National Transportation Safety Board
Office of Research and Engineering
Washington, DC 20594

DCA22FM022

MATERIALS LABORATORY

Factual Report 22-080

November 4, 2022

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A. ACCIDENT INFORMATION

Location: Norfolk, Virginia
Date: June 7, 2022
Vehicle: Spirit of Norfolk
Investigator: Michael Karr, MS-10

B. COMPONENTS EXAMINED

Two pipe sections and a hydraulic hose with fittings.

C. EXAMINATION PARTICIPANTS

Specialist	[redacted], Ph.D. NTSB Washington, DC
Engineering Technician	[redacted] NTSB Washington, DC
Specialist	[redacted], Ph.D. NTSB Washington, DC
Specialist	[redacted] NTSB Washington, DC

D. DETAILS OF THE EXAMINATION

Overall views of the submitted components are shown as received in figure 1. One pipe piece (upper image in figure 1 shown labeled pipe A for this report) was cut from a location at the outboard side of the port engine. The other pipe piece (middle image in figure 1 shown labeled pipe B for this report) was cut from pipe located in the hydraulic pump space. The hydraulic relief valve hose and fittings were also collected from the hydraulic pump space. All components were reportedly associated with the hydraulic steering system. The fittings at the upper end of the hose were disassembled from the steering hydraulic pump reservoir, and the hydraulic hose was disassembled from the relief valve.

The engineering drawing for the vessel's hydraulic steering system included pipe sections specified as 1-inch, schedule 80, black-pickled pipe made to ASTM standard A106.[1] Flexible hoses in the system were specified to be an Aeroquip SAE 100R2A hose.[2]

All components were tinted dark and were heavily oxidized consistent with exposure to heat and fire. On the hydraulic hose, heat damage was more substantial at the upper end of the hose where the liner and external sheath were both missing, leaving only the braided reinforcement. On the lower half of the hose, the external sheath remained in place. The condition of the internal liner at the lower end of the hose was not determined. The reinforcement braid consisted of two layers of reinforcement, consistent with the system engineering drawing specification.

The two pipes were fractured longitudinally at the upper side of each pipe. On pipe A, the longitudinal fracture transitioned to circumferential fractures that extended around most of the pipe circumference at each end of the longitudinal fracture. The hydraulic hose had separated from the crimped sleeve for the hose end fitting at the upper end of the hose.

The section of pipe A between the circumferential fractures was deformed from a cylindrical shape to a shape resembling a wavy plate with curled edges. The fractured and deformed section was placed into a Keyence VL 500 series 3D scanner, and a thickness contour map showing thickness variations for the section between the circumferential fractures was produced as shown in figure 2. The thickness contours showed the wall thickness was relatively thinner in a circular area (appearing yellow, green and blue in figure 2) that would have been at the upper side of the pipe before fracture. The thinner area was also associated with an outward bulge in the wall.

Next, both pipe pieces were initially cleaned using a soft-bristle brush dipped in a solution of Alconox detergent and warm water to remove loose particles and oily deposits. However, relatively thick oxides remained on all surfaces including the fracture surfaces. To facilitate oxide removal, transverse cuts were made through intact pipe within 1 to 2 inches of the fractures, and the reduced pieces with the fractures were submerged in a bath of Evapo-Rust.[3] The parts were initially submerged for 1 hour followed by a 24-hour soak. The parts were brushed with a soft-bristle brush several times during the soak.

Views of the pipe A fracture after soaking in Evapo-Rust are shown in figures 3 and 4. The longitudinal fracture occurred on a slant plane consistent with ductile overstress fracture. At the middle of the fracture, the wall showed thinning deformation and outward deformation, consistent with substantial local plastic deformation before fracture.

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[1] ASTM Standard A106, *Standard Specification for Seamless Carbon Steel Pipe for High-Temperature Service*, ASTM International, West Conshohocken, Pennsylvania (1991).
[2] SAE Standard J517_199104, Hydraulic Hose, SAE International, (1991).
[3] Evapo-Rust is manufactured by Harris International Laboratories, Springdale, Arkansas.

One of the pieces cut from pipe A before starting the oxide removal procedure was further sectioned to prepare a sample for metallographic examination of the transverse cross-section. An approximately ¼-inch ring section from pipe A was submerged in Alconox and warm water and cleaned using an ultrasonic cleaner before mounting in a metallurgical mount using a hot press. The mounted sample was then polished and etched with 2% nital[4] to reveal the microstructure as shown in figure 5. The microstructure consisted of mostly ferrite with partially spheroidized pearlite, consistent with a low-carbon steel exposed to high heat.

Next, pipe B was examined after the 24-hour soak in Evapo-Rust. The longitudinal fracture occurred mostly in planes perpendicular to the pipe surfaces. Although general macroscopic features were visible, relatively thick oxides remained covering all surfaces including the fracture surfaces. To assist in removing more oxides, pipe piece B submerged in a beaker of Evapo-Rust, and the beaker was placed in an ultrasonic cleaner for 1 hour followed by brushing to remove loose material. Views of the pipe B piece after deoxidation in the ultrasonic cleaner are shown in figures 6 and 7. The middle portion of the fracture occurred on multiple planes in longitudinal segments linked by short circumferential fractures joining the longitudinal segments to form a step-like pattern to the fracture. Many of the step edges were curled inward consistent with the final separation at the step edges as the pipe fracture opened. Multiple longitudinal crack-like pits were also observed adjacent to the fracture surface such as those indicated with unlabeled arrows in figure 7. The longitudinal fracture planes appeared to coincide with the locations of the crack-like pits such as the one shown by the arrow at the right side of the image in figure 7.

A view of the fracture surface for pipe B at the location of greatest opening displacement is shown in figure 8. The fracture surface had shallow pits in the oxidation layer likely from uneven removal of oxides during the ultrasonic removal stage, and fine fracture features remained obscured and likely obliterated by post-fracture oxidation. However, the overall pattern of fracture showed flat fractures on multiple planes with limited wall thinning associated with the fracture. At the step edges, there was more overlap of adjacent fracture planes at the outer surface, consistent with fracture initiation from the longitudinal crack-like pits on the exterior surface.

Corrosion pits were also observed on the interior surface on the lower side of the pipe after deoxidation in the ultrasonic cleaner. A view of some of the exposed pits is shown in figure 9. No cracks were observed associated with the pits on the lower side of the pipe.

One of the pieces cut from piece B before starting the oxide removal steps was further sectioned to prepare a sample for metallographic examination of the

[4] 2% nital is a solution of concentrated nitric acid (2% by volume) diluted in methanol.

transverse cross-section. An approximately ¼ inch ring section from pipe B was submerged in Alconox and warm water and cleaned using an ultrasonic cleaner before mounting in a metallurgical mount using a hot press. The mounted sample was then polished and examined using a Zeiss AxioObserver inverted metallograph. A stitched montage of micrographs imaging the as-polished lower section of the pipe is shown in figure 10. Arrows point to corrosion pits on the inner surface of the pipe. No cracks were observed emanating from the pits.

The polished cross-section of pipe B was then etched with 2% nital. The transverse cross-section intersected multiple longitudinal crack-like pits on the exterior surface on the upper side of the pipe. One of the larger of these crack-like pits is shown in figure 11 on the etched cross-section. A thick oxide layer covered the surface as shown, including the crack-like pit. The profile of the crack-like pit had a rounded tip like that of a pit. A crack extended from the lower end of the pit as indicated in figure 11.

A micrograph of the etched sample showing typical microstructural features for pipe B is shown in figure 12. The microstructure consisted of mostly ferrite with mostly spheroidized pearlite, consistent with a low-carbon steel exposed to high heat.

Dimensions of pipe A and pipe B were measured both on pieces that had oxides removed and on pieces that remained without oxide removal. Near the fracture location after oxide removal, pipe A had an outer diameter of 1.332 inch and a wall thickness measuring between 0.168 inch and 0.187 inch. On a piece of pipe A without oxide removal, the outer diameter measured 1.331 inch, and the wall thickness measured between 0.175 inch and 0.188 inch. On the pipe piece B with oxide removal, the cross-section was slightly ovalized near the fracture surface, measuring 1.547 inch across in the horizontal plane and 1.452 inch across in the vertical plane with a wall thickness of between 0.148 inch and 0.163 inch. On a piece of pipe B without oxide removal at one of the transverse cuts, the outer diameter measured 1.507 inch, and the wall thickness measured between 0.148 inch and 0.167 inch. However, the diameter of pipe B was smaller adjacent to the 90-degree elbow fitting, where the diameter measured as little as 1.410 inch. Schedule 80, 1-inch pipe has a nominal outer diameter of 1.315 inches and wall thickness of 0.179 inch.

A close view of the separated end of the hydraulic hose and the corresponding crimped sleeve is shown in figure 13. The reinforcement braids on the hose were disturbed and splayed slightly outward within approximately 3/8 inch of the cut end of the hose. The crimped sleeve on each end of the hose was marked "EATON 08U-608". The nuts were marked "-8" on one flat and "EATON" on the opposite flat. No part markings could be detected on the hose. The crimps on each end had similar geometry. The average nominal crimped diameter measured 0.926 inch and 0.922 inch on the separated and intact sleeves, respectively. According to the

Danfoss website, the specified nominal crimp diameter is 0.915 inch for an Eaton U-series fitting connected to a size 08, Weatherhead H425, SAE 100R2AT hose.[5, 6] According to a representative in product support at Danfoss, the crimp specification has a tolerance of ±0.005 inch. Crimp specifications for U-series fittings with an Aeroquip SAE 100R2A hose for sale at the time of ship construction in 1992 were not readily available.

The fitting at the intact end of the hose was examined using radiographic (x-ray) imaging, and the resulting radiograph is shown in figure 14. The overall geometry of the of the braided hose reinforcement within the crimped sleeve had a slight outward flare within the last ¾ inch from the tube end with no significant change in the last 3/8 inch. The fitting at the separated end was also examined using radiographic imaging as shown in figure 15. No braided hose reinforcement remnants were detected within the crimped sleeve.

Submitted by:

[redacted] Ph.D.
Chief Technical Advisor - Materials

[5] www.eatonpowersource.com accessed on October 27, 2022. According to the Danfoss website at www.danfoss.com, Danfoss acquired Eaton's hydraulics business in 2021.

[6] The SAE 100R2A hose was discontinued from SAE standard J517 in 2020 due to lack of demand. For U. S. Department of Defense orders, the 100R2A hose is replaced with the 100R2AT hose.

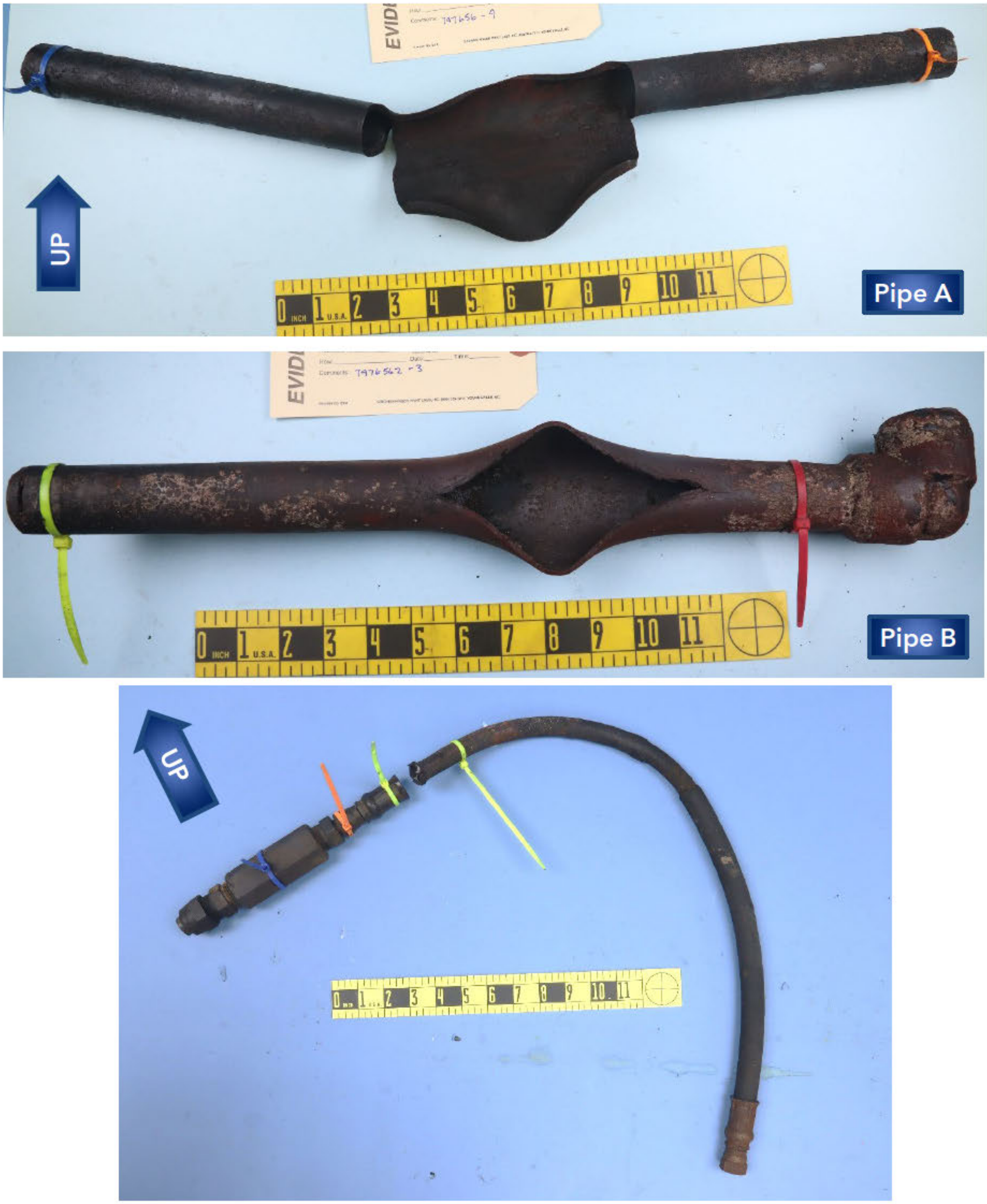

Figure 1. Overall views of the hydraulic pipe located at the outboard side of the port engine (upper image), upper side of the hydraulic pipe from the hydraulic pump space (middle image), and hydraulic relief valve hose and fittings (lower image).

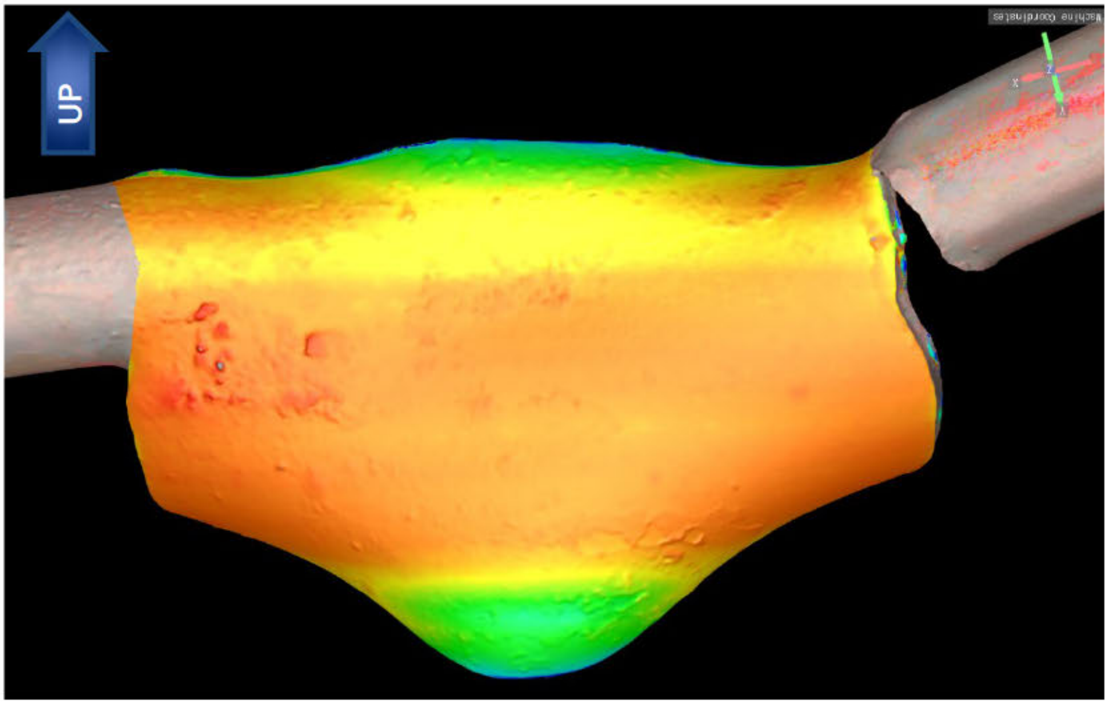

Figure 2. Thickness contour map image of pipe A obtained using a Keyence VL 500 series 3D scanner showing the external side of the pipe fracture (opposite view from figure 1). Blue, green, yellow, orange, and red colors indicate thickness variation from thinner to thicker.

Figure 3. Closer view of the pipe A fracture after sectioning and partial oxide removal. Areas of reduced wall thickness at the fracture location are indicated.

Figure 4. View from the lower side of pipe A showing wall thinning at the center of the bulge in the fracture location.

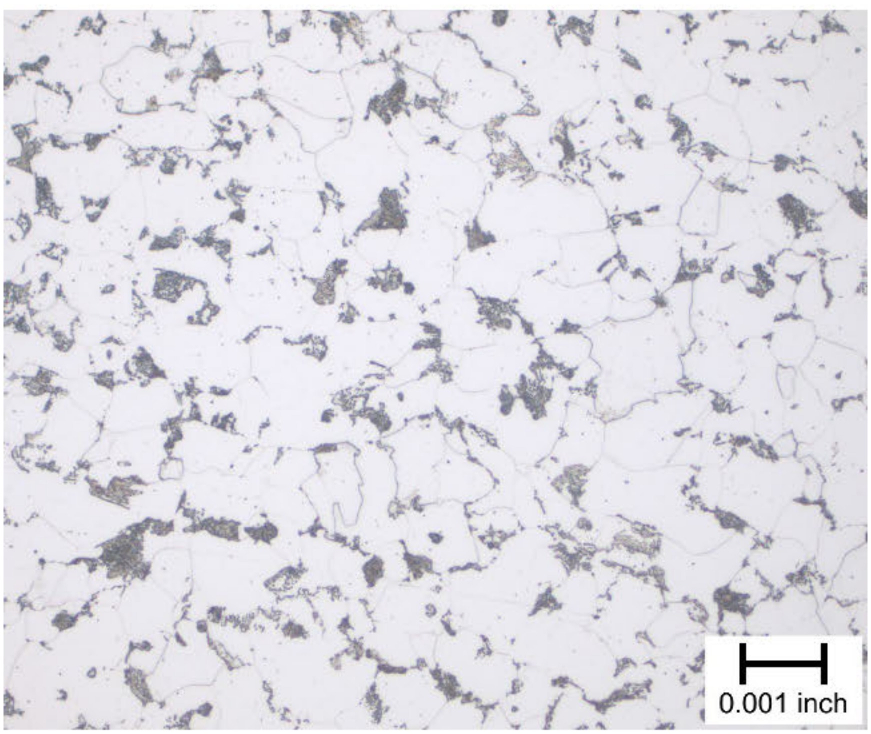

Figure 5. Typical microstructure for pipe A. White areas are ferrite, and darker areas are partially spheroidized pearlite. (Etched with 2% nital.)

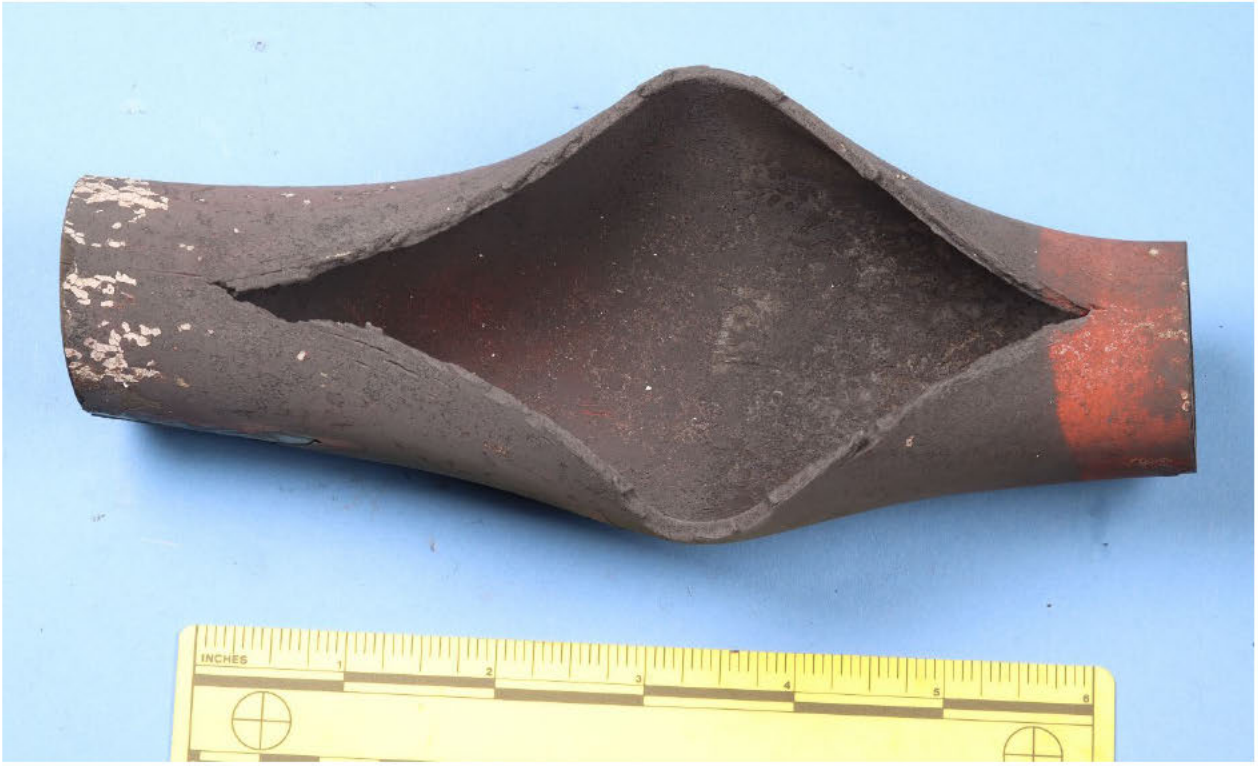

Figure 6. Close view of the pipe B fracture after sectioning and partial deoxidation.

Figure 7. Oblique view of the pipe B fracture showing step features in the fracture plane corresponding to longitudinal crack-like pits (indicated with unlabeled arrows) on the exterior surface.

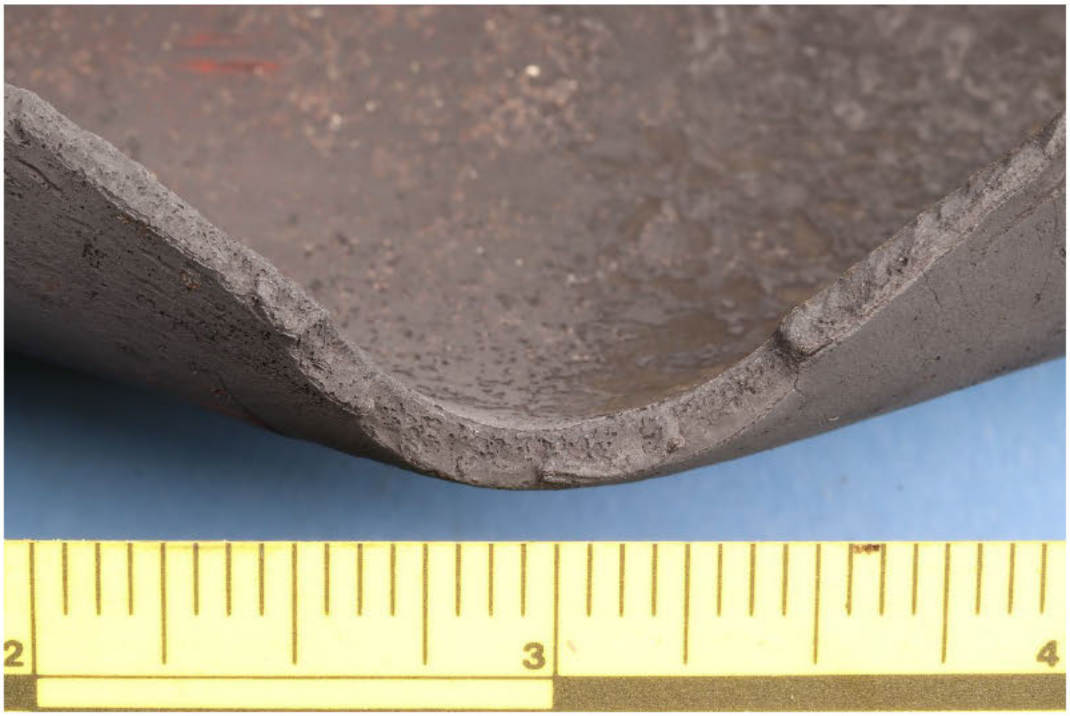

Figure 8. Fracture surface at the center of the longitudinal fracture in pipe B.

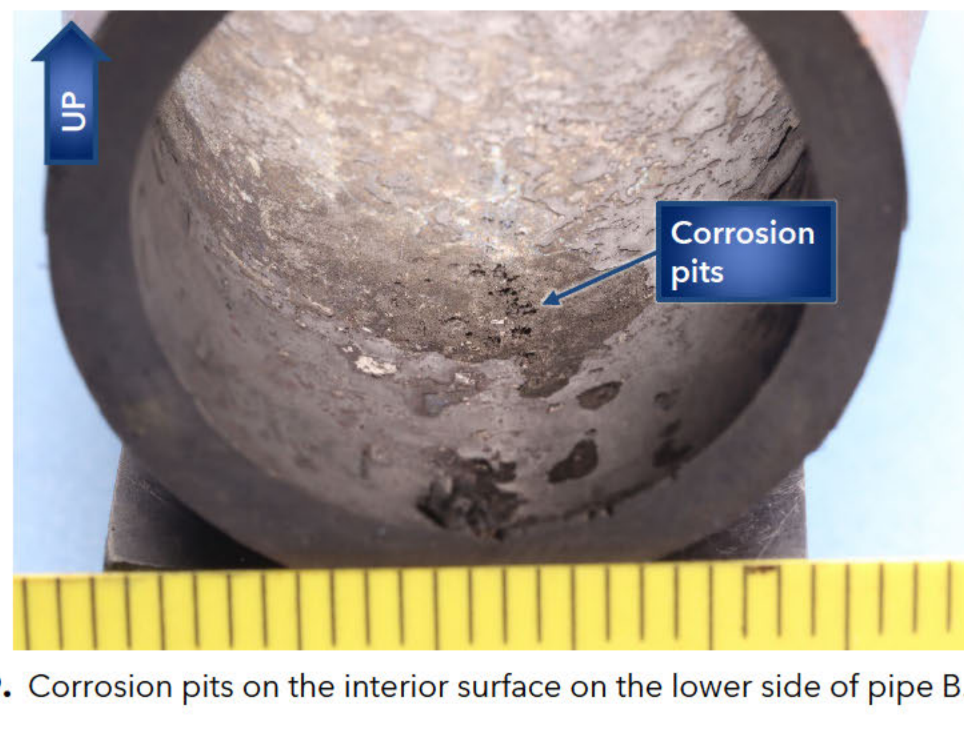

Figure 9. Corrosion pits on the interior surface on the lower side of pipe B.

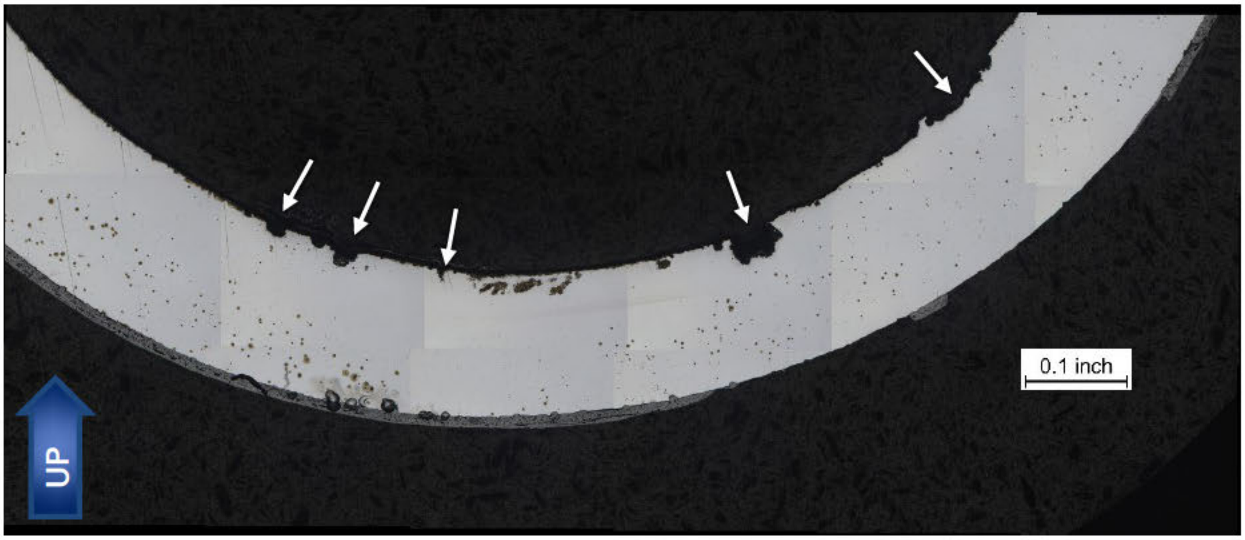

Figure 10. Stitched montage of micrographs of the as-polished cross-section through pipe B. Arrows point to corrosion pits on the interior surface at the lower side of the pipe.

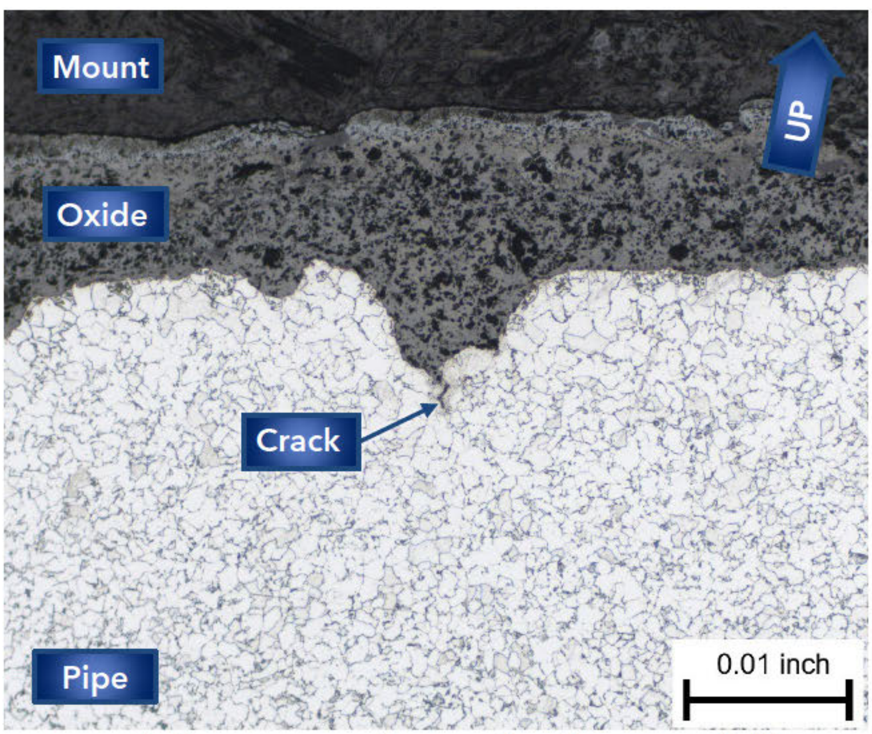

Figure 11. Micrograph showing a crack extending from a crack-like pit in the exterior surface on the upper side of pipe B.

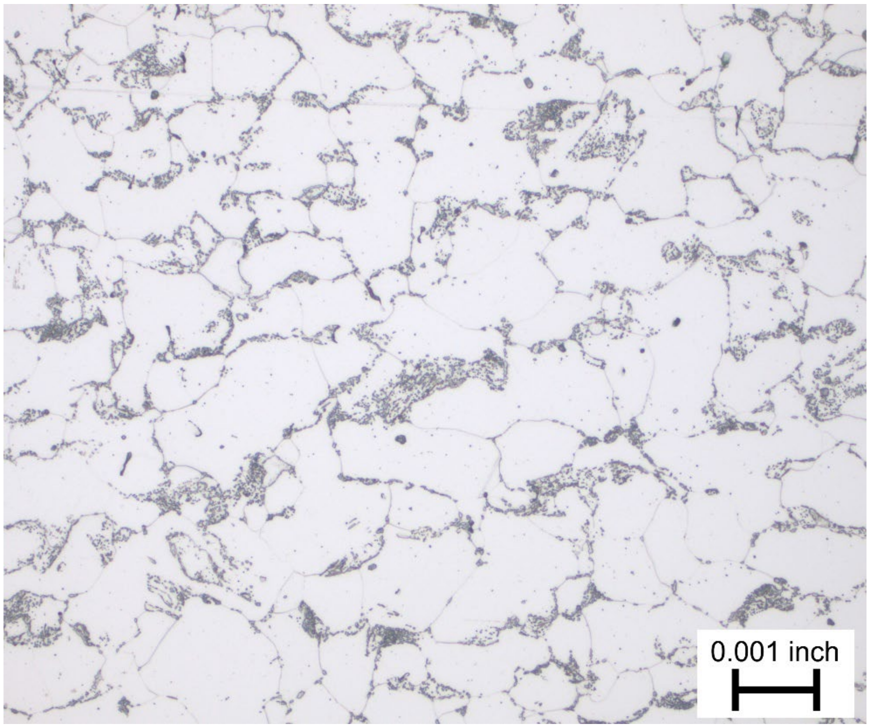

Figure 12. Typical microstructure for pipe B. White areas are ferrite, and darker areas are pearlite that has been mostly spheroidized. (Etched with 2% nital.)

Figure 13. Close view of the separated end of the hose and corresponding crimped sleeve. The reinforcement braid adjacent to the cut end was disturbed and splayed slightly outward within 3/8 inch of the end face.

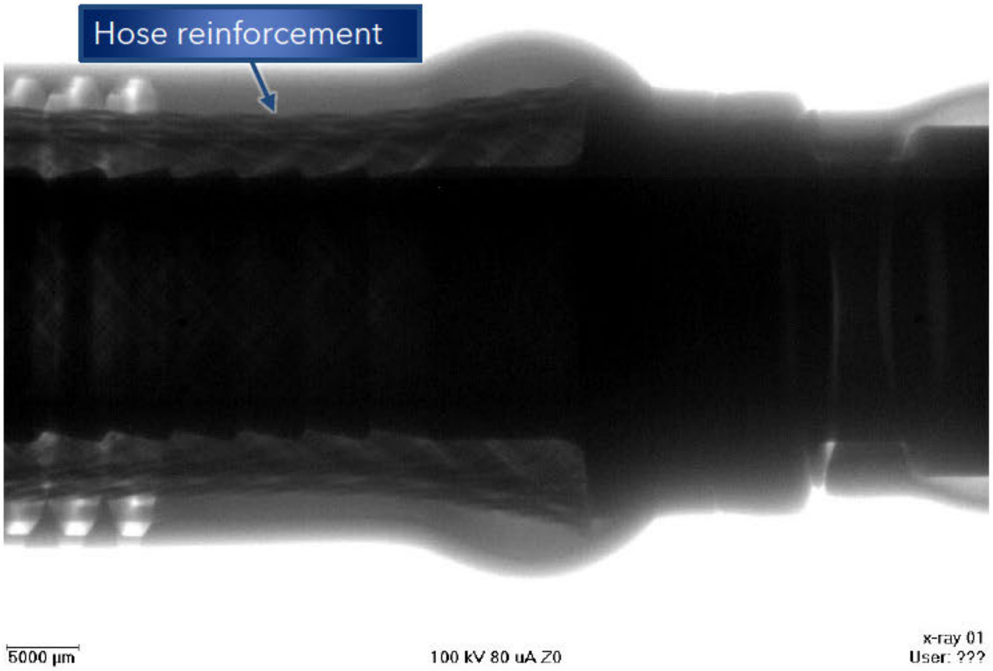

Figure 14. Radiograph of the intact hose end within the crimped sleeve at the lower end of the hose.

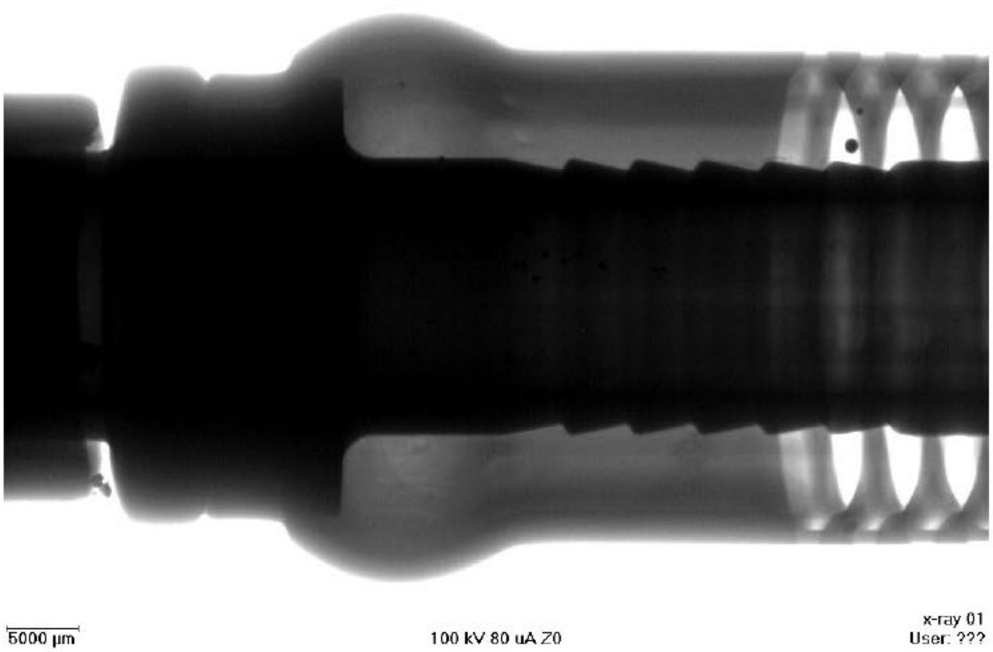

Figure 15. Radiograph of the crimped sleeve at the upper end of the hose.