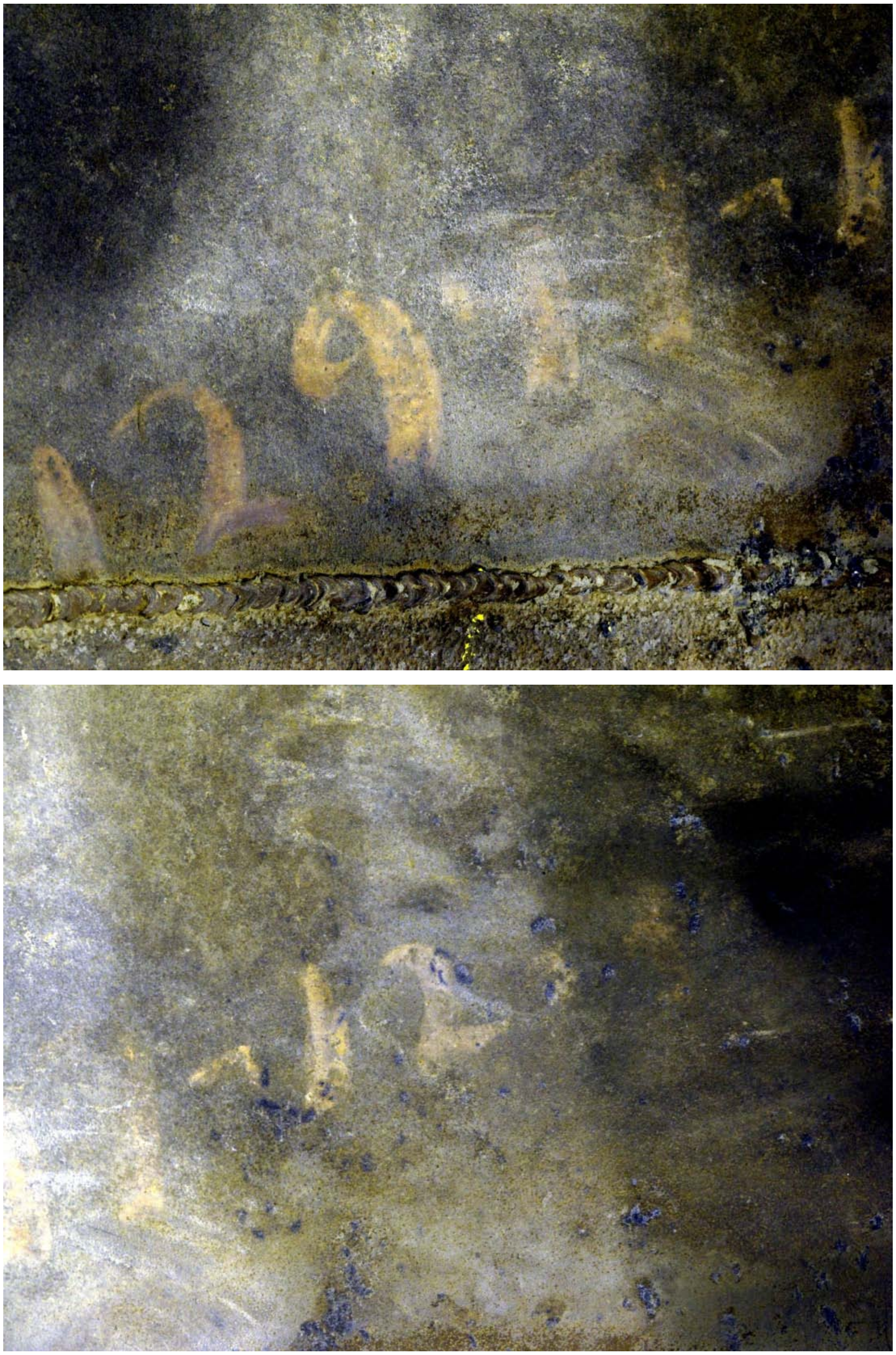


Figure 21: a) Inner weld bead on the long joint south of pup 1. The weld bead was ground over 1.75 inch. The photograph was taken after grit blasting and magnetic particle inspection; b) Inner weld bead on the long joint north of pup 6. The weld bead was ground over approximately 12 inch. The photograph was taken in the laboratory after the section of pipe was removed using a plasma cutter.



a)

b)

Figure 22: Photographs of number painted on the inside of the long joint south of pup 1. The contrast has been altered to enhance the visibility of the numbers.

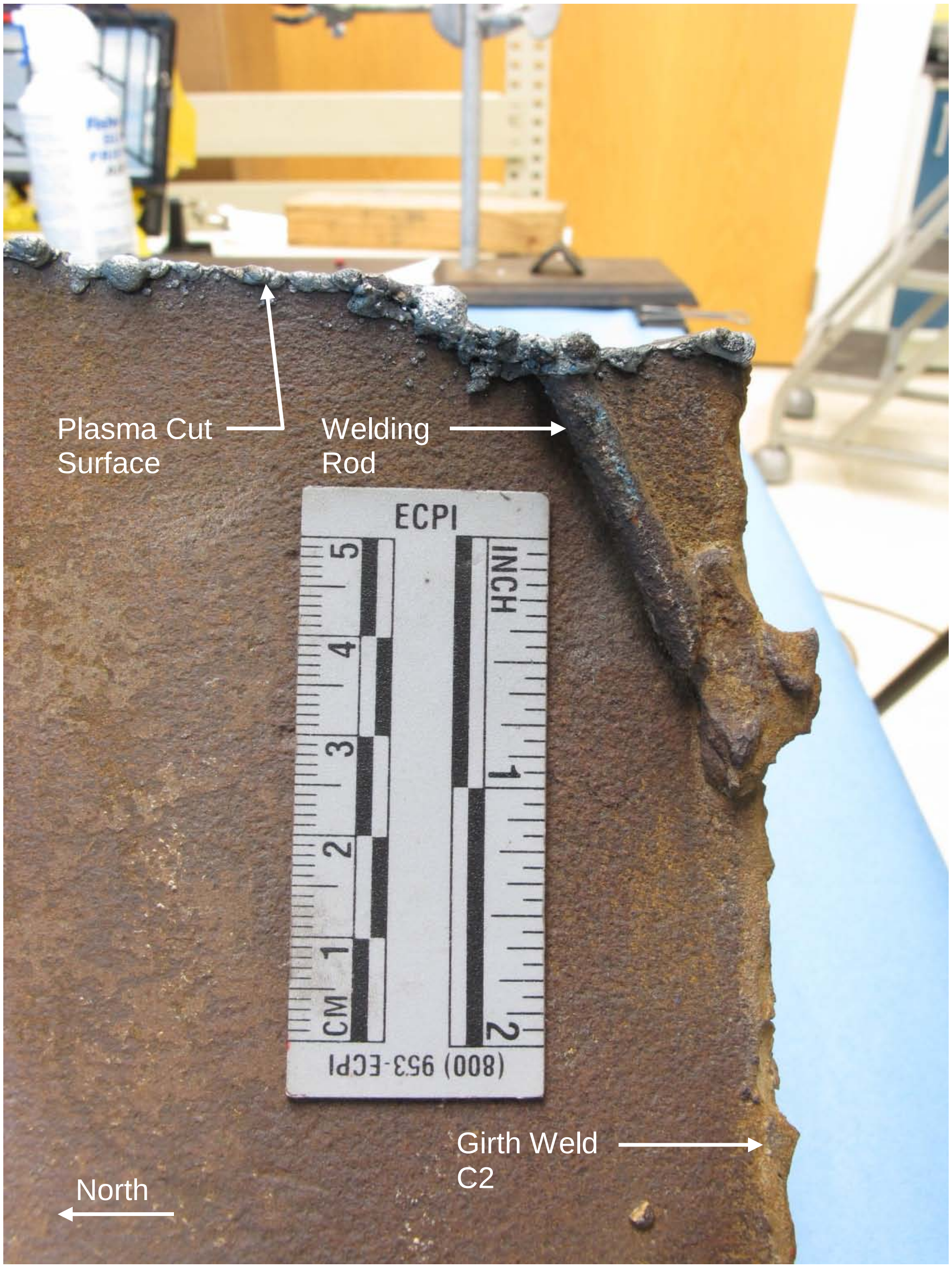


Figure 23: Laboratory photo showing length of welding rod fused to the inside of the C2 girth weld on the inner diameter of pup 2.

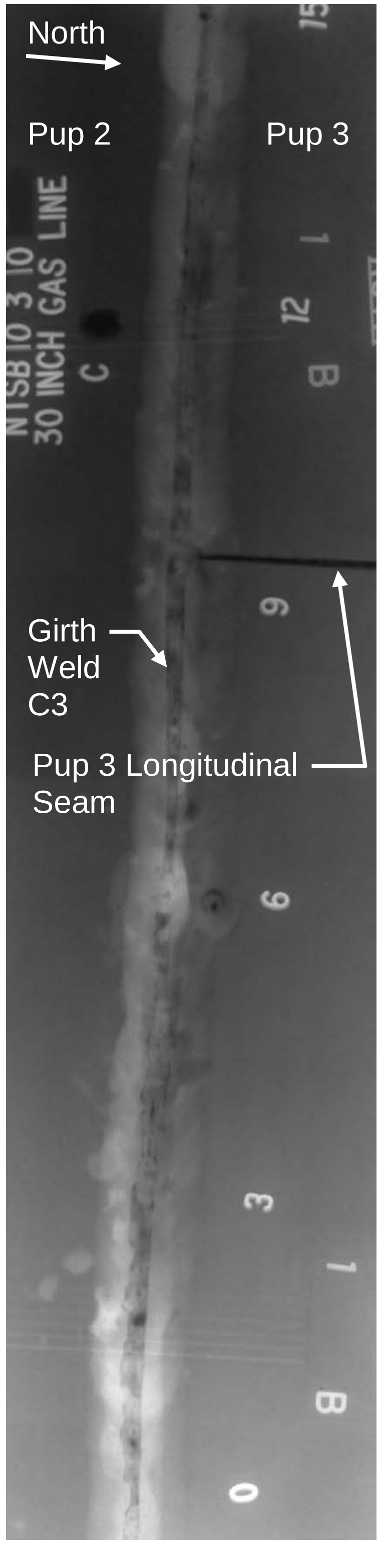
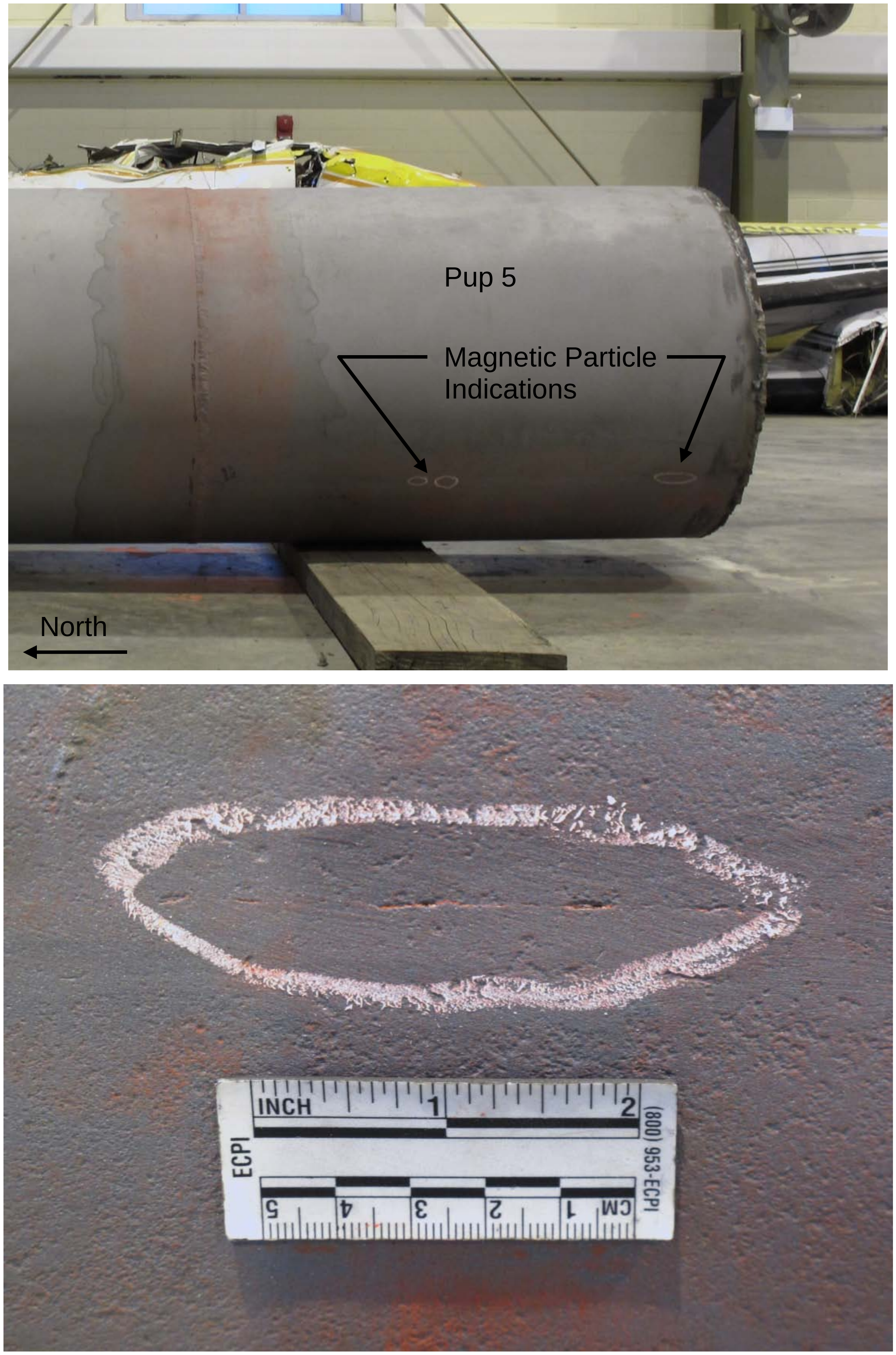


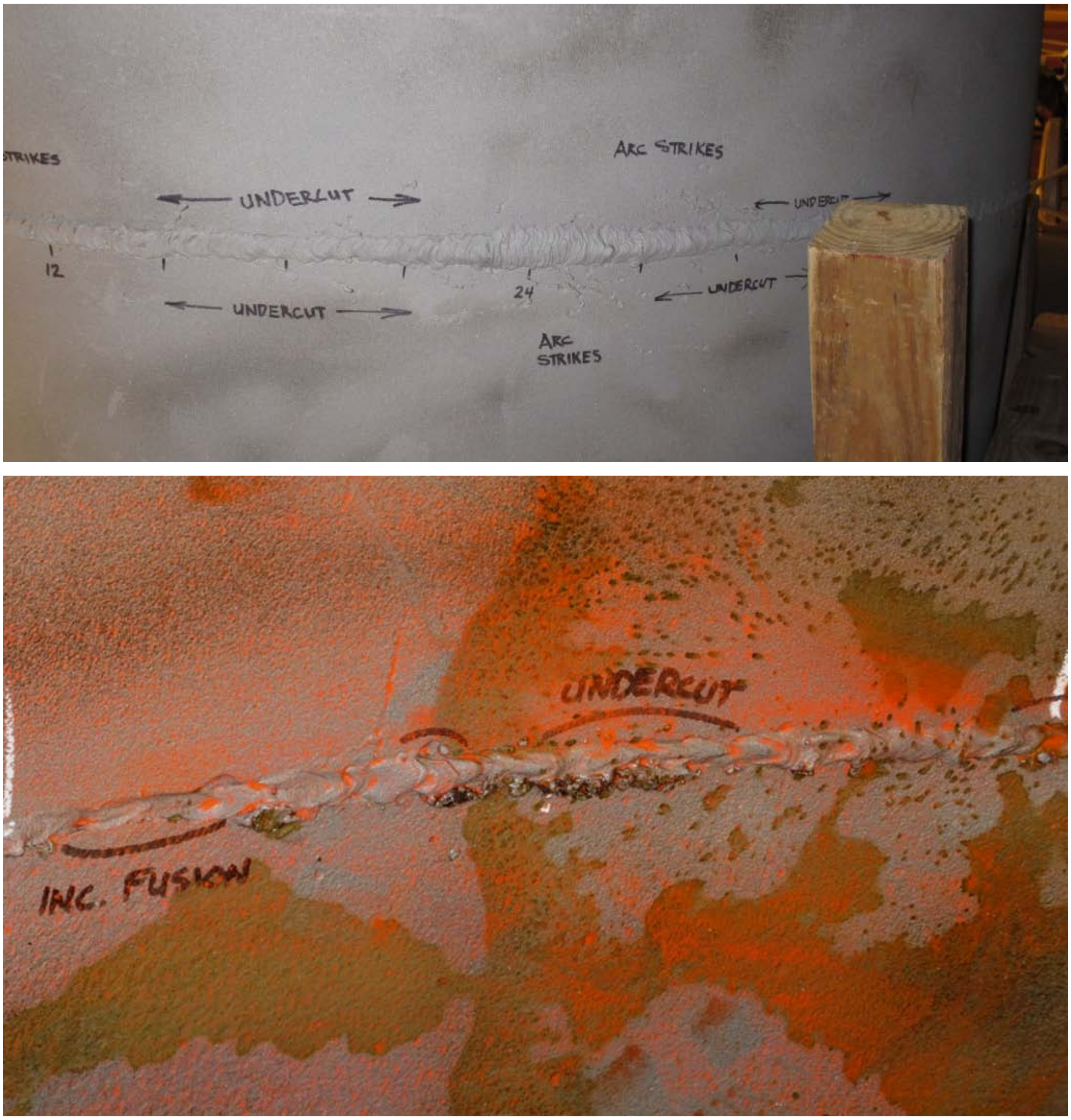
Figure 24: Radiograph of girth weld C3 from 0 inch – 15 inch (see Table B2) between pup 2 and pup 3. Part of the pup 3 longitudinal seam is visible.

Figure 25: Radiograph of the pup 5 longitudinal seam from 0 inch – 12 inch (see Table B1) adjacent to the C5 girth weld fracture.



a)
b)

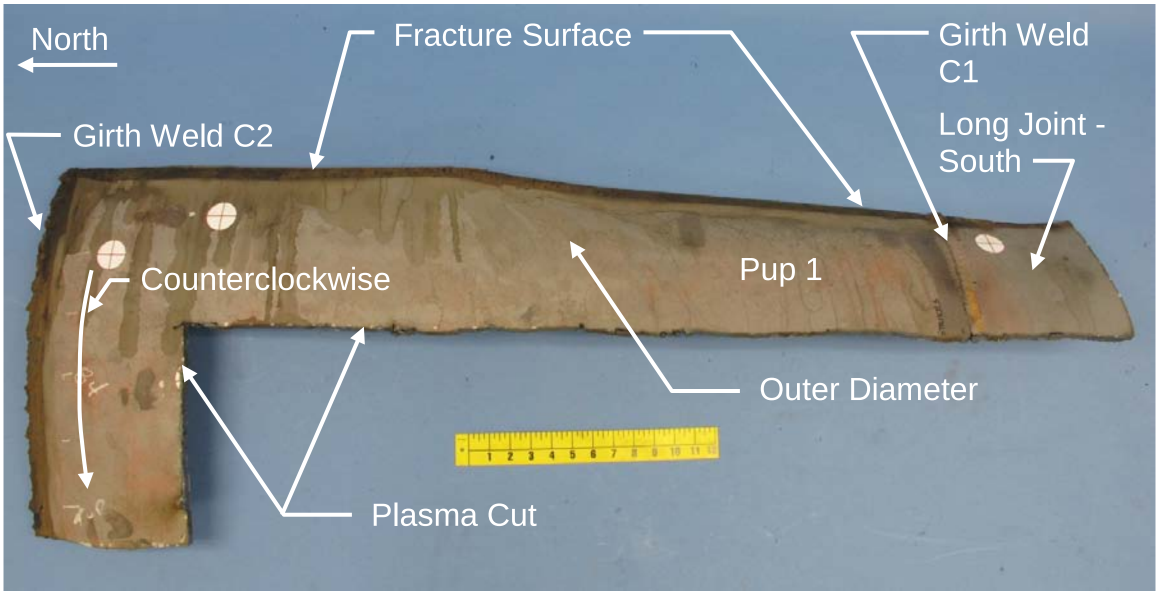
Figure 26: a) Pup 5 showing the location of features detected by magnetic particle inspection; b) Macrophotograph of the feature 5.5 inch north of the C5 girth weld.



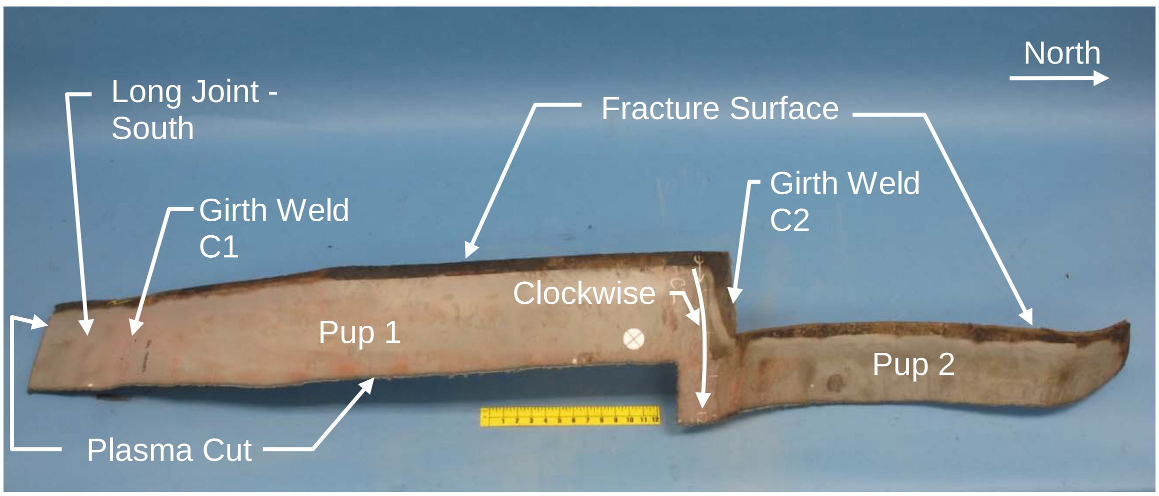
a)

b)

Figure 27: a) Weld imperfections indicated by visual examination on the external surface of girth weld C1; b) Weld imperfections indicated by visual examination on the internal surface of girth weld C2. The photograph was taken after magnetic particle inspection.



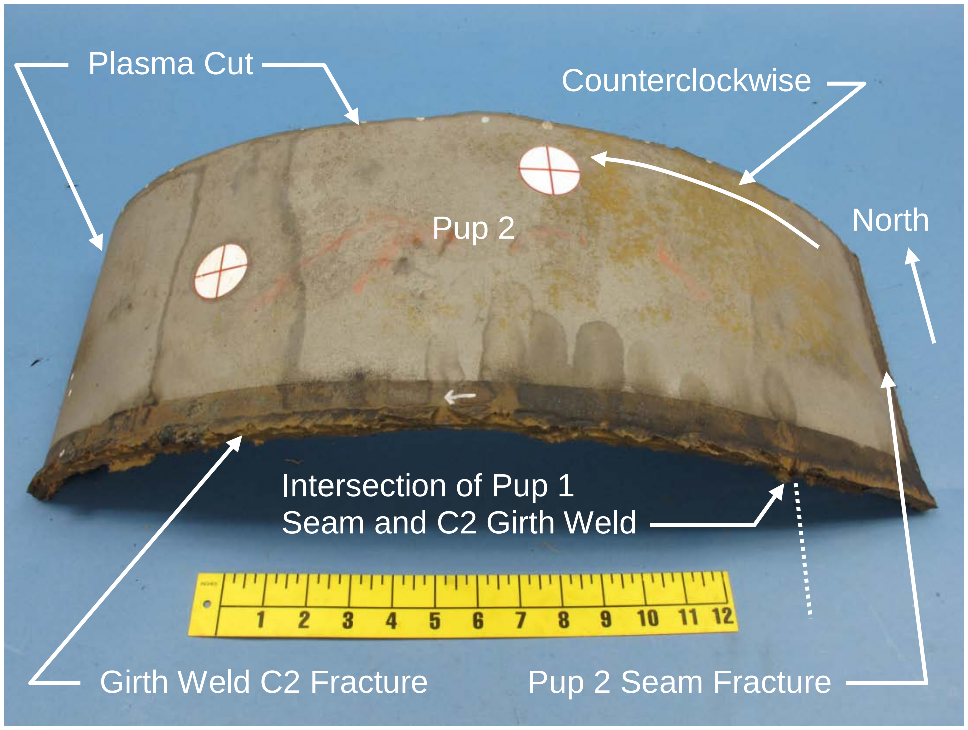
a)



b)

Figure 28: Laboratory photos of the sections cut from the pipe for fractographic examination; a) Pup 1 counterclockwise fracture surface; b) Pup 1 and pup 2 clockwise fracture surface;

c)



d)

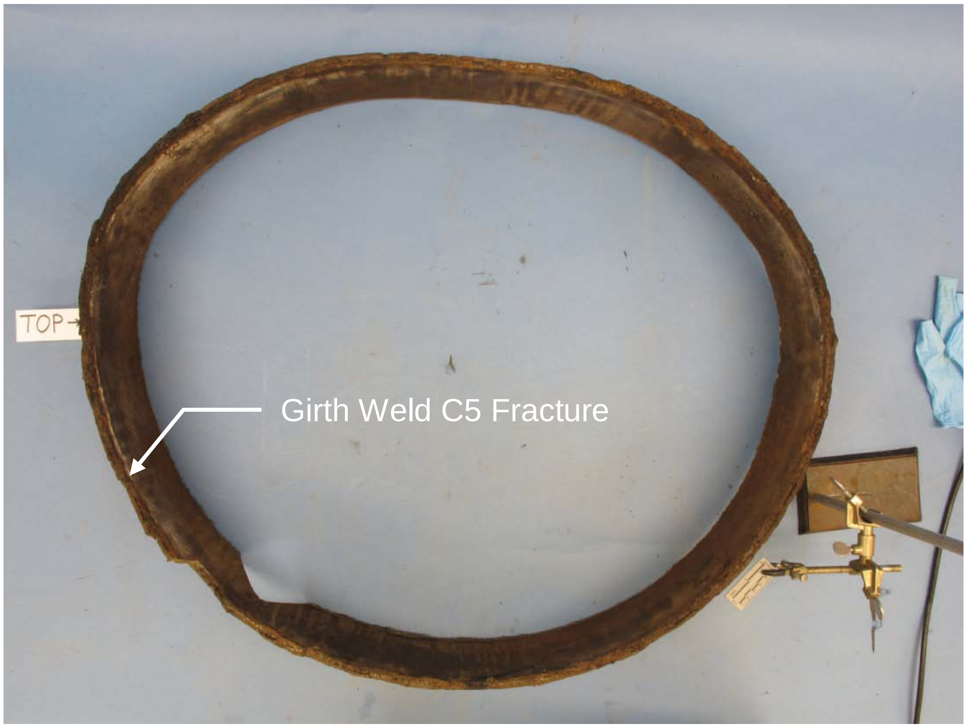


Figure 28 (cont.): c) Section taken from pup 2; d) Ring cut from north end of pup 4 containing girth weld C5 fracture.

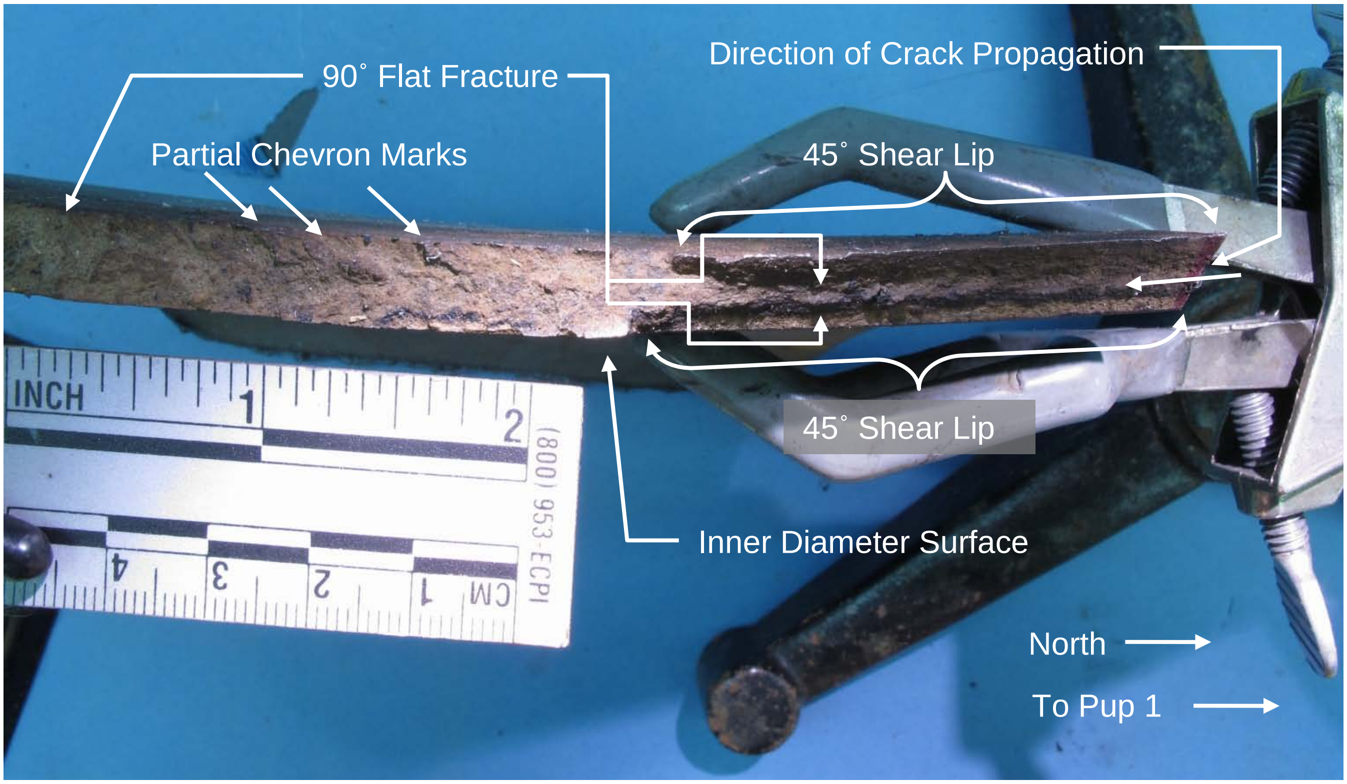


Figure 29: Counterclockwise fracture surface on the long joint south of pup 1 (see figure 28a). Partial chevron marks and 45˚ shear lips on the inner and outer wall were consistent with overstress fracture emanating from pup 1.

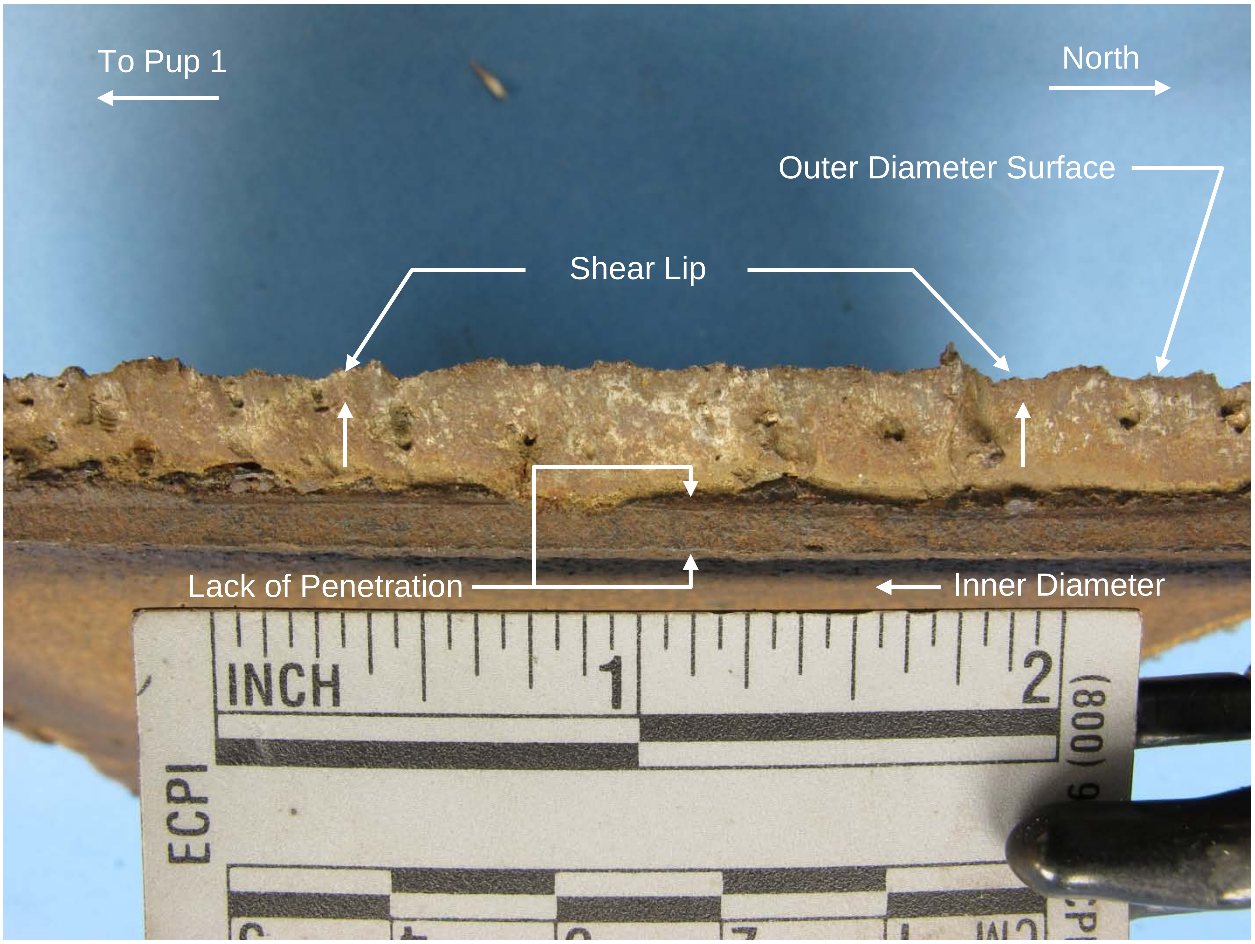


Figure 30: Counterclockwise half of longitudinal fracture on pup 2 (see figure 28c). Out of plane shear was observed along the longitudinal seam.

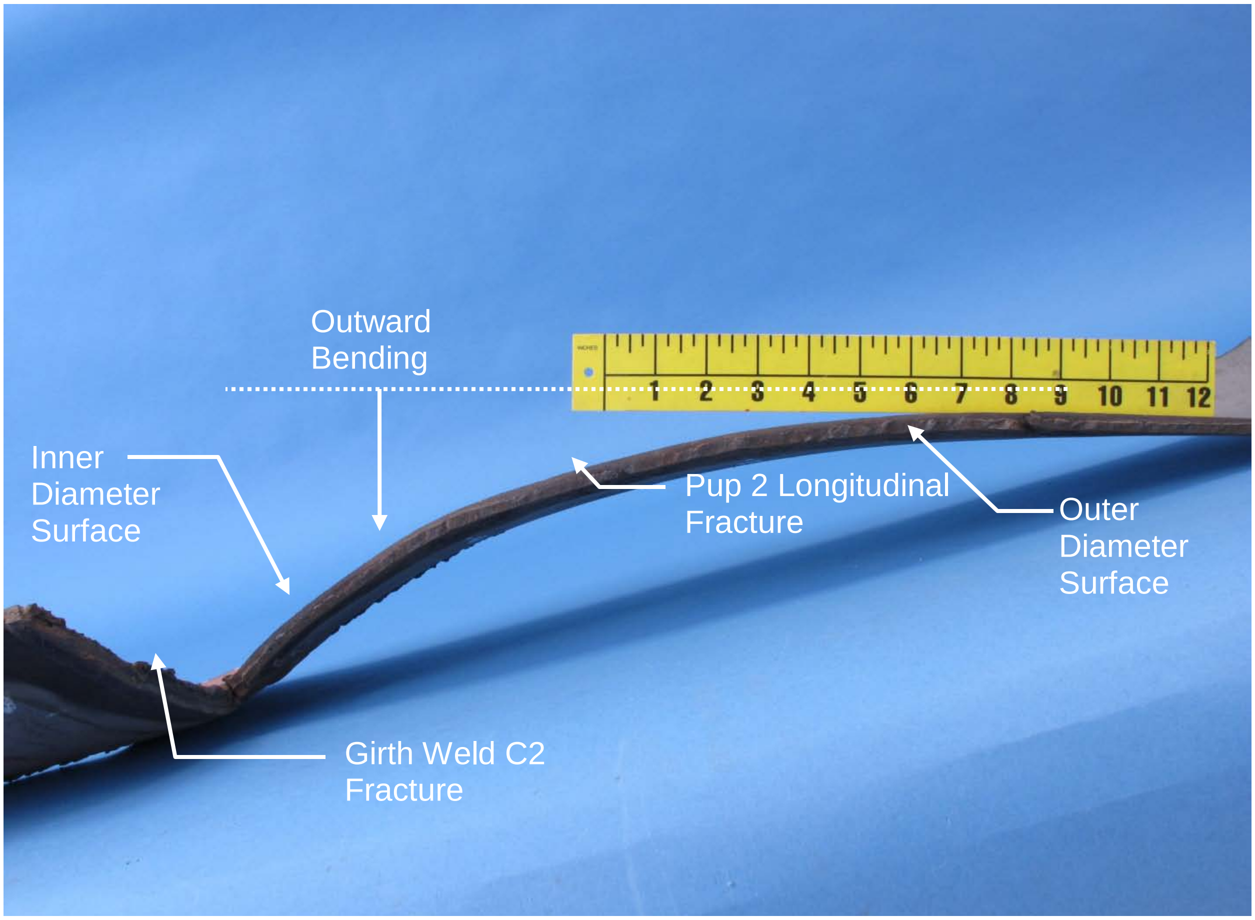


Figure 31: Clockwise half of pup 2 fracture viewed in the transverse direction. The wall was bent radially outward with the highest curvature at girth weld C2 and decreased continuously to a straight wall at mid length.

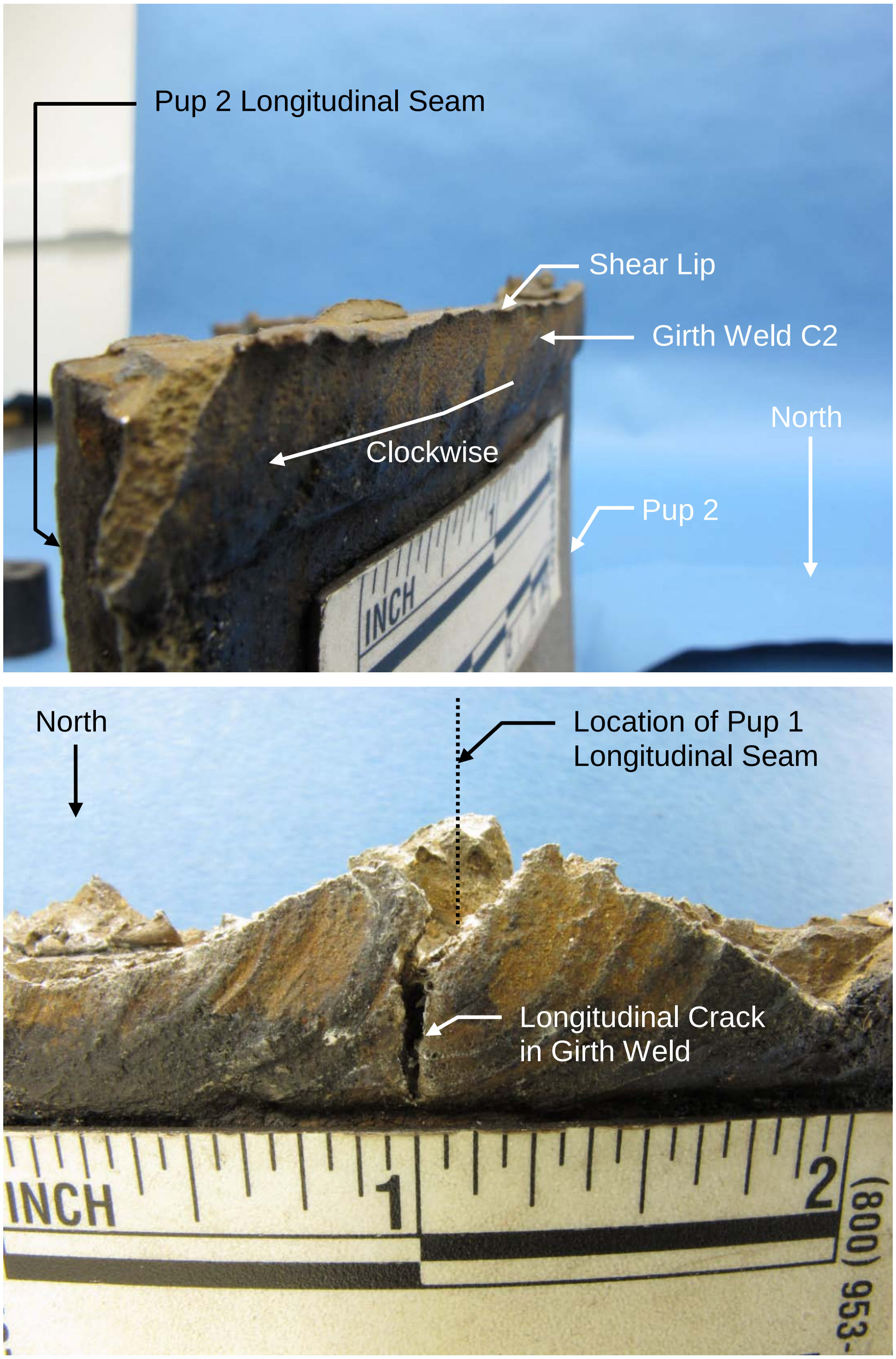
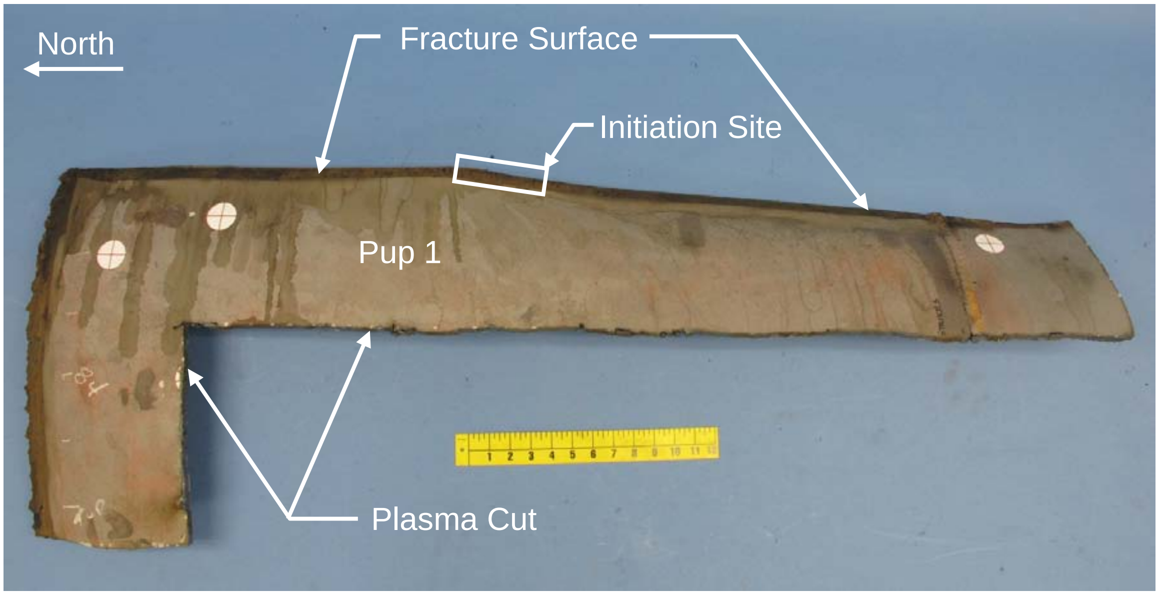
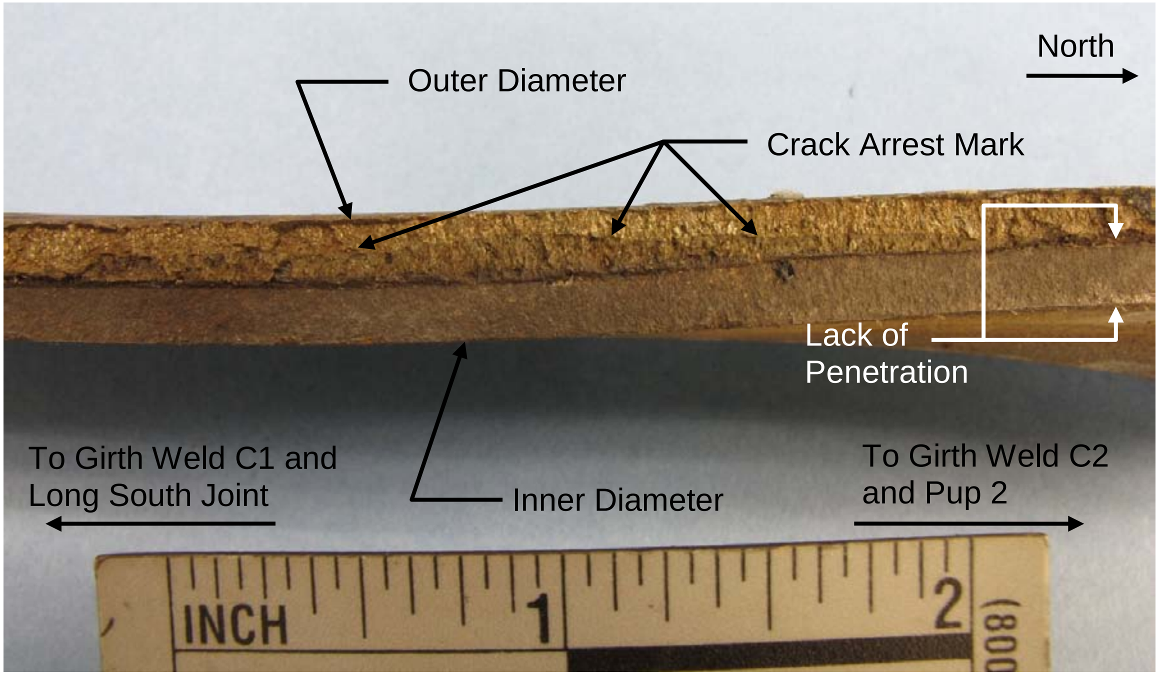


Figure 32: a) Shear lip on girth weld C2 fracture surface approaching the pup 2 longitudinal seam; b) Longitudinal crack in girth weld C2 in line with the longitudinal seam in pup 1.



a)



b)

Figure 33: a) Counterclockwise half of pup 1 longitudinal fracture with the location of the crack initiation site indicated; b) cross section view of the longitudinal seam at the initiation site.

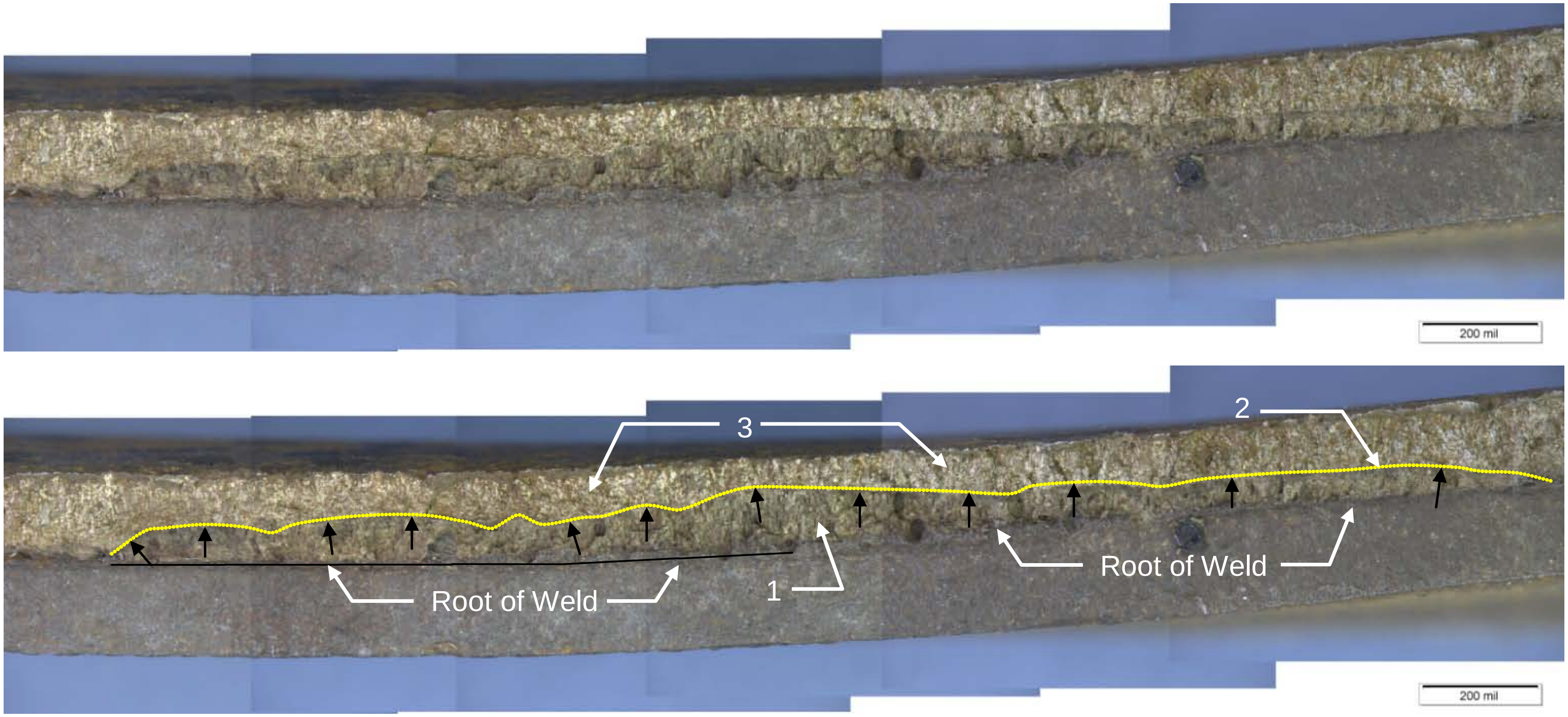


Figure 34: Optical micrographs of the fracture initiation site in pup 1. Top: Unlabelled micrograph, Bottom: Same micrograph with a crack arrest mark indicated by a yellow dotted line and the three fracture surface morphologies identified by scanning electron microscopy, 1 - ductile overstress (dimple rupture), 2 – progressive fracture, 3 –quasicleavage. The black arrows indicate the approximate direction of crack propagation. Note: The micrographs were taken after an inhibited acid solution was used to remove iron oxides.

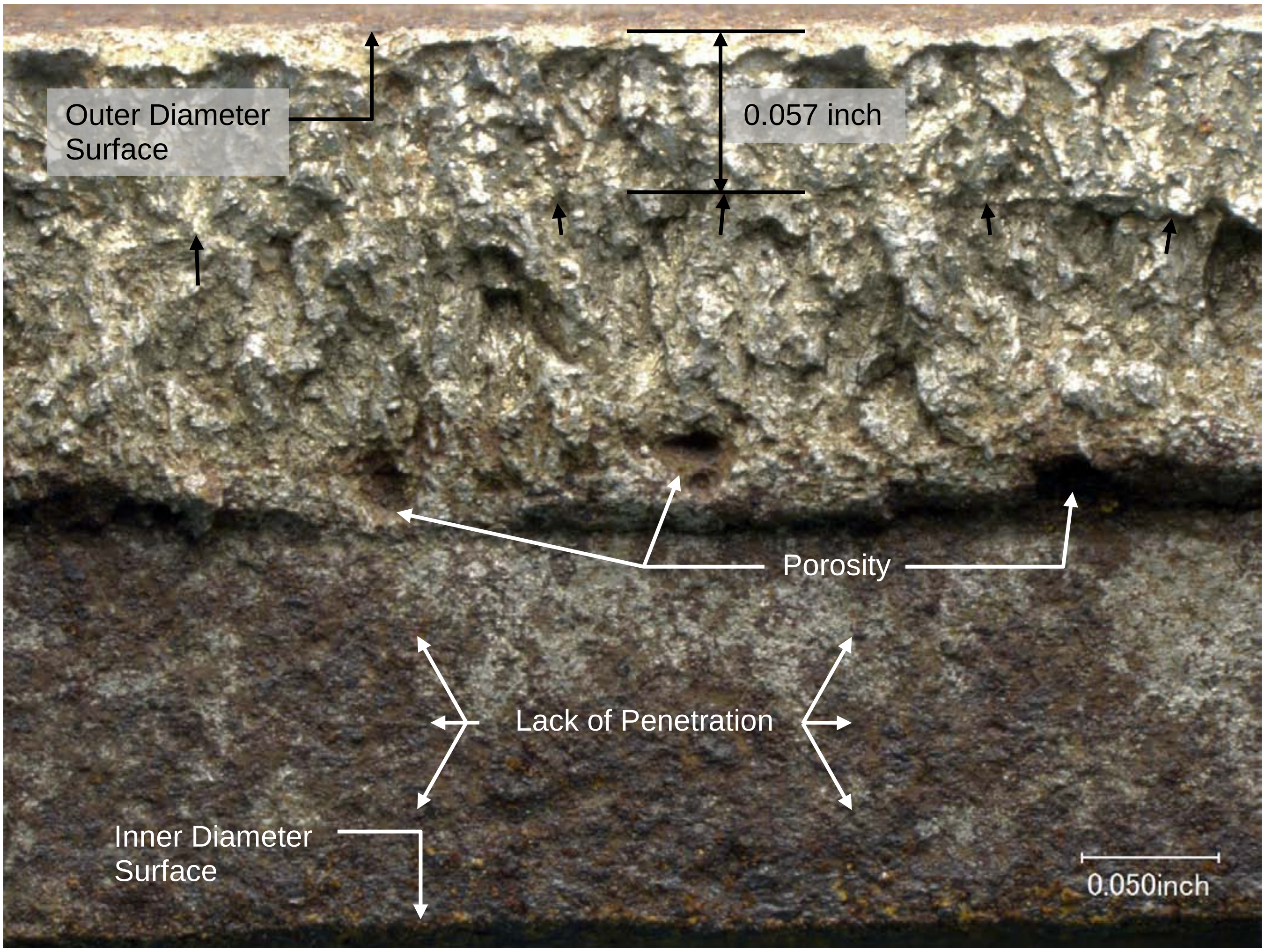


Figure 35: Micrograph of the initiation site in pup 1 at the 21.4 inch mark, the deepest point of the crack arrest mark. The profile of the arrest mark is indicated by the black arrows.

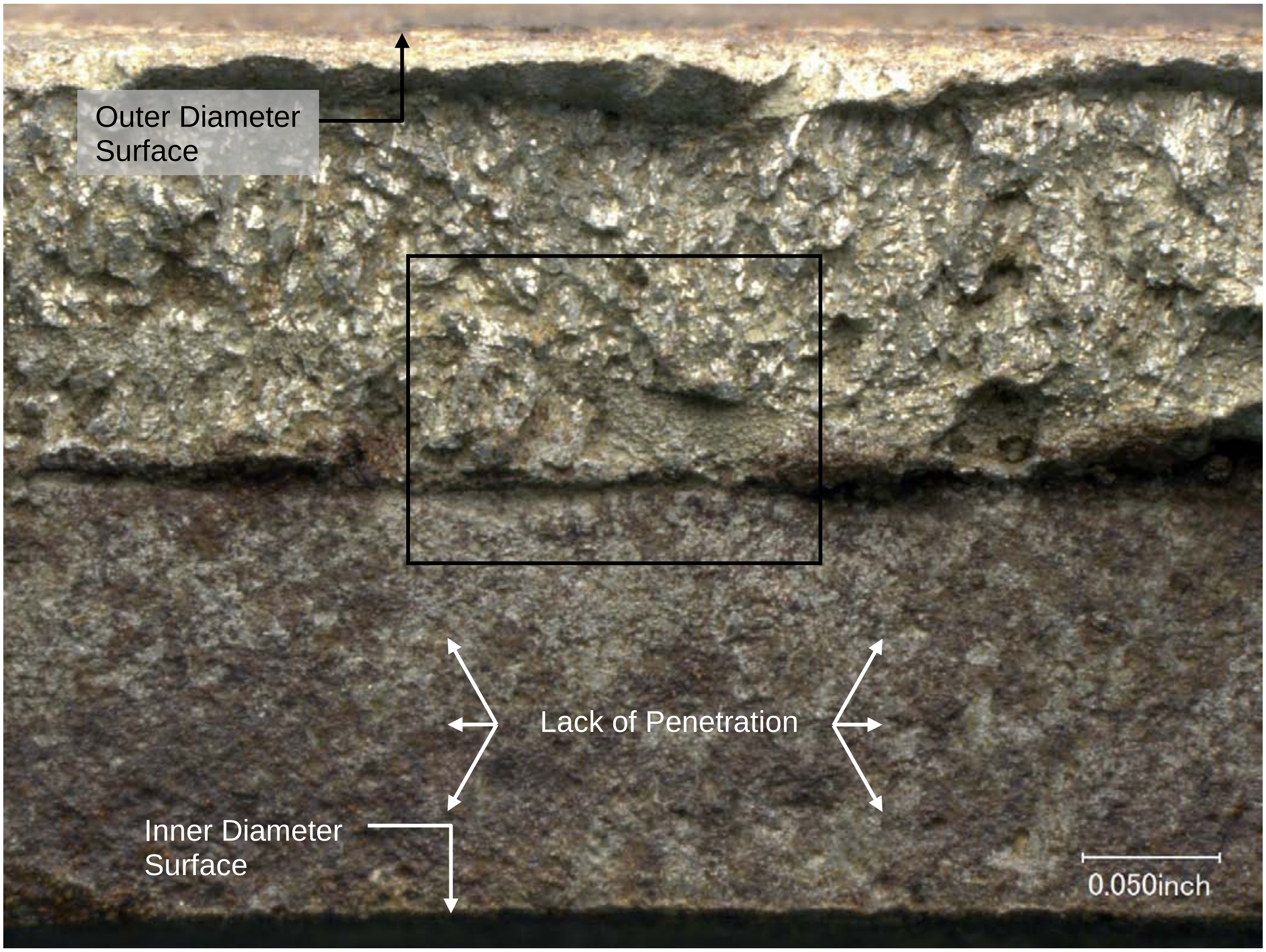


Figure 36: Micrograph of the north end of the initiation site at the 22.7 inch mark. A higher magnification view of the fracture surface in the black box is shown in figure 37.

a)

b)

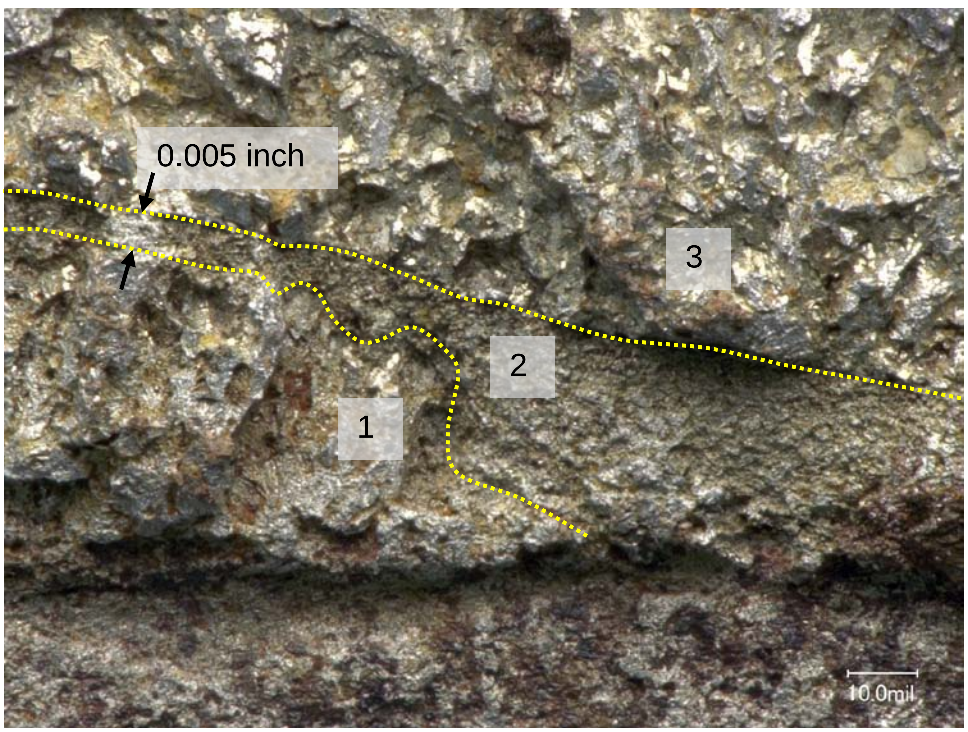


Figure 37: Photomicrograph of the north end of the fracture surface at the 22.7 inch mark. A flat fracture surface region at the crack arrest mark was observed between the yellow dashed lines in the bottom micrograph; a) micrograph without annotations; b) micrograph with annotations.

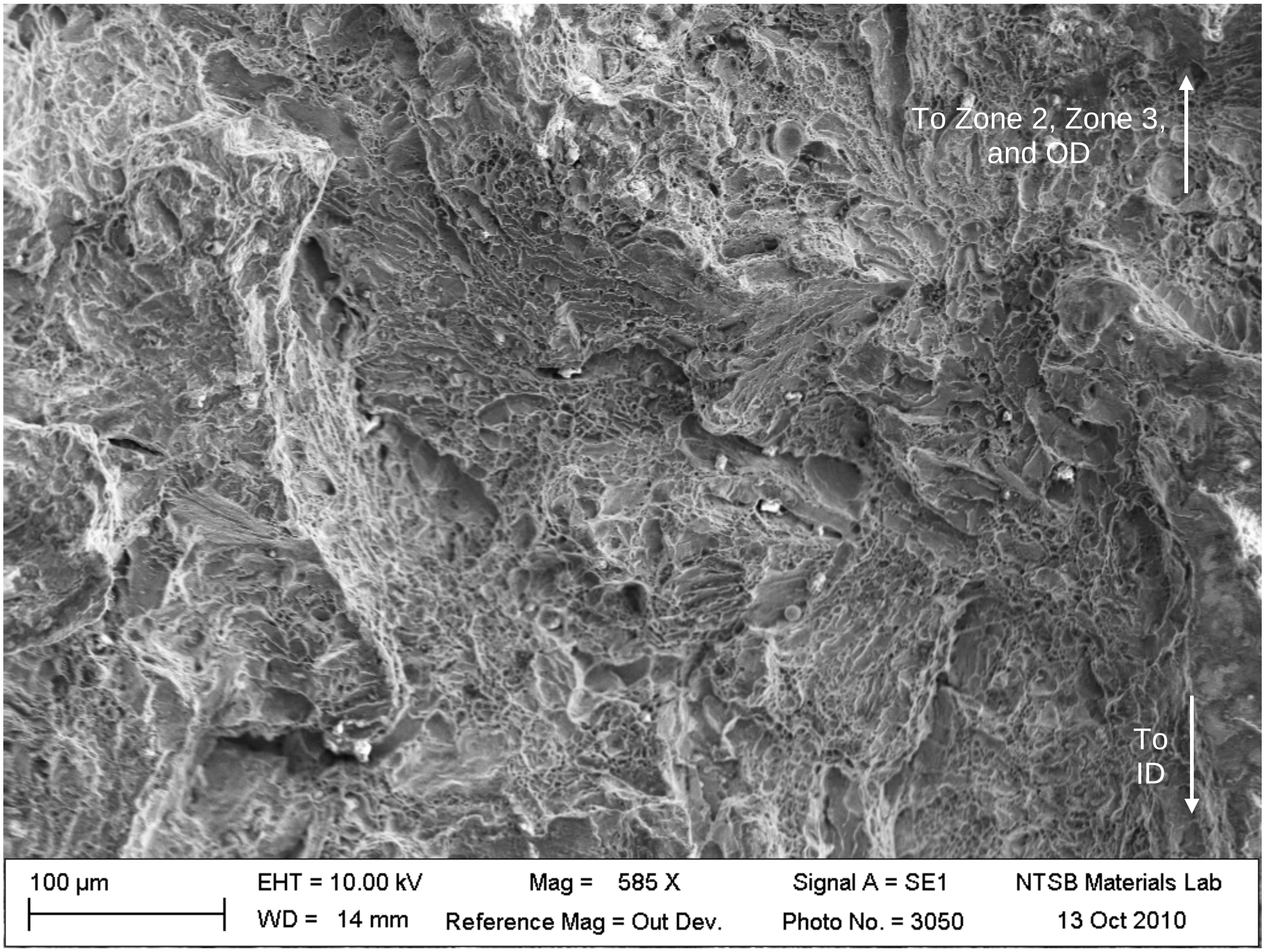


Figure 38: Scanning electron micrograph from zone 1 of the initiation site. Dimples were observed on the fracture surface consistent with ductile fracture.

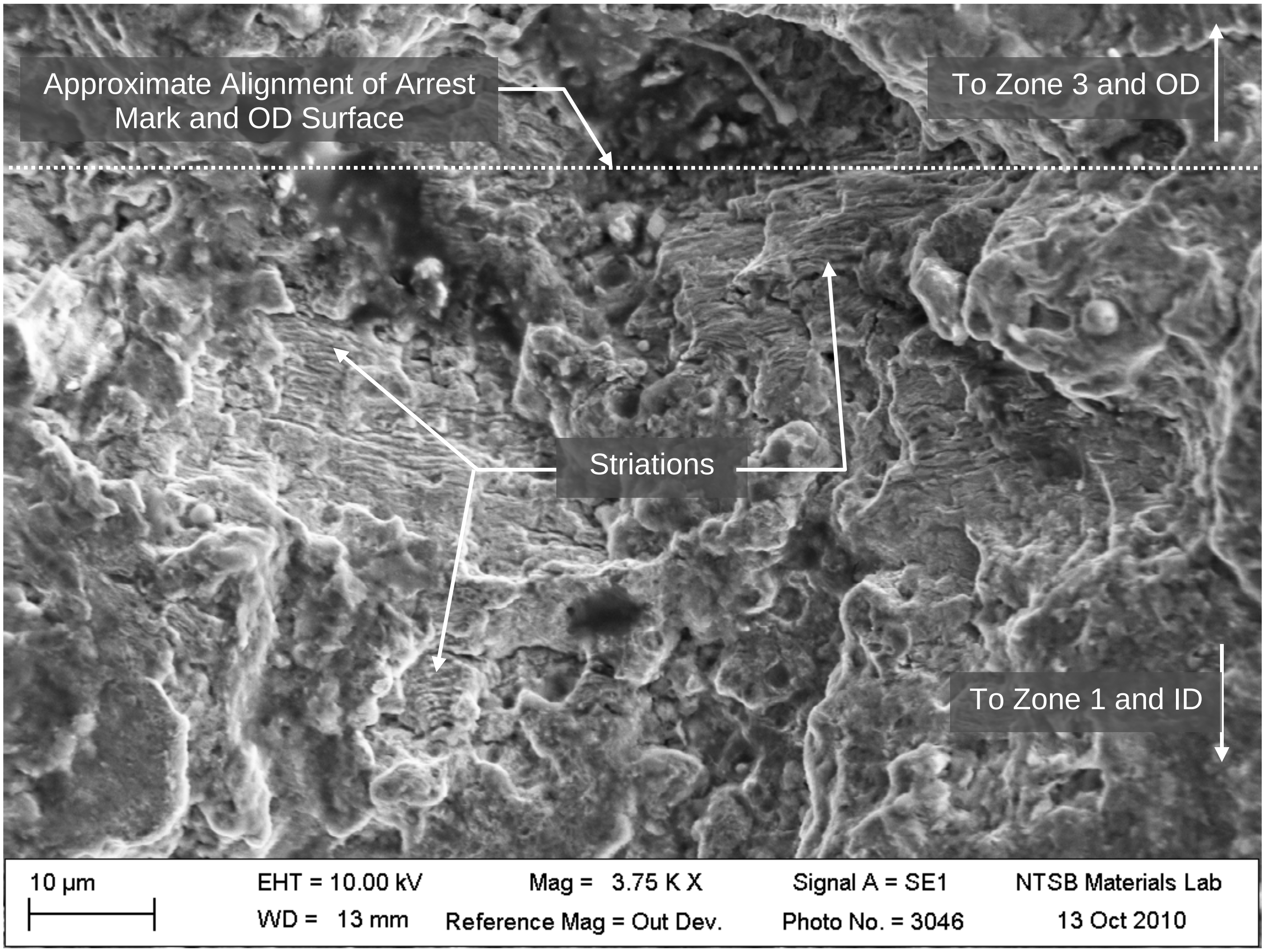


Figure 39: Scanning electron micrograph from zone 2 of the initiation site near the 22 inch mark. Striated features were observed on the fracture surface.

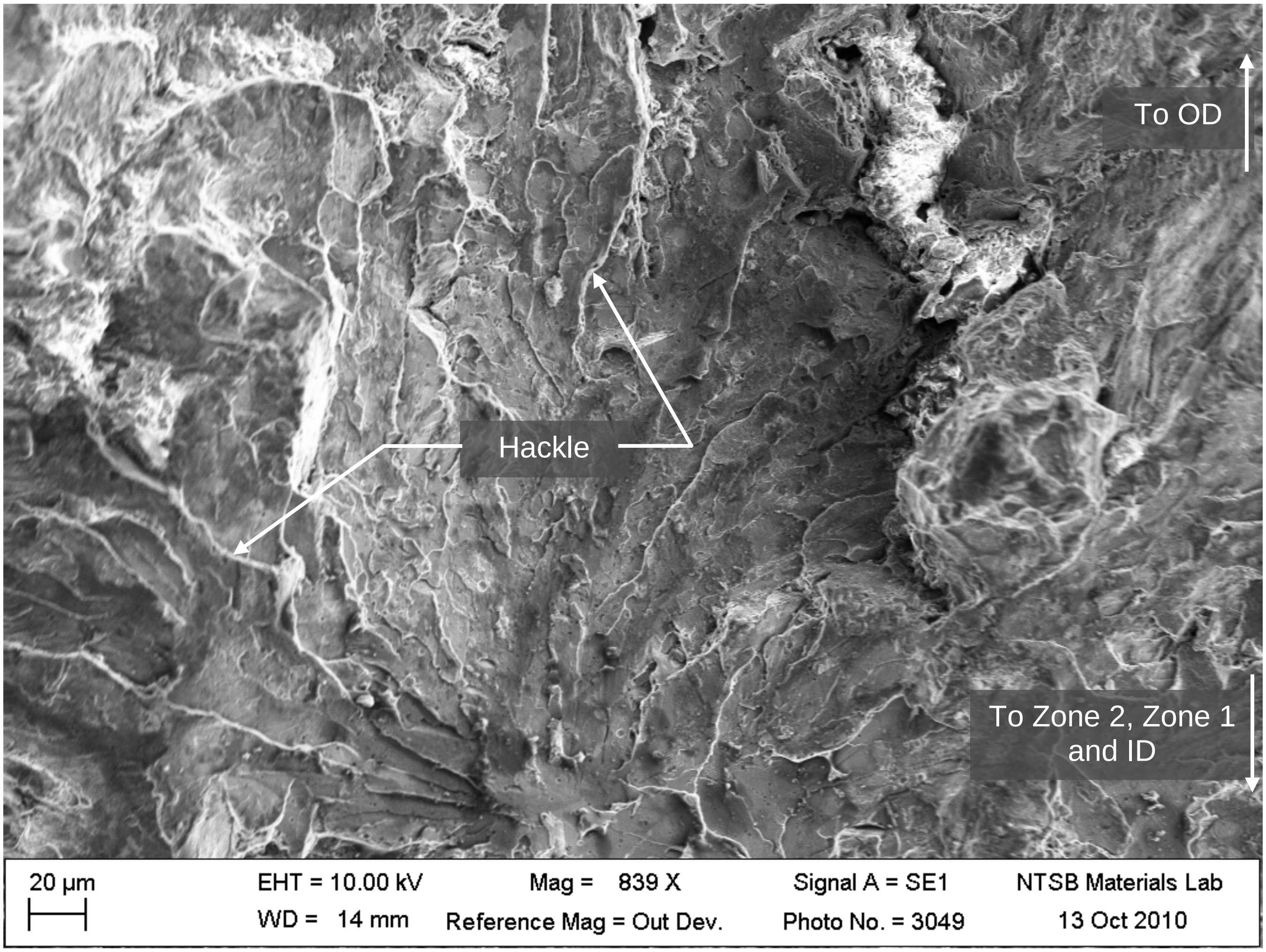


Figure 40: Scanning electron micrograph from zone 3 of the initiation site. The fracture surface had a smooth appearance with hackle marks propagating across the surface consistent with quasicleavage fracture.

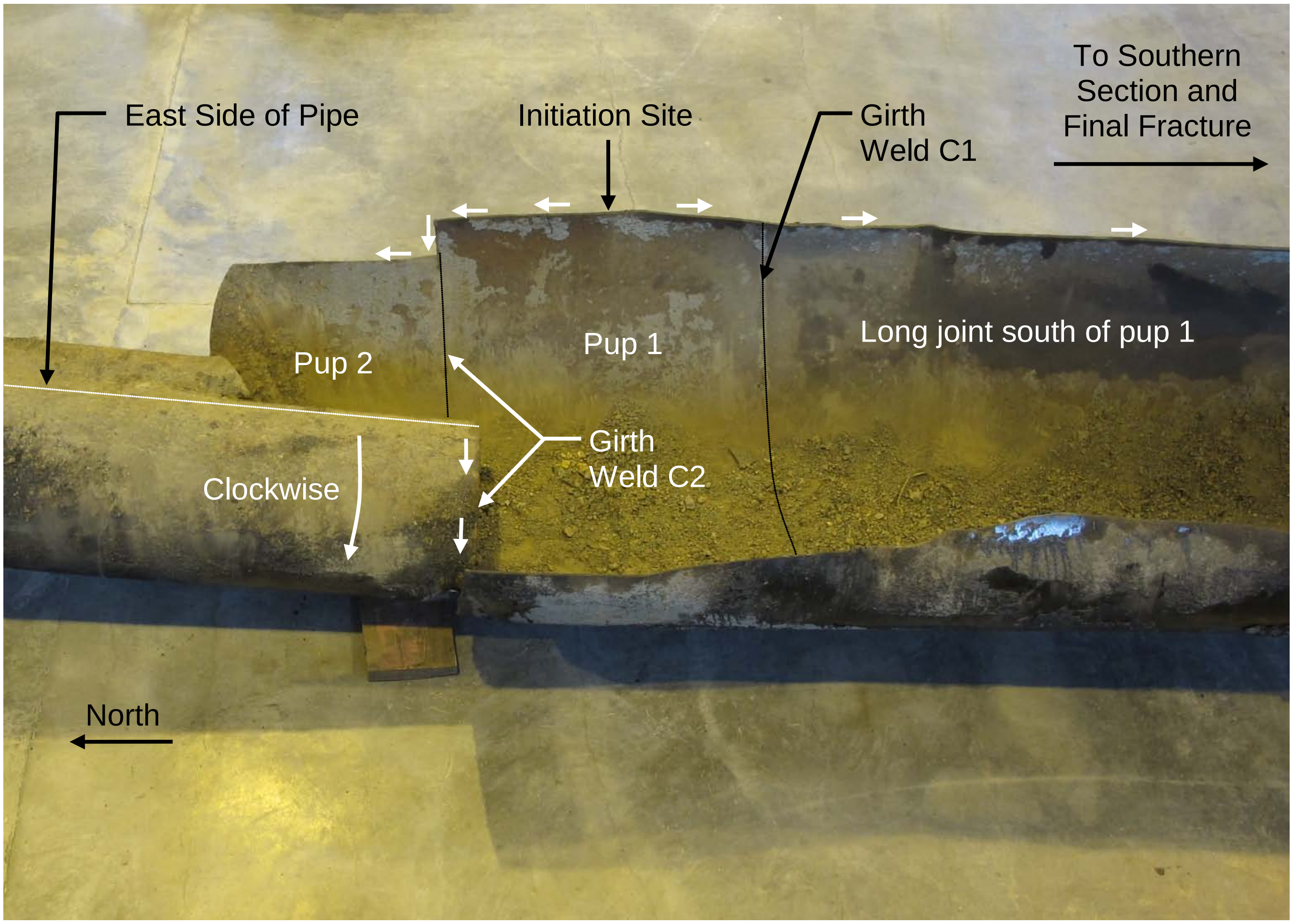


Figure 41: Photograph of center section showing the location of the initiation site in pup 1 and white arrows indicating the direction of crack propagation consistent with the observed fracture features.

Figure 42: Photograph of the south half of the girth weld fracture at C5 between pup 4 and pup 5. The view is of the half associated with pup 4 viewed in the south direction (north out of the page). Yellow arrows in the figure indicate where the location and direction of crack propagation could be determined.

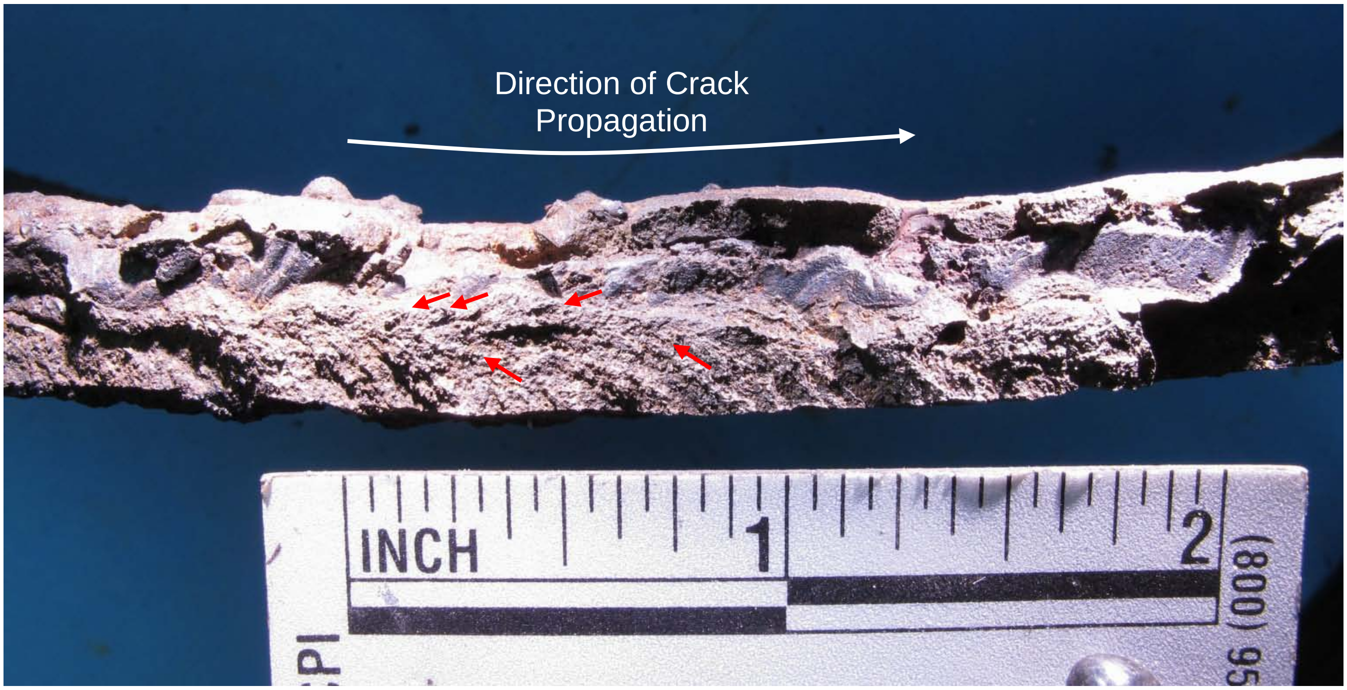


Figure 43: Example macrophotograph of the girth weld fracture surface approximately 150° clockwise from the true top of the pipe. The red arrows indicate lines on the fracture surface that point back in the direction of the crack origin.

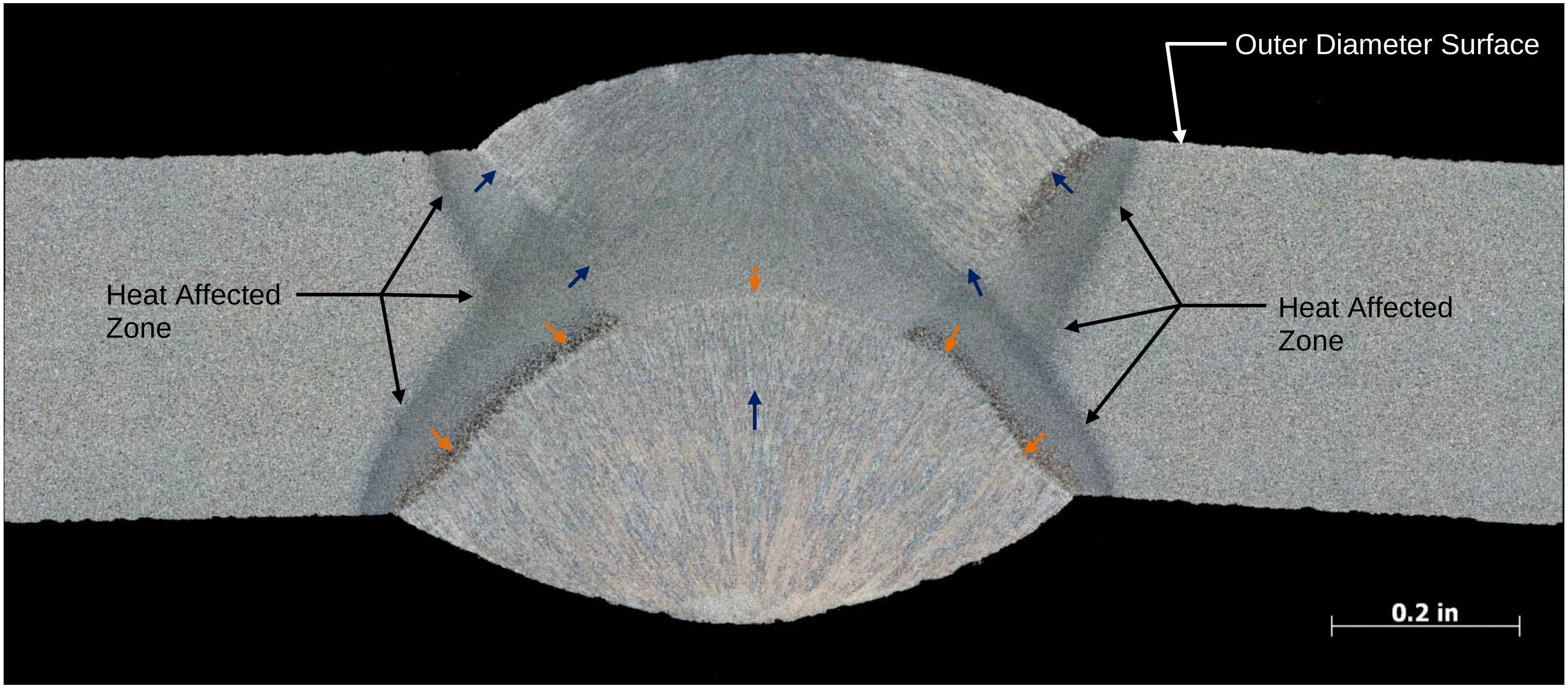


Figure 44: Etched metallographic cross section of the longitudinal seam in the long joint south of pup 1 taken 6 inch south of girth weld C1. The microstructure of the weld was consistent with a double submerged arc welding process. Blue arrows – weld pool from first pass along outer diameter surface. Orange arrows – weld pool from second pass along inner diameter surface.

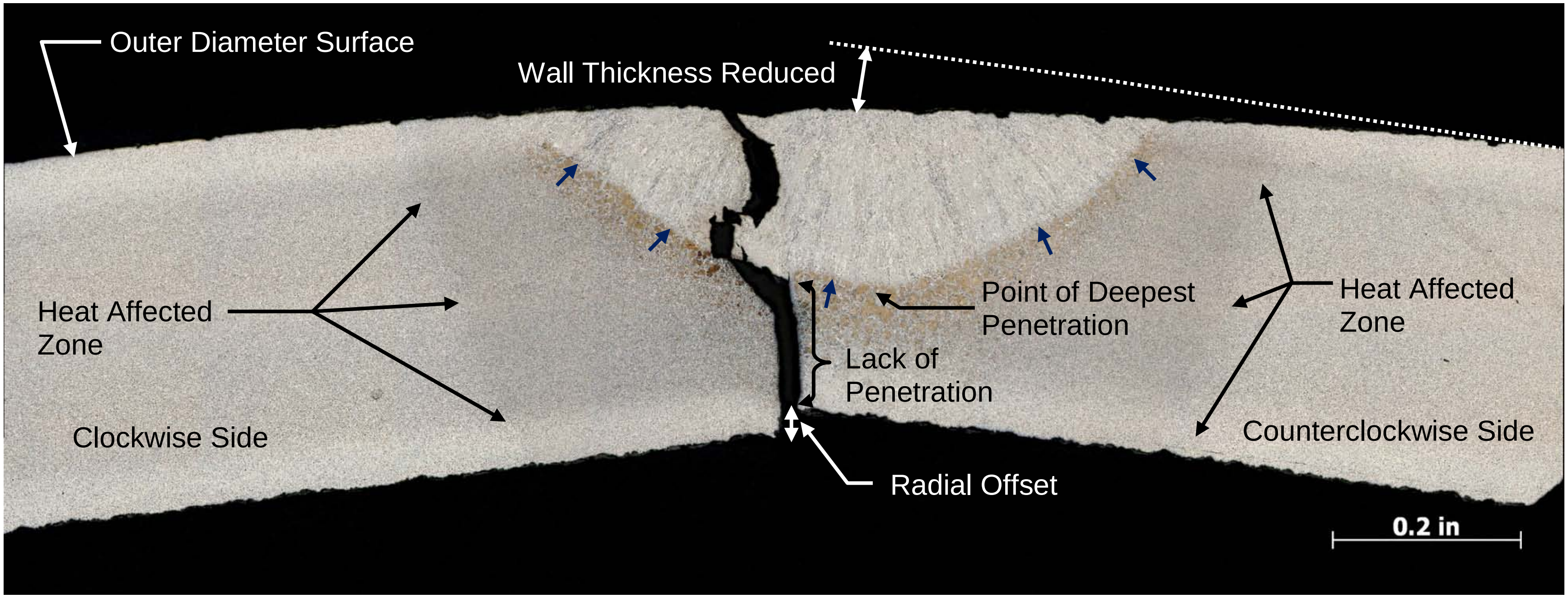


Figure 45: Etched metallographic mating fracture cross section of the longitudinal seam in pup 1 taken 9 inch north of girth weld C1. The two sides of the seam are aligned to within 0.005 inch in the longitudinal direction. The microstructure of the weld was consistent with a fusion welding process along the outer diameter surface of the seam. Blue arrows – weld pool boundary along outer diameter surface seam.

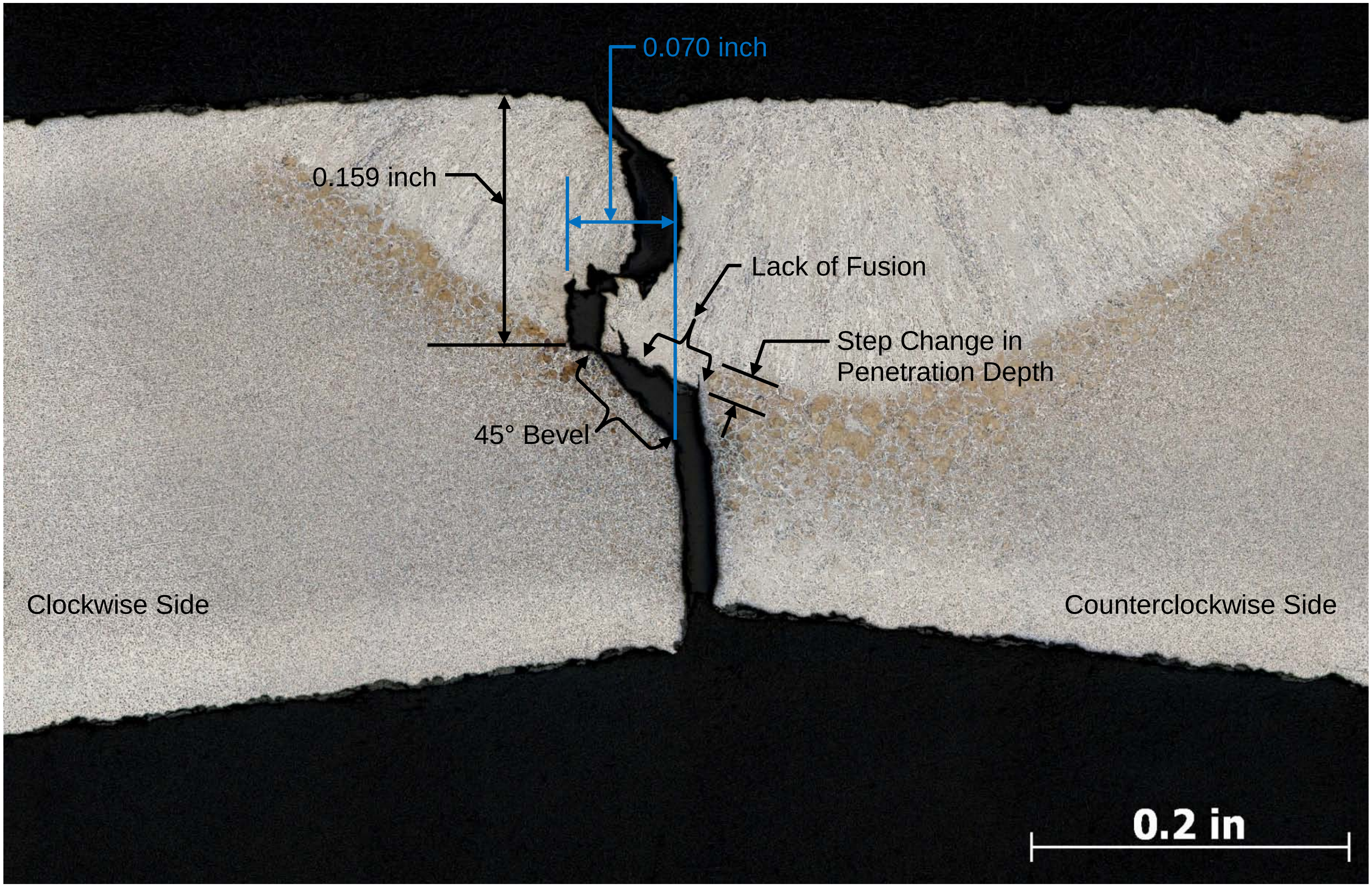


Figure 46: Higher magnification view of the seam in pup 1 (see figure 44) showing the offset from the seam and depth of penetration at the plane of fracture.

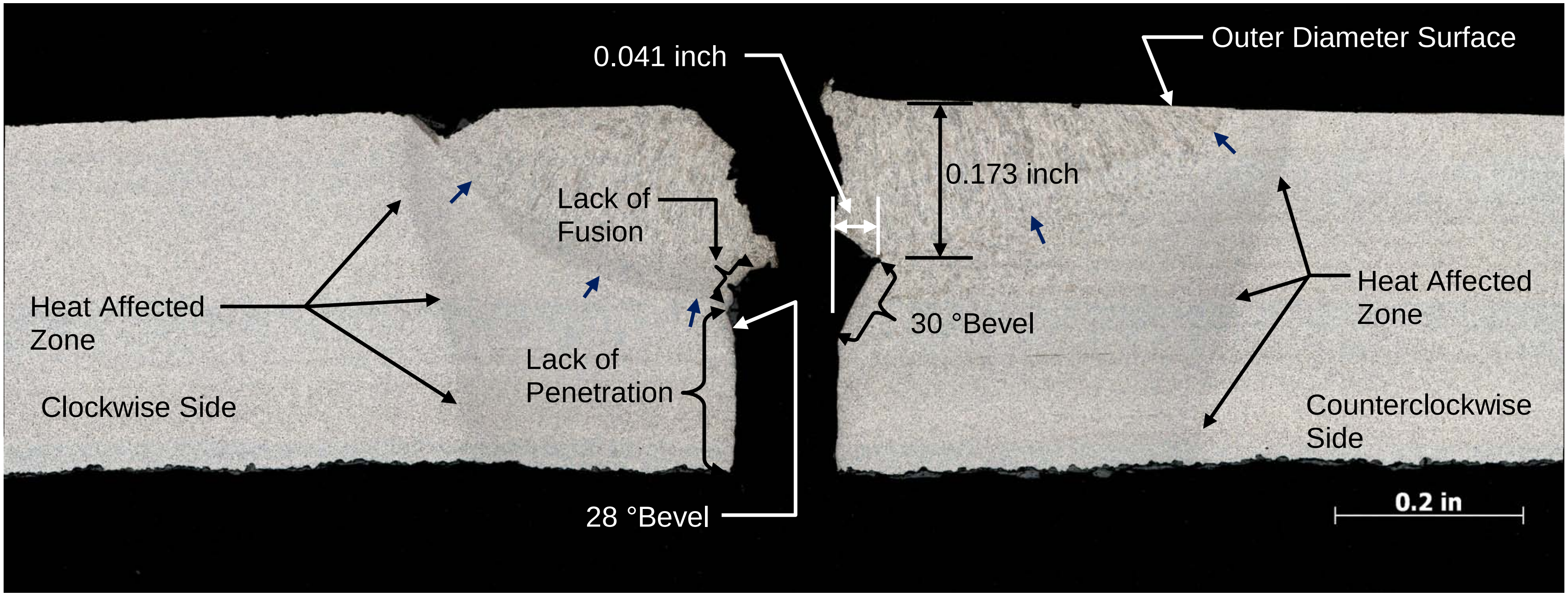


Figure 47: Etched metallographic mating faces cross section of the longitudinal seam in pup 2 taken 9 inch south of girth weld C3. Lineup in the longitudinal direction is within 0.05 inch. The microstructure of the weld was consistent with a fusion welding process along the outer diameter surface of the seam. Blue arrows – weld pool boundary along outer diameter surface seam.

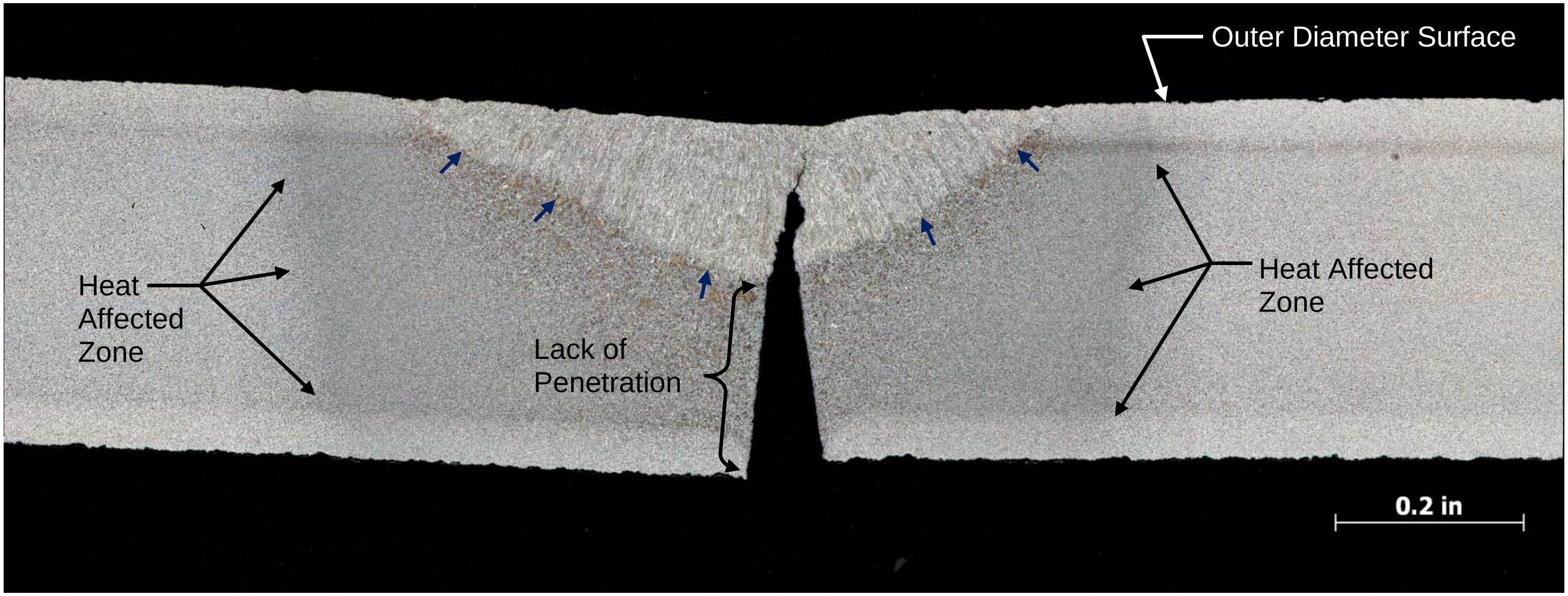


Figure 48: Etched metallographic cross section of the longitudinal seam in pup 3 taken 10 inch north of girth weld C3. The microstructure of the weld was consistent with a fusion welding process along the outer diameter surface of the seam. Blue arrows – weld pool boundary along outer diameter surface seam.

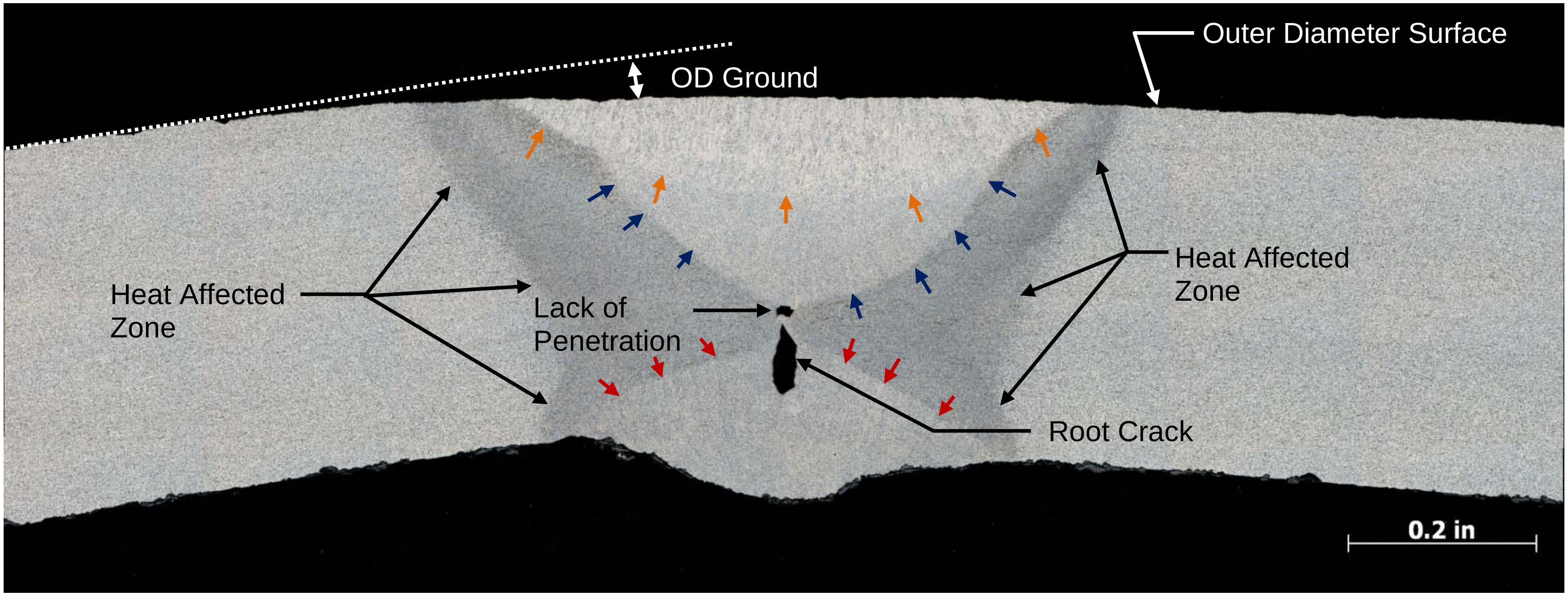


Figure 49: Etched metallographic cross section of the longitudinal seam in pup 4 taken 8 inch south of girth weld C5. The microstructure of the weld was consistent with a multi-pass fusion welding process along the outer diameter surface of the seam and a fusion welding process along the inner diameter surface of the seam. Blue arrows – weld pool boundary from first pass along outer diameter surface. Orange arrows – weld pool boundary from second pass along outer diameter surface. Red arrows – weld pool boundary from pass along inner diameter surface.

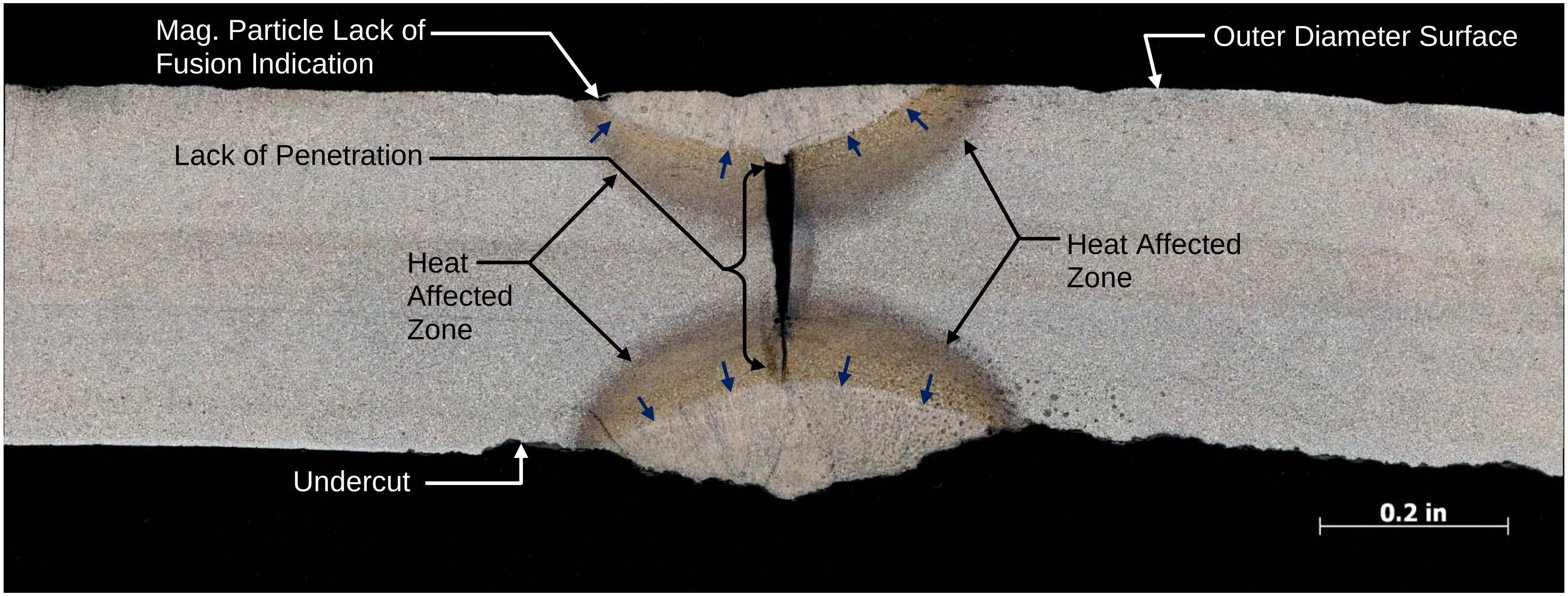


Figure 50: Etched metallographic cross section of the longitudinal seam in pup 5 taken 5.5 inch north of girth weld C5 where magnetic particle inspection indicated lack of fusion. The microstructure of the weld was consistent with a fusion welding process along the outer diameter surface of the seam and a fusion welding process along the inner diameter surface of the seam. Blue arrows – weld pool boundaries along outer and inner diameter surface seams.

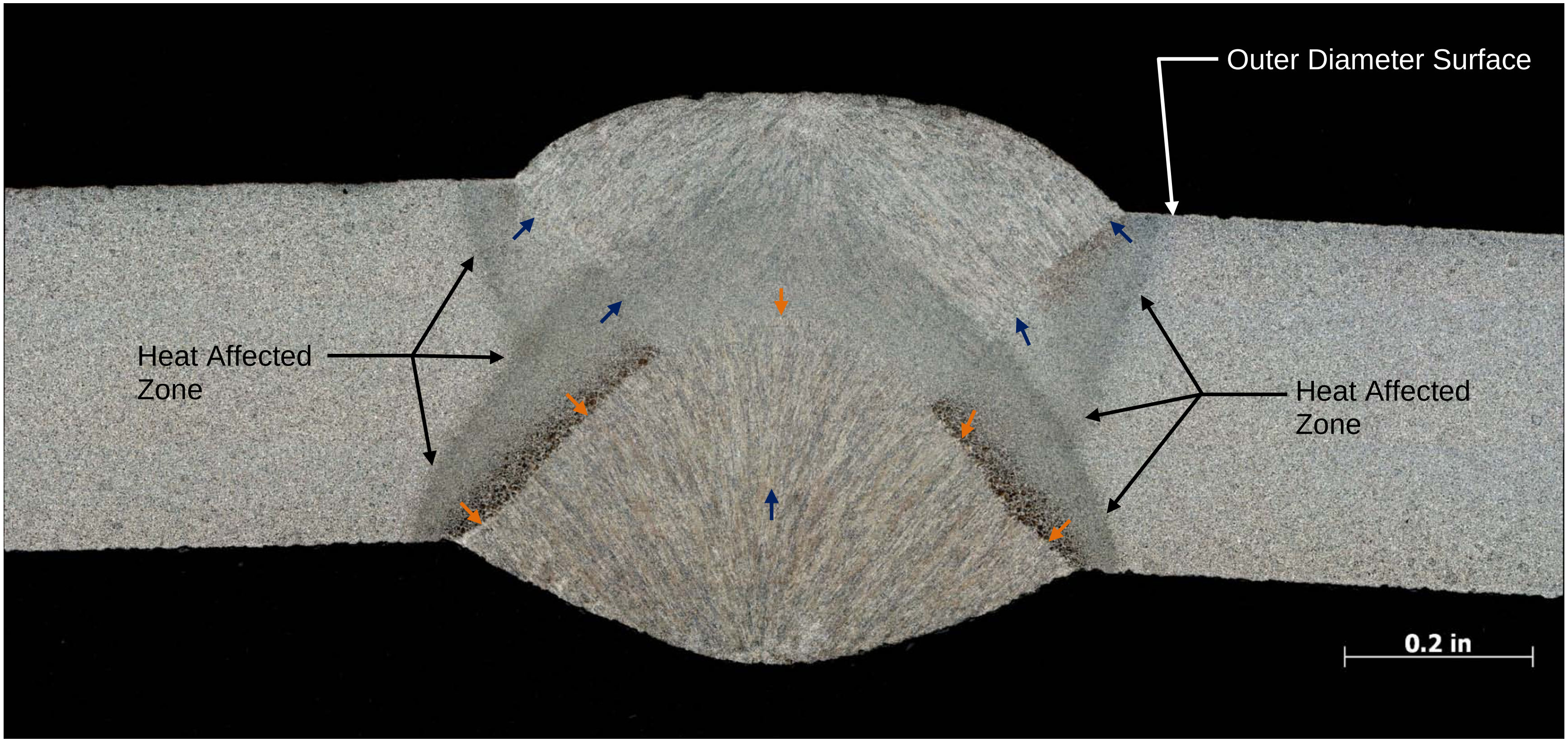


Figure 51: Etched metallographic cross section of the longitudinal seam in the pup 6 taken 6 inch north of girth weld C6. The microstructure of the weld was consistent with a double submerged arc welding process. Blue arrows – weld pool from first pass along outer diameter surface. Orange arrows – weld pool from second pass along inner diameter surface.

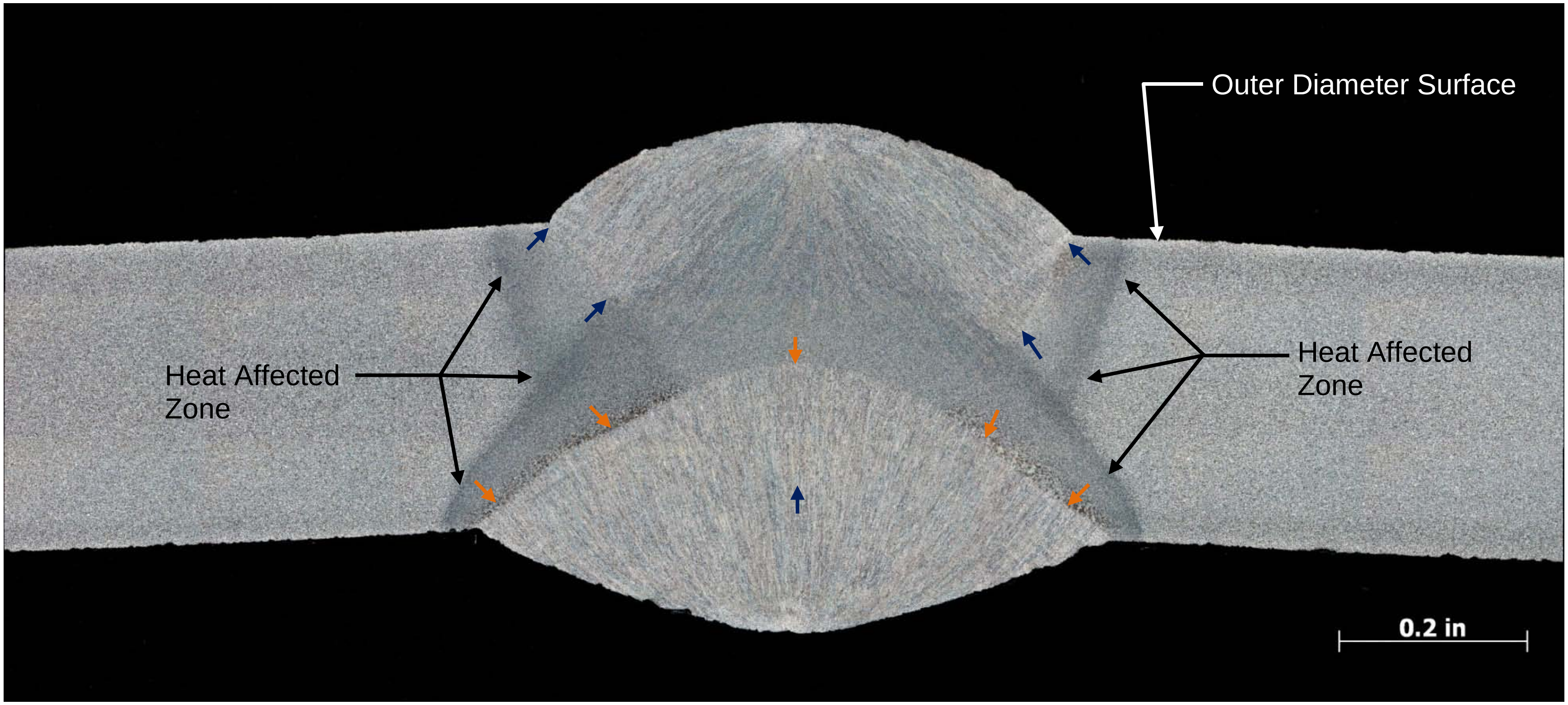


Figure 52: Etched metallographic cross section of the longitudinal seam in the long joint north of pup 6 taken 14 inch north of girth weld C7. The microstructure of the weld was consistent with a double submerged arc welding process. Blue arrows – weld pool from first pass along outer diameter surface. Orange arrows – weld pool from second pass along inner diameter surface.

APPENDIX A: ULTRASONIC THICKNESS DATA

Table A1: Ultrasonic thickness measurements for the 6 pups measured at approximately 30° intervals.

	Wall Thickness at Clock Position Relative to Top of Pipe, inch											
Pipe Piece	12:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Pup 1	0.367	0.365	0.367	0.366	0.368	0.367	0.367	0.369	0.369	0.365	0.369	0.368
Pup 2	0.363	0.361	0.360	0.359	0.353	0.354	0.355	0.359	0.359	0.361	0.361	0.359
Pup 3	0.365	0.366	0.363	0.364	0.365	0.360	0.362	0.363	0.363	0.364	0.366	0.368
Pup 4	0.377	0.381	0.379	0.379	0.381	0.382	0.380	0.378	0.385	0.385	0.381	0.380
Pup 5	0.368	0.365	0.366	0.366	0.366	0.366	0.369	0.363	0.368	0.363	0.367	0.367
Pup 6	0.366	0.362	0.363	0.361	0.362	0.362	0.364	0.362	0.361	0.363	0.363	0.361

Table A2: Ultrasonic thickness measurements for the 6 pups measured at approximately 30° intervals.

Distance from Cut End of Southern Section, inch	Wall Thickness at 6 o'clock Position, inch	Wall Thickness 12 inch CCW of 6 o'clock Position, inch	Wall Thickness CW of 6 o'clock Position, inch
3	0.384	0.377	0.382
6	0.382	0.381	0.382
9	0.382	0.377	0.383
12	0.382	0.383	0.382
15	0.383	0.385	0.381
18	0.381	0.389	0.379
21	0.378	0.379	0.380
24	0.381	0.383	0.381
27	0.380	0.384	0.380
30	0.379	0.384	0.379
33	0.381	0.383	0.380
36	0.381	0.388	0.380
39	0.380	0.384	0.381
42	0.380	0.380	0.381
45	0.380	0.380	0.377

APPENDIX B: RADIOGRAPHIC INDICATIONS

Table B1: Description of weld discontinuities and comparison of rejection limits between API 1104 – 1956 and 2005 editions.

Lack of Penetration – Incomplete filling of the weld groove with weld metal.	
1956	**2005**
Individual indication not to exceed 1 inch. Total length of indications in 12 inch not to exceed 1 inch. Total length in 2 succeeding 12 inch lengths not to exceed 2 inch. Individual indications separated by at least 6 inch.	Individual indication not to exceed 1 inch. Aggregate length of indications in any continuous 12 inch length not to exceed 1 inch.

Incomplete Fusion – Lack of a bond between weld beads or between a weld bead and the parent metal.	
1956	**2005**
Individual indication not to exceed 1 inch. Total length of indications in 12 inch not to exceed 1 inch. Total length in 2 succeeding 12 inch lengths not to exceed 2 inch. Individual indications separated by at least 6 inch.	Incomplete Fusion (due to cold lap): Individual indication not to exceed 2 inch. Aggregate length of indications in any continuous 12 inch length not to exceed 2 inch.

Burn-Through – A portion of the root bead where excessive penetration has caused the weld puddle to be blown into the pipe.	
1956	**2005**
Individual burn-through not to exceed 0.5 inch. Total length of burn-through in 12 inch not to exceed 1 inch. Total length of burn-through in 2 succeeding 12 inch lengths not to exceed 2 inch. Individual defects separated by at least 6 inch.	Maximum dimension not to exceed 0.25 inch. Sum of maximum dimensions not to exceed 0.5 inch in any continuous 12 inch length.

Slag Inclusion (Elongated) – A non-metallic solid trapped in the weld metal or between the weld metal and parent metal, usually found at the fusion zone.	
1956	**2005**
Length not to exceed 2 inch and width not to exceed 1/16 inch. Parallel slag lines considered individual indications if width exceeds 1/32 inch. Total length in 12 inch not to exceed 2 inch. Total length in 2 succeeding 12 inch lengths not to exceed 4 inch. Adjacent defects separated by at least 6 inch.	Length not to exceed 2 inch and width not to exceed 1/16 inch. Parallel slag lines considered individual indications if width exceeds 1/32 inch. Total length in any continuous 12 inch not to exceed 2 inch.

Slag Inclusion (Isolated) – Isolated slag inclusions are irregularly shaped and may be located anywhere in the weld.	
1956	**2005**
Maximum width not to exceed 1/8 inch. Total length in 12 inch not to exceed 0.5 inch. No more that 4 inclusions of maximum width in 12 inch. Total length in 24 inch not to exceed 1 inch. Adjacent inclusions separated by 2 inch.	Maximum width not to exceed 1/8 inch. Total length in any continuous 12 inch not to exceed 0.5 inch. No more than 4 inclusions with maximum width in any continuous 12 inch.

Porosity – Gas trapped by the solidifying weld metal before the gas can escape from the surface of the molten puddle.	
1956	**2005**
Maximum dimension not to exceed 1/16 inch. Distribution in accordance with standard figure.	Maximum dimension not to exceed 1/8 inch or 25% of the nominal wall thickness. Distribution in accordance with standard figure. For Cluster Porosity, size of cluster not to exceed 1/2 inch and aggregate length not to exceed 1/2 inch in any continuous 12 inch length. For hollow-bead porosity, length not to exceed 1/2 inch. Aggregate length not to exceed 2 inch in any continuous 12 inch length. Individual indications greater than 1/4 inch to be separated by 2 inch minimum.

Cracks	
1956	**2005**
No cracks allowed. Minor cracks in surface and filler beads may be repaired if so authorized. Minor cracks defined as cracks visible in surface bead not more that 2 inch in length.	No cracks except shallow crater cracks or star cracks. Length of shallow crater crack or star crack not to exceed 5/32 inch.

Undercutting – A groove melted into the parent material adjacent to the toe or root of the weld and left unfilled by weld metal.	
1956	**2005**
Undercutting adjacent to cover bead not to exceed 1/32 inch in depth and 2 inch in length. Undercutting adjacent to root bead not to exceed 2 inch in length.	Aggregate length adjacent to cover bead or root bead in any continuous 12 inch not to exceed 2 inch.

Table B2: Radiographic discontinuities found on the longitudinal seams. An “X” designates a defect that did not meet the present day API 1104 acceptance criteria. An “O” designates a discontinuity that was within the acceptance criteria of present day API 1104. The location numbers indicate distance in inches from the nearest upstream girth weld.

Location	Lack of Penetration	Incomplete Fusion	Slag Inclusion	Porosity	Undercut
Long South Joint					
120-132				O	
Pup 3					
0-15	X				
12-27	X		O	O	
24-36	X			O	
33-50	X			O	
Pup 4					
0-12		X		X	X
12-24		X	X	X	X
24-36		X	X	X	X
36-45		X		X	X
Pup 5					
0-12	X			O	
12-24	X			O	
21-36	X			X	
33-42	X			O	
Pup 6					
0-12				O	
12-24				X	
24-39				X	
39-51				X	
Long Joint North					
0-12		X			
12-24					

Table B3: Radiographic discontinuities found on girth welds C1 – C4. An “X” designates a defect that did not meet the present day API 1104 acceptance criteria. An “O” designates a discontinuity that was within the acceptance criteria of present day API 1104. The location numbers indicate distance in inches around the circumference of the pipe.

Location	Lack of Penetration	Incomplete Fusion	Burn-Through	Slag Inclusion	Crack	Porosity	Undercut	Excess Reinforcement
C1								
0-12				X	X	X	X	
12-24		X					X	
21-36		X		X		X	X	
36-48		X		X		X	X	
48-63		X		X		X	X	
60-72		X				X	X	
72-84		X		X		X	X	X
81-93		X		X		X	X	X
C2								
6-15	X			X		X		X
12-24	X			X		X		
24-36	X		X	X		X		
33-48	X			X	X	X		
45-60	X	X		X		X		X
60-72	X			X		X		X
C3								
0-15	X	X		X		X		
12-24	X	X		X		X		
24-36	X	X		X		X		
36-48	X	X		X		X		
48-60	X	X		X		X		
60-72	X	X		X		X		
72-84	X	X		X	X	X		
84-0	X	X		X		X		
C4								
0-12	X	X		X		X		
12-24	X	X		X		X	X	
24-36	X	X		X		X		
36-48	X	X		X		X		
48-60	X	X		X		X		
60-72	X	X		X		X		
72-84	X	X		X		X		
84-0	X	X		X		X	X	X

Table B2 (cont.): Radiographic indications found on girth welds C6 – C7.

Location	Lack of Penetration	Incomplete Fusion	Burn-Through	Slag Inclusion	Crack	Porosity	Undercut	Excess Reinforcement
C6								
0-15					X	X	X	X
12-24		X					X	X
21-36		X		X		X	X	
36-48				O			O	
48-60				O	X	O		
60-72		X		X			X	
72-84		X	X	X			X	X
84-0				X		X	X	X
C7								
0-12				X		O		
12-24				X		O		
24-36	X	X		X				X
36-48				X		X	X	
48-60				X	X	X	X	
60-72	X			X		X		
72-84				X		X		
81-0				X				

APPENDIX C: WELD PENETRATION MEASUREMENTS

Table C1: Lack of penetration depth measurements and total wall thickness measurements along the fractured pup 1 longitudinal seam. The depth measurements were taken on calibrated digital images taken using an optical microscope.

Location	Distance from C1 Girth Weld, inch	Lack of Penetration Depth, inch	Total Wall Thickness, inch	Weld Penetration Depth, inch	Percent Weld Penetration
1	4.25	0.115	0.319	0.204	63.9
2	8.25	0.129	0.318	0.189	59.4
3	12.25	0.143	0.281	0.138	49.1
4	16.25	0.145	0.300	0.155	51.7
5	20.25	0.170	0.326	0.156	47.9
6	24.25	0.168	0.319	0.151	47.3
7	28.25	0.141	0.305	0.164	53.8
8	32.25	0.120	0.304	0.184	60.5
9	36.25	0.160	0.322	0.162	50.3
10	40.25	0.112	0.329	0.217	66.0