NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

September 8, 2005

MATERIALS LABORATORY DRAFT FACTUAL REPORT — Report No. 05-071

A. ACCIDENT

Place	:	Graniteville, South Carolina
Date	:	January 6, 2005
Vehicle	:	Tank Car UTLX 900270
NTSB No.	:	DCA05MR008
Investigator	:	Jim Henderson (RPH-30)

B. COMPONENTS EXAMINED

Tank car UTLX 900270 and flatbed car CSXT 496430.

C. DETAILS OF THE EXAMINATION

I. Off-site Examination

Tank car UTLX 900270 and flatbed car CSXT 496430 were examined in detail at a railcar repair facility, Union Tank Car, Altoona, Pennsylvania, on February 16 and 17, 2005. Figure 1 shows a photograph of the tank car.

A. Tank Car UTLX900270

The following information regarding construction of this tank car was received from a representative of Union Tank Car. According to the certificate of construction, application for approval for construction of tank car UTLX900270 was made on August 1993.[1] The bare portion of the tank car was built to Department of Transportation (DOT) 105A500W specification, the completed car, which also includes the insulation and head protection systems, was originally constructed and stenciled DOT 105S500W. This tank car later was re-stenciled to DOT 105J500W specification.[2] Examination of the accident tank car revealed the exterior shell was marked "DOT 105J500W". The same certificate of construction indicated that the shell and head of the tank car were specified as Association of American Railroad

[1] The actual built date was December 1993.
[2] After DOT sponsored tests showed that the insulation systems used on most chlorine tank cars met the thermal protection requirements of 49 Code of Federal Regulations, Part 179.18.

TC-128 Grade B (TC128B) normalized steel.[3] The barrel portion (shell) was specified as 0.777-inch (nominal) thick steel plates, and the head was specified as 53/64-inch (0.8281-inch) nominal thick steel plate before forming. During construction, the tank assembly was post-weld heat treated (approximately 1,200 °F for one hour). This tank car was transporting chlorine at the time of the accident.

1. Shell

The shell at the "AR"[4] end of the tank car contained a puncture (referred to in this report as a fracture) with surrounding inward deformation. At the scene of the accident, the outer jacket was removed from the general area of the fracture. A steel patch, measuring approximately 72-inches by 48.5-inch, was bolted over the fracture to contain leakage. Several portholes were made near the center of the patch, and a steel tube was welded to each porthole, allowing chlorine to be removed from the tank car through the tubes. After removal of all chlorine product, tank car UTLX 200970 was cleaned and purged for subsequent inspection by Safety Board investigators.

At the Union Tank Car facility, the patch was disassembled to expose the fracture for examination. Figures 2 and 3 show photographs of shell in the process of and after disassembly of the patch, respectively. The fracture was located approximately 16 feet from the circumferential weld for the head on the "A" end of the tank car. The length of the fracture (along the fracture path) measured approximately 34 inches, and the opening that resulted from the fracture measured a maximum of approximately 4.7 inches.[5] Figure 4 shows an overall view of the fracture and figure 5 shows the middle portion of the fracture. The fracture was centered about the 3:30 o'clock position relative to the "B" end. The shell contained four impression marks in the area of the fracture, randomly labeled "1" through "4", from the highest to the lowest portion of the photograph. Figure 6 shows the location of the four impression marks. Of significance, the distance between impressions "1" and "2" was approximately 4.5 inches. The significance of this measurement will be explained in section IB and IC of this report. Impressions "1" and "2" were located on the shell portion that contained the "A" end of the fracture. Impression "3" was intersected by the fracture. Impression "4" was located on the shell portion that contains the "B" end of the fracture. A strip of tape was placed horizontally across the fracture so that the ends of the strip were on relatively undamaged portions of the shell. The depth of the dent (radial distance between the strip of tape and the deepest portion of the dent) measured approximately 20 inches.

[3] The plates for the head and shell were manufactured by Bethlehem Steel Corporation. According to heat treatment records from Bethlehem Steel, the steel plates for the shell and head were subjected to a normalizing heat treatment (approximately 1,600 degrees Fahrenheit).

[4] The ends of railcars are referred as "A" and "B" ends. "B" denotes the end with the handbrake. The second character denotes the sides as left (L) or right (R) when viewed from the "B" end. Left and right sides of the tank car are positions when viewed from the "B" end.

[5] The length of the fracture path is different than the linear distance between the ends of the fracture.

The thickness of the steel plate around the circumference of the shell was measured by an ultrasonic method. Thickness measurements were performed by “R-NDT Incorporated” at the 0, 1:30, 3, 4:30, 6, 7:30, 9, and 10:30 o’clock positions around the circumference of the shell at an area that was located approximately 12 inches from the fracture towards the “A” end.[6] The measurements were made in areas that showed no evidence of deformation. The thickness of the shell measured between 0.787 and 0.802 inches, greater than the nominal thickness specified in the certificate of construction (0.777-inch).

The shell was made from a welded assembly that contained five cylinder segments. Each cylinder segment was made from a single plate of steel. The fracture was located in the second cylinder segment from the “A” end. A coupon was excised from the left side of the tank car, at approximately the 7:30 o’clock position, from the same plate of steel that contained the fracture and dent. Figure 15 shows a photograph of the shell coupon that was excised from the tank car and the coupon shows a hand sketch of its location on the tank car. The area from which the coupon was removed showed no visible evidence of deformation. The coupon was approximately 24-inches by 24-inches.

2. Head

The head at the “B” end contained a rectangular opening approximately 24-inches by 40-inches. This opening was made at the accident site. To facilitate entry into the tank car at the Union Tank Car facility, another portion of the head at the “B” end was excised in the area below this opening. In addition, a test coupon, which measured approximately 24-inches by 24-inches, was excised from the head in an area that was near the center of the head, as indicated by the box marked “H” in figure 1. The coupon was removed from an area that contained no evidence of deformation.

3. Internal Examination of the Tank Car

Visual examination of the internal wall of the tank car revealed no evidence of corrosion damage.

B. Flatbed Car CSXT 496430

The coupler assembly at the “B” end of flatbed car CSXT 496430 reportedly was found next to the dented and fractured area of tank car UTLX 900270. Flatbed car CSXT 496430 was brought to the Union Tank Car repair facility for detailed examination of the coupler. Figures 7 and 8 show photographs of the “B” end of the flatbed car. Figures 9 through 12 show photographs of the coupler assembly at the “B” end. This coupler assembly contains a shaft, knuckle, pin protector, and lower shelf portion. The pin protector is located on the lower shelf portion of the coupler

[6] Clock positions when viewed from the “B” end of the tank car.

assembly. The lower shelf of the accident coupler assembly was deformed down and toward the “A” end. The coupler assembly below the knuckle contained a gaping crack, one end of which is indicated by an arrow in figures 11 and 12. The crack extended through approximately 75% of the cross sectional thickness of the connection between the lower shelf and the shaft of the coupler assembly. The pin protector at the lower corner showed evidence of metal flow in the area indicated by arrow “1” in figure 10. The lower shelf at the lower corner also showed evidence of metal flow in the area indicated by arrow “2” in figure 10. The distance between the lower corner of the pin protector and the lower corner of the lower shelf measured approximately 4.5 inches. Identification marks found on the surface of the coupler at the “B” end indicate this coupler assembly was model “SBE67CE”, manufactured on March 2000, by McConway and Tourley, at the facility located in Kutztown, Pennsylvania.

For comparison purposes, figure 13 shows a photograph of an exemplar coupler assembly that was not involved in the accident. On this exemplar coupler assembly, the length of the pin protector was vertically aligned and was perpendicular to the length of the tank car, and the lower shelf did not show evidence of deformation.

C. Fit-up

The coupler assembly was brought next to the shell so that the deformation marks on the shell could be compared with the impact marks (metal flow resulting from impact) found on the coupler assembly. Two methods were used to bring the coupler assembly near the shell portion. In the first method, the disassembled coupler assembly was lifted by a fixture (see figure 12) and placed next to the shell. With this fixture, the coupler assembly could be rotated 360 degrees around the vertical axis. This exercise proved impractical because of difficulty in tilting the coupler about its longitudinal and lateral axes. There was concern that handling the coupler assembly with this fixture set-up could damage the mating fractures on the shell, so this exercise was terminated.

In the second method, the disassembled coupler assembly was placed up side down on the floor. A portion of the shell that contained the fracture and dent was torch cut from the tank car along the areas indicated by a solid line in figure 4. The mating faces of the fracture were separated by making circumferential saw cuts between the edges of the rectangular piece and the ends of the fracture. The excised shell portion that contained the fracture piece closer to the “A” end of the tank car was placed over the coupler assembly. Figure 14 shows the lower corner of the pin protector and the lower corner of the lower shelf of the coupler assembly aligned with dents “1” and “2” in the “A” end piece from the tank car. As indicated earlier, the exterior surface of the shell contained two impression marks (indicated by arrows “1” and “2” in figures 4 and 5) on the “A” end side of the fracture. Impression “1” was curved, with a radius similar to the lower corner for the pin protector. The deepest portion of impression “2” was consistent with the size of the lower corner of the lower shelf of the coupler assembly. The distance between impressions "1" and "2" measured approximately 4.5 inches inches, same as the distance between the lower corner of the pin protector and the lower corner of the lower shelf.

The excised shell portion with the "B" end of the fracture was also placed over the various parts of the coupler assembly. A portion of the lower corner of the lower shelf was the only area that fitted within the impression at deformation marks "3" and "4".

II. Laboratory Examination

Figure 15 shows a photograph of excised head and shell coupons, and mating fracture pieces from the shell of tank car UTLX 900270 that were submitted to the Safety Board Materials Laboratory.

A. Fracture

The mating fractures faces were cleaned with a nylon brush and rinsed with alcohol. Figure 16 show a composite photograph of the fracture face at the "A" end and close-up photograph of a portion of the fracture near the center of the fracture. Examination of the fracture face at the "A" end revealed a fracture on a slant plane typical of a shear fracture in an area located nearly midway between the ends of the fracture. The length of the fracture in the shear region measured approximately 2.5 inches, which is approximately 7% of the total length of the fracture (34 inches). Additional photographs of the fracture in the shear region are shown in figure 17. The remaining portion of the fracture exhibited a chevron pattern typical of a brittle overstress fracture. The chevron pattern emanated from the upper and lower ends of the shear region and extended approximately 15.5 inches above upper end of the shear fracture and approximately 16 inches below the lower end of the shear fracture. The fracture faces contained no evidence of crack arrest marks. Visual examination of the fracture faces with a magnifying glass revealed that fine fracture features appeared to have been etched away, probably from exposure to the accident conditions.

B. Thickness Measurement of Impression Marks

The ultrasonic measurements indicated that the average thickness of the shell was approximately 0.79 inch. The thickness of the wall at impression marks "1" through "3" was measured with a point micrometer, and the thickness of the wall at impression "4" was measured by an ultrasonic method. The portion of impression "3" on the "A" side was deeper than the portion on the "B" side of the fracture. Results of the thickness measurements are indicated in the following table. The table lists the most severely thinned area associated with each impression.

Thickness Measurements at Various Impressions			
Impression Number	Wall Thickness at Impression	Approx. Original Wall Thickness	Calculated Reduction of Original Wall Thickness
1	0.640 inch	0.79 inch	19 %
2	0.365 inch	0.79 inch	54 %
3	0.415 inch	0.79 inch	47 %
4	0.470 inch	0.79 inch	41 %

C. Chemical Analysis

The head and shell coupons were analyzed for chemical composition by a glow discharge spectrometer, model Leco Corporation GDS500A. The coupons were tested for elements that are specified in M-1002 for AAR TC128B steel, and for certain elements that were not specified.[7] Table 1 indicates which elements were specified and the maximum amount or range that was specified. The results of the chemical analysis indicate that samples removed from the two coupons conform to the requirements of AAR TC128B steel.

D. Microstructure

Rectangular pieces were excised from the head and shell coupons. The shell's circumferential and longitudinal planes and the internal plane that was located midway between the shell's interior and exterior surfaces were prepared for metallograph examination and etched with Nital reagent. Similar sections (circumferential, radial, and internal plane located midway between the interior and exterior surfaces) were prepared from the head coupon. Figures 18 through 25 show typical microstructures from the shell and head coupons.

Examination of the etched sections revealed that each coupon contained a microstructure of pearlite and ferrite. The etched sections from the head and shell showed that both the circumferential and radial planes contained rows of predominantly ferrite grains that were separated by rows of predominantly pearlite grains. The pearlite and ferrite grains formed bands that were oriented parallel to the surface of the plate consistent with banding. The head and shell contained nearly equiaxed grains.

The microstructure in the head and shell as viewed on the metallurgical sections that were located midway between the tank car's interior and exterior surfaces showed colonies of pearlite grains that followed an irregular preferred orientation, see figures 20, 21, 24, and 25. Based on this preferred orientation, test specimens that were manufactured from the head and shell were labeled "Longitudinal" or "Transverse". "Longitudinal" indicated that the length of the test specimen was oriented parallel to the length of the irregular pearlite grain colonies. Similarly, "Transverse" indicated that the length of the test specimen was perpendicular to the length of the "Longitudinal" test

[7] When M-1002 is mentioned in this report, it is in reference to edition dated September 1, 1992.

specimen.[8] The microstructure evaluation determined that the rolling direction of the steel plate for the shell was parallel to the circumferential direction of the shell, and the rolling direction of the head was aligned parallel to an imaginary line that was drawn vertically up and down the head, as if the tank car was on the rail.

Artech Testing LLC[9] determined the prior austenitic grain size after carburizing samples of the shell and head in accordance with ASTM E112 Section A3.2.1.2 (McQuaid-Ehn test procedure). Photomicrographs were taken of an etched microstructure at 400X (photographs not shown). The size of the austenitic grains was determined by the Heyn Lineal Intercept Procedure. The grain size was determined by counting the number of intersections between austenitic grain boundaries for 10 random lines placed on each photograph. Two photographs were taken for each sample. The austenitic grain size of the head and shell was determined to be 9.71 and 9.69, respectively. Grain sizes typically range from 1 to 10. A larger number represents a finer or smaller grain size. M-1002 (AAR TC128B) indicates that the austenitic grain size should be finer than number 5 (number that is larger than 5). The measured austenitic grain numbers were finer than 5, in compliance with AAR TC128B steel.

A metallurgical section was made through impression “3” in the area indicated by section line “A-A” in figure 17. Figure 26 shows photographs of the polished and etched section. The etched section showed that the banded microstructure was deformed to approximately follow the surface of the impression. An area of metal flow was noted, as indicated in figure 26.

The etched sections from all the tank car coupons showed no evidence of corrosion pitting, general corrosion damage, or blisters[10] on either the interior or exterior surface. Also, the sections showed no evidence of stress corrosion cracking (such as branching cracks) associated with the fracture.

E. Tensile Testing

AAR M-1002 indicates that TC128B steel should have a yield strength of 50 kilo pounds per square inch (ksi) minimum, an ultimate tensile strength between 81 and 101 ksi, and an elongation of 22% minimum. In addition to these requirements, AAR M-1002 indicates that all tests shall comply with requirements in ASTM A20 "General Requirements for Steel Plates for Pressure Vessels". ASTM A20 indicates that the

[8] ASTM E-616 titled “Standard Terminology Relating to Fracture Testing,” uses a two-letter code for specifying the crack plane orientation code for rectangular sections. The first letter indicates the direction normal to the crack plane, and the second letter the expected direction of crack propagation. As an example, a longitudinal specimen indicated in this report is equivalent to a specimen in the long-transverse (L-T) crack plane orientation, and a transverse specimen is equivalent to a specimen in the transverse-long (T-L) crack plane orientation for rolled plate.
[9] Artech Testing LLC, Chantilly, Virginia, performed austenitic grain size measurements, tensile and Charpy V-notch impact testing.
[10] Blisters are associated with hydrogen induced cracking.

longitudinal axis of the tension-test specimens shall be transverse to the final rolling direction, referred as "transverse" specimens. [11]

A total of four tensile specimens were tested. One longitudinal specimen and one transverse specimen were tested from the shell. One test specimen from the head was prepared so that the length of the specimen was oriented parallel to the length of the irregular pearlite colonies. Another test specimen from the head was prepared so that the length of the specimen was oriented perpendicular to the orientation of the pearlite colonies. The results of the tensile tests are shown in Table 2.

F. Charpy V-notch Impact Testing

Four groups of Charpy V-notch impact test specimens[12] were machined from the coupons listed in Table 3. Each test specimen was broken at a specified temperature in the range between minus 150 °F and 150 °F. A ductile to brittle transition curve was prepared for each group by plotting the temperature at which the Charpy V-notch specimen was tested versus the impact energy that was absorbed as the specimen fractured. A ductile to brittle transition temperature (DBTT) was derived from the constructed curve. The curve will typically have an upper and lower shelf where the energy required to break the specimen remains nearly constant relative to temperature. For the purposes of this report, the DBTT was defined as the temperature corresponding to the average of the energy of the upper and lower shelves. The individual transition curves are shown in Appendices ”A” and ”B” along with the test data for each tested specimen.

Table 4 shows the calculated DBTT for each group of Charpy specimens. The following are general observations regarding the DBTT. The DBTT for the head and shell coupons was between minus 8 °F and zero °F, with the exception that the shell coupon in the “Transverse” orientation showed a significantly higher DBTT (40 °F) than all the specimens.

The tank reportedly was loaded with liquefied chlorine at minus 14 °F approximately 48 hours prior to the accident.[13] The accident occurred at 2:40 A.M. and the ambient temperature at the accident site was approximately 55 °F.[14] Union Tank Car Company performed computer simulation to determine the approximate temperature of the chlorine at the time of the accident for a variety of assumed ambient temperatures. Using an estimated average ambient temperature, the computer simulations indicated that the temperature of the chlorine at the time of the accident

[11] Similarly, a longitudinal test specimen would have the length of the specimen that was oriented parallel to the rolling direction of the steel plate.
[12] Standard size specimen, Type A, 10 mm x 10 mm x 55 mm, per ASTM A370 “Standards Methods and Definitions for Mechanical Testing of Steel Products”, and ASTM E23 “Standard Methods for Notched Bar Impact Testing of Metallics”.
[13] The tank car was finished filling on January 4 at 3:10 am, at August, Georgia.
[14] Closest weather reporting location to Graniteville, SC, was from Augusta, Georgia, located approximately 17 miles south. According to NOAA, National Climatic Data Center, Local Climatological Data, the average temperature for Augusta, GA was 57 °F, for the period between the time of loading and the time of derailment.

was approximately 6 °F. Because the space between the jacket and shell was insulated, the temperature of the shell was estimated to be at approximately the same temperature as that of chlorine. Table 5 shows the energy required to fracture specimens at 6 °F. The impact energy required to fracture specimens from the shell in the "Transverse" orientation was lower (30 ft-lbs) compared to specimens in the "Longitudinal" orientation (75 ft-lbs). The impact energy required to fracture the head coupon in the Transverse" and "Longitudinal" orientation was 77 ft-lbs and 85 ft-lbs, respectively.

G. Fracture Examination of Charpy Specimens

The fracture face of the Charpy specimens from the head and shell were examined to determine the temperatures where the fracture faces showed 100% fibrous (ductile) features, 100% granular (brittle), and 50% brittle - 50% percent ductile (also known as the fracture appearance transition temperature [FATT]).

The fracture faces of Charpy specimens from the head that were tested at and above 70 °F in both orientations of testing showed 100% fibrous (ductile) features. The fracture faces of the head specimens that were tested at minus 100 °F and lower in both orientations of testing showed 100% brittle features. The fracture faces of the head specimens that were tested between minus 100 °F and 70 °F showed mixed-fracture features (combination of ductile and brittle fractures). The fracture faces of head specimens that were tested at 32 °F showed nearly equal distribution of the two fracture features (nearly 50% of the specimen fracture area showed brittle features and the remaining fracture showed ductile features), an indication that the FATT for specimens in both orientations of testing was approximately 32 °F.

The fracture faces of Charpy specimens from the shell that were tested at and above 100 °F in both orientations of testing showed 100% ductile features. The fracture faces of the shell specimens that were tested at minus 50 °F and lower in both orientations of testing showed brittle features. The fracture faces of the shell specimens that were tested between minus 50 °F and 100 °F showed mixed-fracture regions (combination of ductile and brittle fractures). Based on the appearance of the fractures, the FATT for the longitudinal and transverse specimens from the shell was 32 °F and 70 °F, respectively.

H. Wall thickness

The thickness of the head and shell were measured with a point micrometer at the Safety Board's Materials Laboratory. The thickness of the head in areas that showed no evidence of deformation damage measured between 0.83 and 0.835 inch, confirming that the thickness of the head was greater than the nominal thickness specified in the certificate of construction (53/64-inch [0.8281-inch]).

The thickness of the shell measured between 0.780 and 0.81 inch, confirming that the thickness of the shell was greater than the nominal thickness specified in the certificate of construction, 0.777 inch.

49 CFR Part 179.100-6 specifies the minimum thickness of the steel plates for the construction of DOT 105A500W tank cars. This section of the CFR indicated that the minimum thickness shall not be less than the greater of the calculated value (using formula provided in the CFR) or that provided in table 49 CFR Part 179.101-1. The minimum thickness of the steel plate for this tank car was calculated (using the CFR formula) to be 0.777 inch, whereas, table 49 CFR Part 179.101-1 indicates a minimum thickness of 9/16 inch (0.5625-inch). In this case, the calculated value prevails and the minimum thickness should be 0.777-inch. The measured thickness of the head and the shell was greater than the minimum thickness specified for DOT 105A500W tank cars.[15]

Frank P. Zakar
Senior Metallurgist

[15] According to the certificate of construction, the ruptured tank car was originally manufactured as a Department of Transportation (DOT) specification 105A500W tank cars. The first three characters "105" refer to the class. Requirements for class 105 tank cars is specified in 49 Code of Federal Regulations (CFR), Part 179.

Table 1. Steel Coupon Chemical Analysis

Element	Specified by AAR TC128 Product Analysis[16]	Head (weight %)	Shell (weight %)
Aluminum	Not specified	0.035	0.037
Boron	Not specified	< 0.001	< 0.001
Carbon	0.29 max	0.242	0.201
Chromium	0.25 max	0.041	0.177
Copper	0.35 max	0.013	0.024
Manganese	0.92 - 1.62 max[17]	1.33	1.22
Molybdenum	0.08 max	0.055	0.041
Nickel	0.25 max	0.019	0.016
Niobium	Not specified	0.002	0.003
Phosphorus	0.035 max	0.024	0.019
Silicon	0.13 – 0.55 max[18]	0.367	0.318
Sulfur	0.04 max	0.005	0.010
Tin	Not specified	< 0.01	< 0.01
Titanium	Not specified	0.003	0.003
Tungsten	Not specified	0.011	0.011
Vanadium	0.08 max	0.060	0.041
Iron	Remainder	Remainder	Remainder

[16] AAR Tank Car Specification, revision September 1992.
[17] For thickness between 0.75 and 1.00 inch
[18] For thickness between 0.75 and 1.00 inch

Table 2: Tension Test Results

Property	**Specified** (ksi)	**Head Longitudinal** Measured (ksi)	**Head Transverse** Measured (ksi)	**Shell Longitudinal** Measured (ksi)	**Shell Transverse** Measured (ksi)
Yield Strength, 0.2% Offset (ksi)	50	56.9	58.3	53.6	53.5
UltimateTensile Strength (ksi)	81-101	83.6	83.5	80.3	80.7
Elongation (%)	22	34.5	34.3	36.4	34.4

Table 3. Charpy Impact Testing Orientation

Coupon	**Orientation Of Specimens**	**Data Results and DBTT Curve found in Appendix**
Head	Longitudinal	A
Head	Transverse	A
Shell	Longitudinal	B
Shell	Transverse	B

Table 4. Ductile to Brittle Transition Temperature (^{o}F) for Selected Coupons

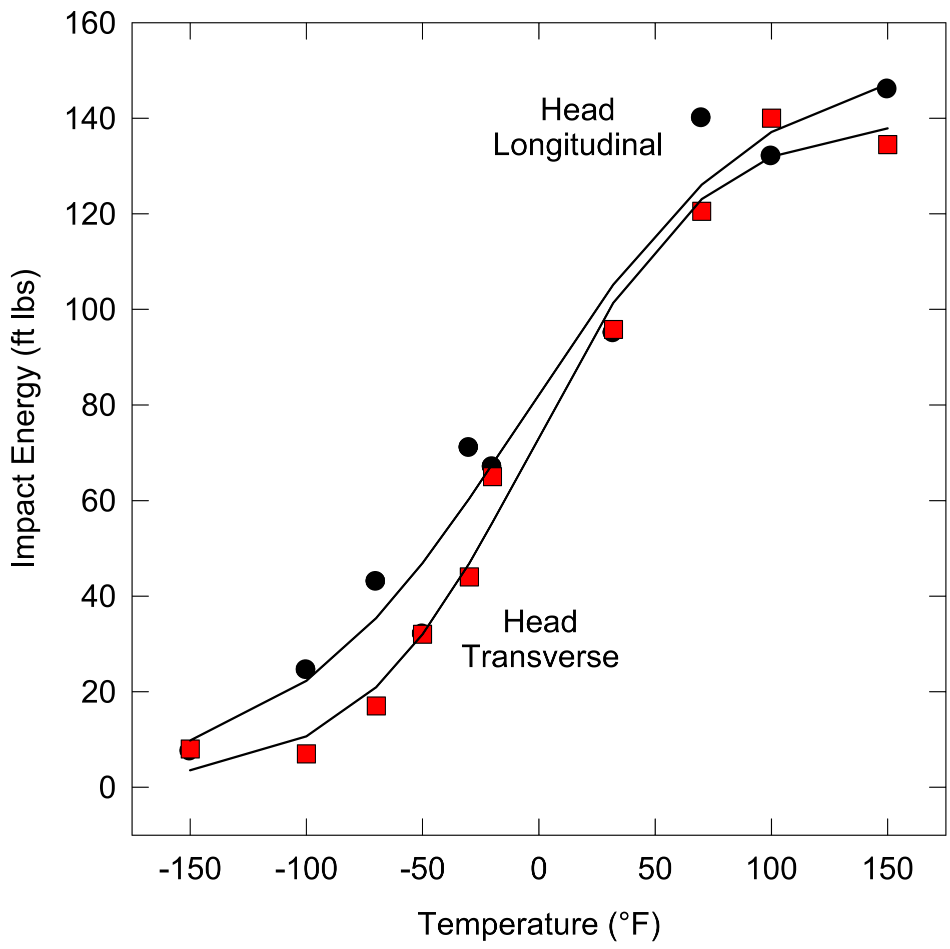
Coupon	**DBTT (^{o}F)**	
	Longitudinal	**Transverse**
Head	-8	-5
Shell	0	40

Table 5. Energy Required to Break Charpy V-notch Specimen at 6 ^{o}F

Coupon	**Energy (ft-lb) at 6 ^{o}F**	
	Longitudinal	**Transverse**
Head	85	77
Shell	75	30

APPENDIX A

DBTT Curve for Head
Longitudinal and Transverse Orientations



Testing Data for Head - Longitudinal Orientation

Test Temperature (°F)	Specimen #1 Impact Energy (ft•lbs)
-150	7.5
-100	24.5
-70	43.0
-50	32.0
-30	71.0
-20	67.0
32	95.0
70	140.0
100	132.0
150	146.0

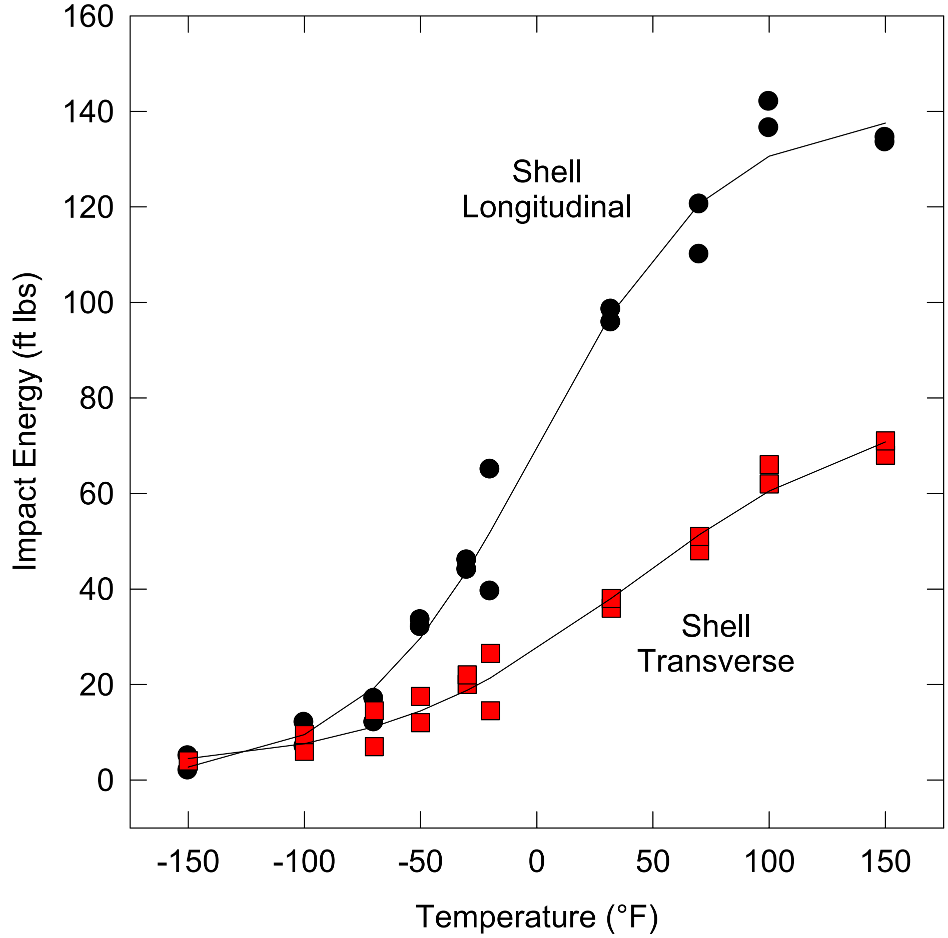
Testing Data for Head - Transverse Orientation

Test Temperature (°F)	Specimen #1 Impact Energy (ft•lbs)
-150	8.0
-100	7.0
-70	17.0
-50	32.0
-30	44.0
-20	65.0
32	95.8
70	120.5
100	140.0
150	134.5

APPENDIX B

DBTT Curve for Shell

Longitudinal and Transverse Orientations



Testing Data for Shell - Longitudinal Orientation

Test Temperature (^oF)	Specimen #1 Impact Energy (ft•lbs)	Specimen #2 Impact Energy (ft•lbs)	**Average** Impact Energy (ft•lbs)
-150	2.0	5.0	3.5
-100	7.0	12.0	9.5
-70	12.0	17.0	14.5
-50	32.0	33.5	32.8
-30	44.0	46.0	45.0
-20	39.5	65.0	52.3
32	95.8	98.5	97.2
70	110.0	120.5	115.3
100	136.5	142.0	139.3
150	133.5	134.5	134.0

Testing Data for Shell - Transverse Orientation

Test Temperature (^oF)	Specimen #1 Impact Energy (ft•lbs)	Specimen #2 Impact Energy (ft•lbs)	**Average** Impact Energy (ft•lbs)
-150	4.0	4.0	4.0
-100	6.0	9.5	7.8
-70	7.0	14.5	10.8
-50	12.0	17.5	14.8
-30	20.0	22.0	21.0
-20	14.5	26.5	20.5
32	36.0	38.0	37.0
70	48.0	51.0	49.5
100	62.0	66.0	64.0
150	68.0	71.0	69.5

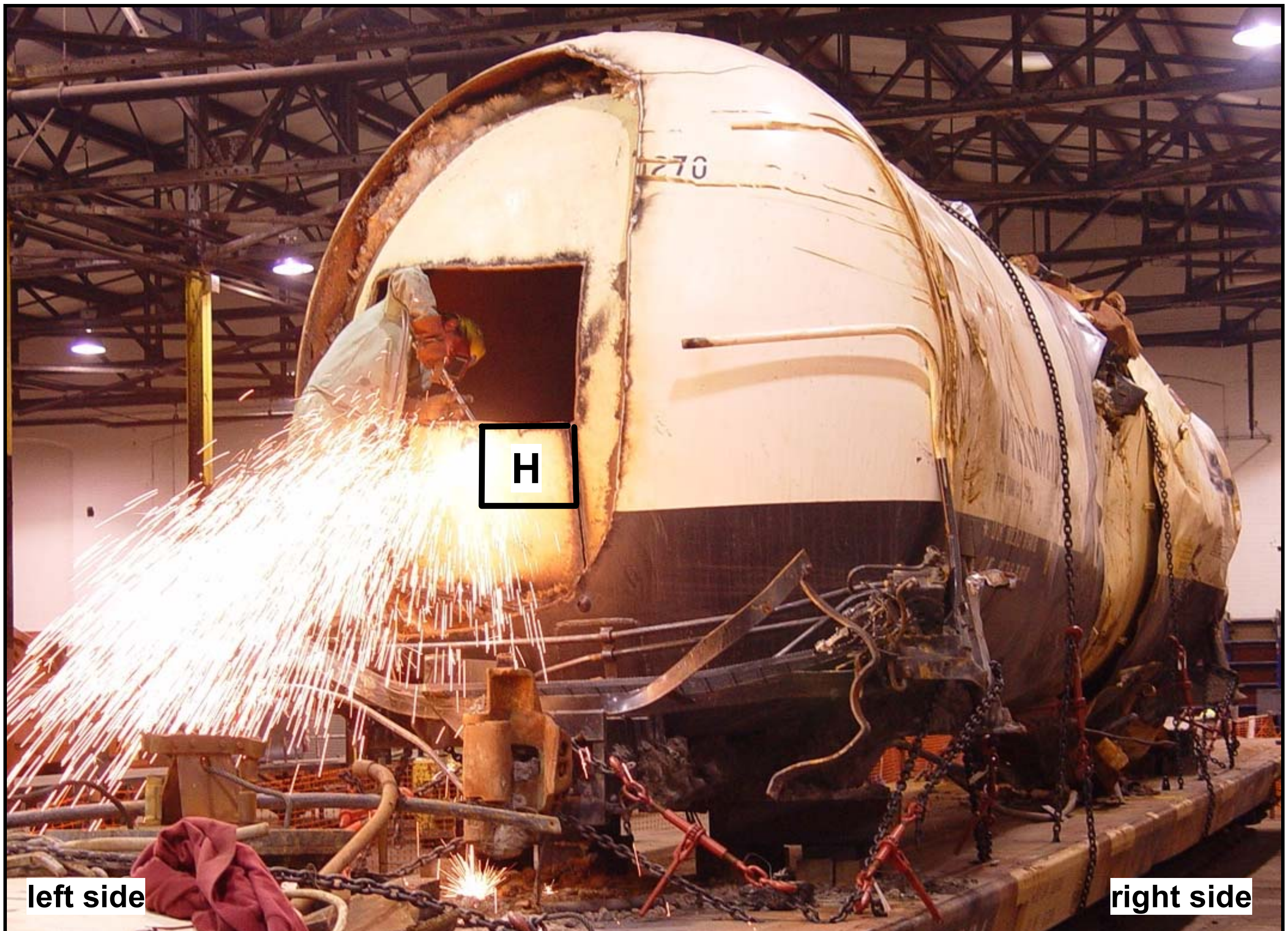


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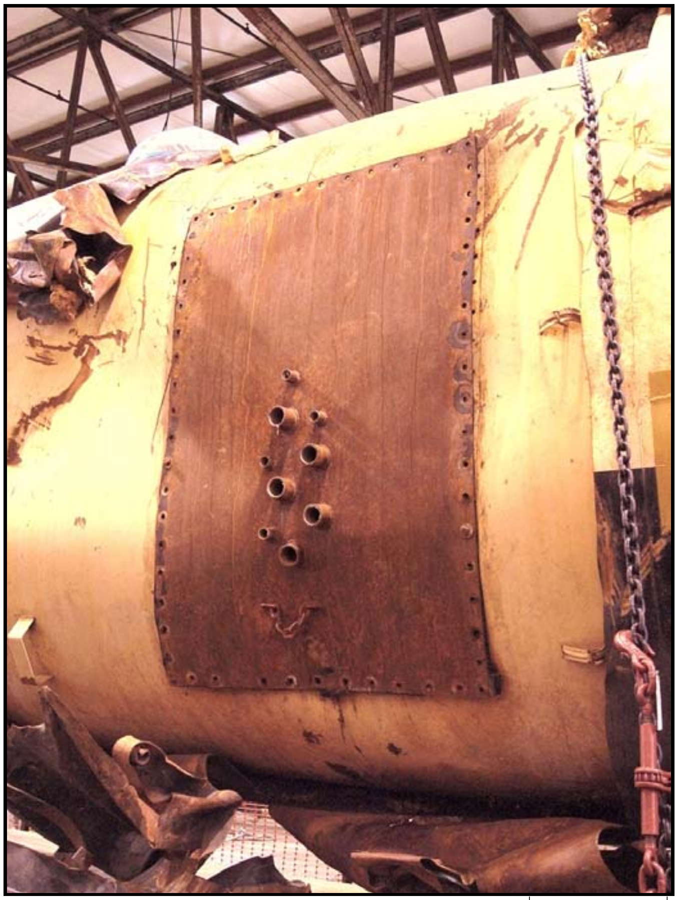
Figure 1. View looking at the "B" end of tank car UTLX 900270. A torch cutting operation is under way to remove a test coupon from the head, from the the area outlined by box "H".

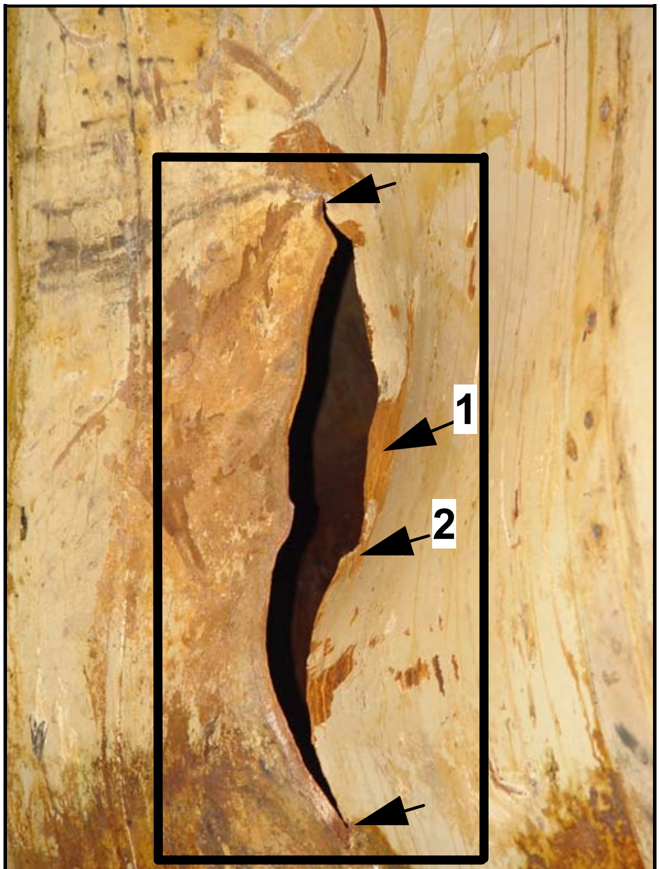


ImageNo:0502A00798, Project No:2005020010 500 mm

Figure 2. View of the right side of the tank car showing a patch that covered the puncture.

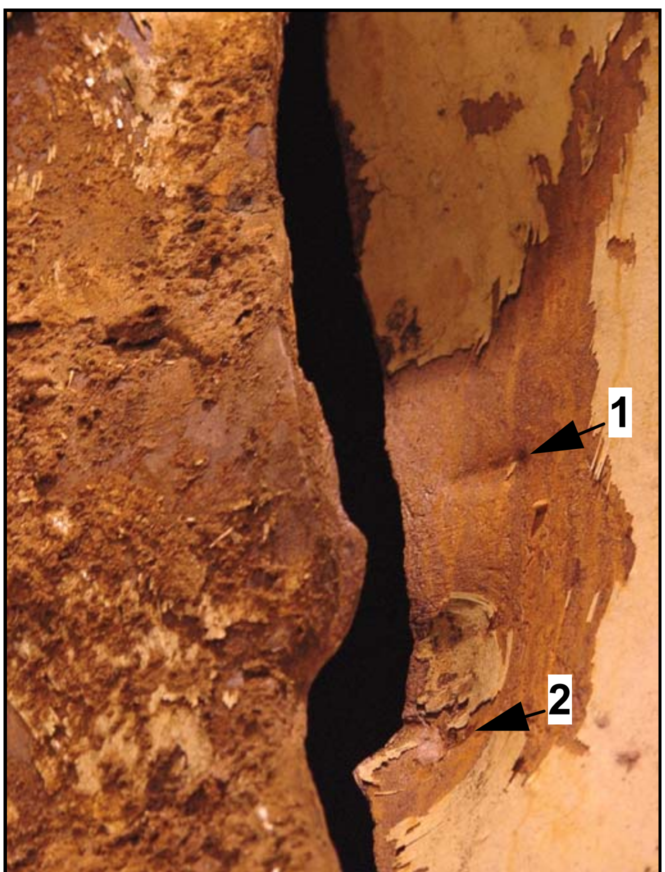
ImageNo: 0502A00808, Project No:2005020010 500 mm

Figure 3. View of the right side of the tank car after the patch was disassembled. Arrows indicate the ends of the puncture (fracture).



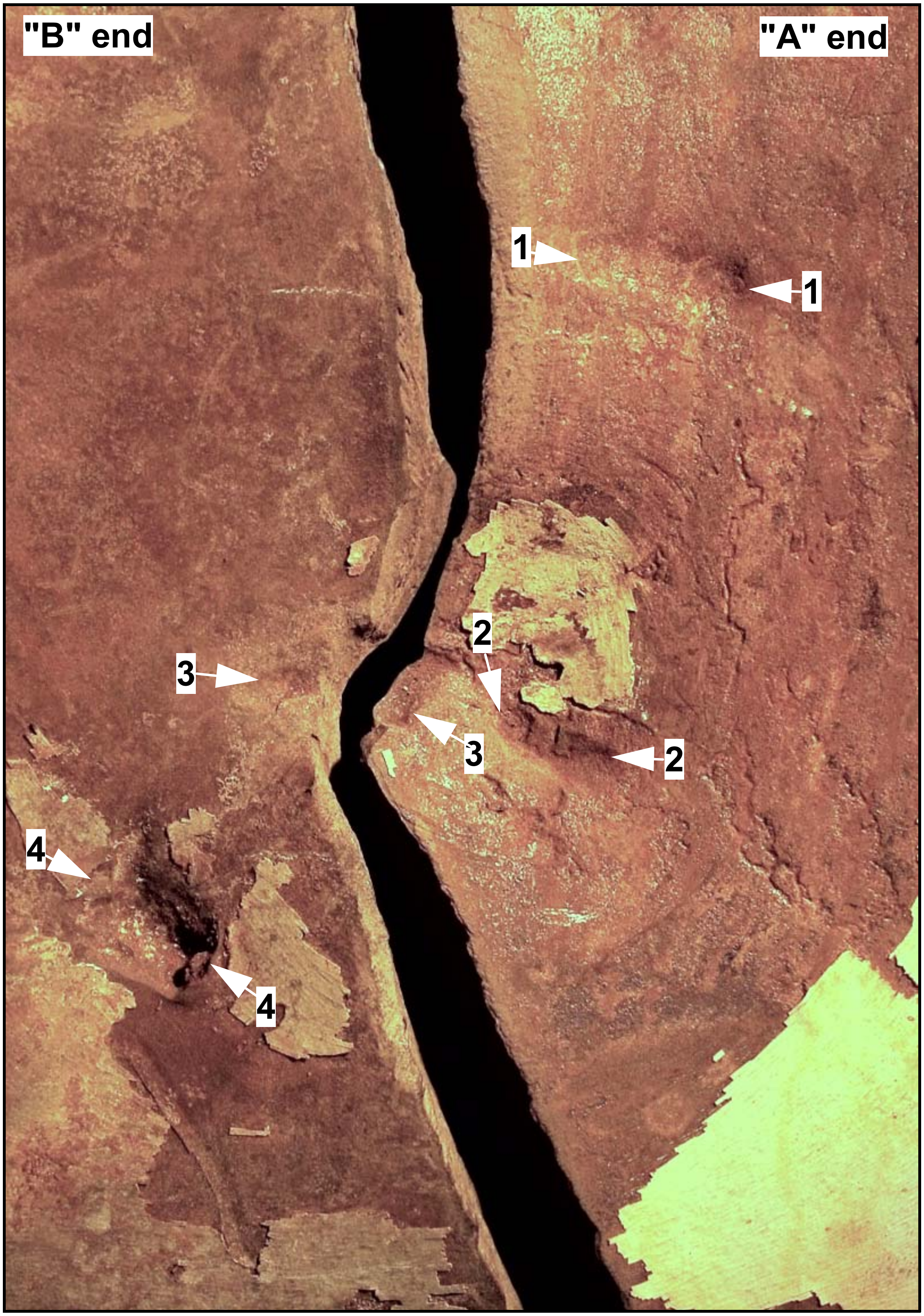
ImageNo:0502A00812, Project No:2005020010 200 mm

Figure 4. Close-up photograph of the fracture. The solid line indicates the portion of the shell that was torch cut to facilitate removal of the fracture. Arrows indicate the ends of the fracture. Arrows "1" and "2" indicate the location of two impression marks.



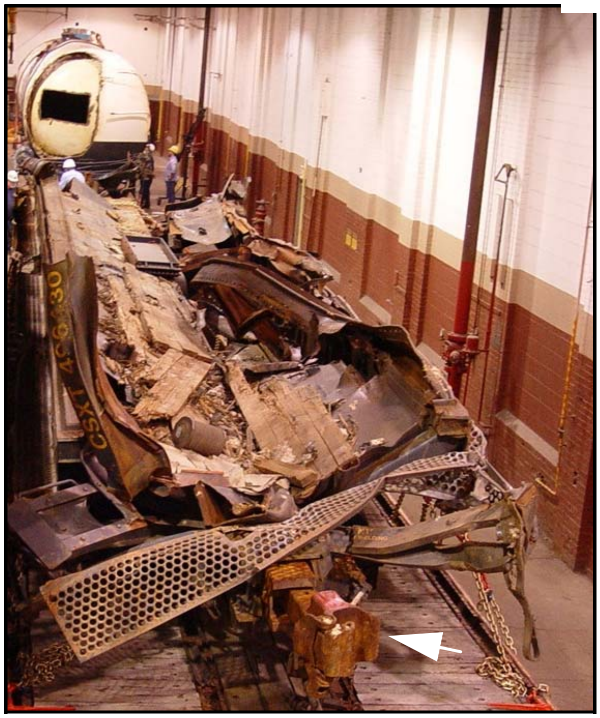
ImageNo: 0502A00820, Project No:2005020010 50 mm

Figure 5. Higher magnification view of impression marks arrowed "1" and "2" in figure 4.



ImageNo:0503A00453, Project No:2005020010

Figure 6. External face of the shell showing a portion of the mating fractures that was located nearly midway between the ends of the fracture. Impression marks arrows "1" through "4" are located between arrows with the same respective numbers. Photograph was taken after the mating fracture was excised and reassembled, as if the shell pieces were intact.



ImageNo:0502A00842, Project No:2005020010

Figure 7. View of the flatbed car at the "B" end. Arrow indicates the coupler assembly.

ImageNo: 0502A00869, Project No:2005020010

Figure 8. Another view of the flatbed car at the "B" end. Arrow indicates the coupler assembly.

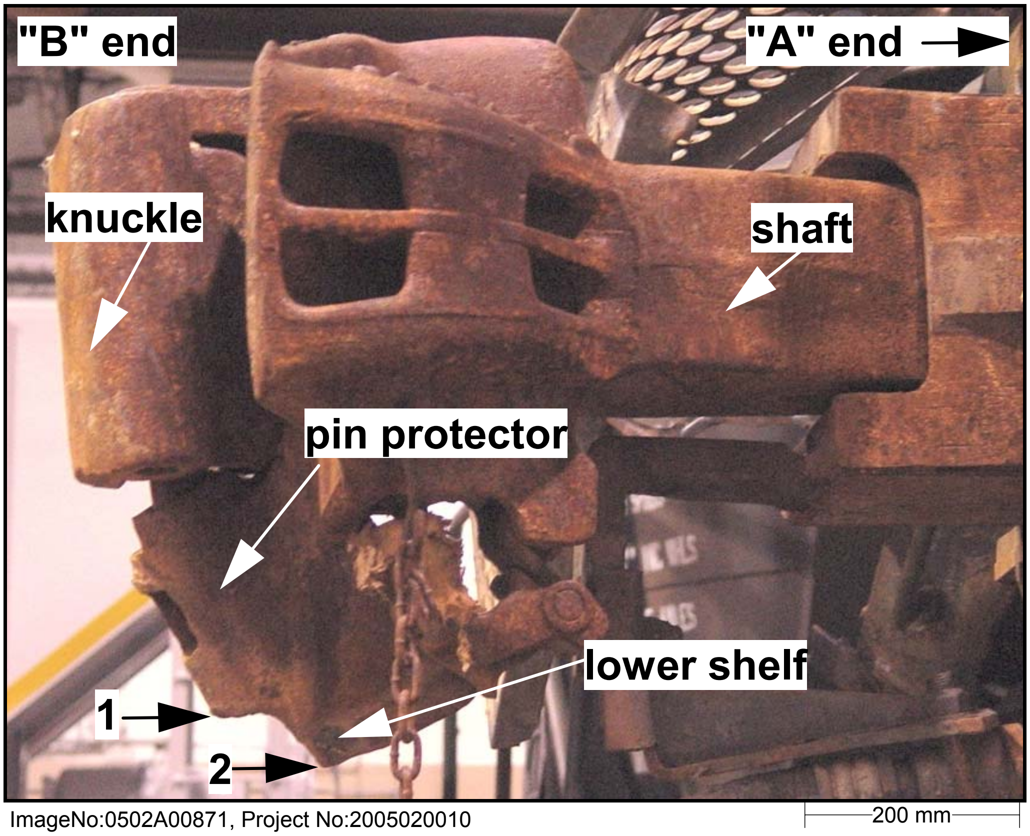


Figure 9. View of the "B" end coupler assembly showing the right side. The lower shelf was deformed toward the "A" end of the tank car.

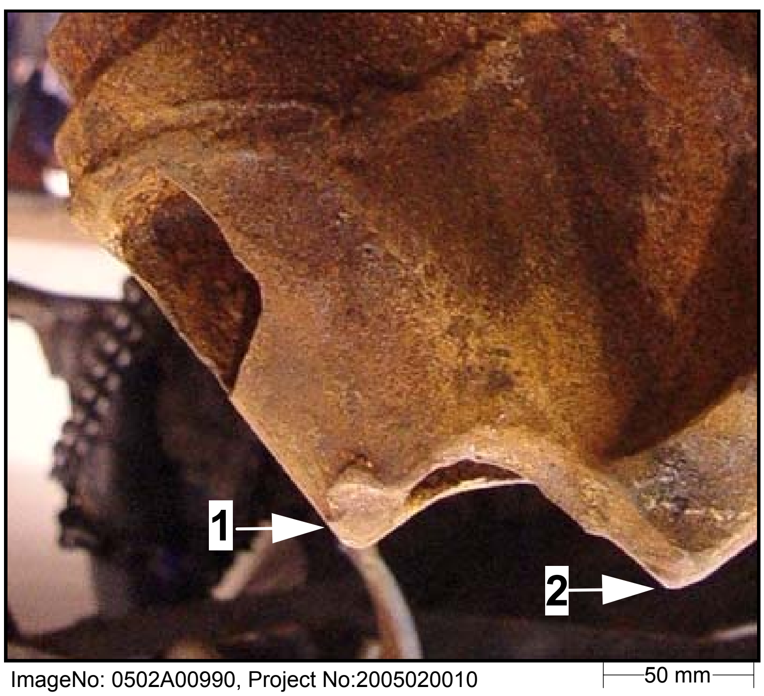
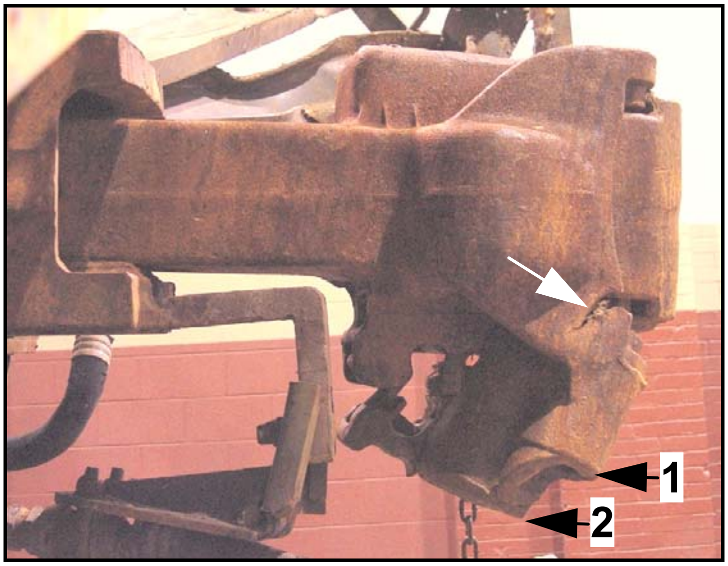
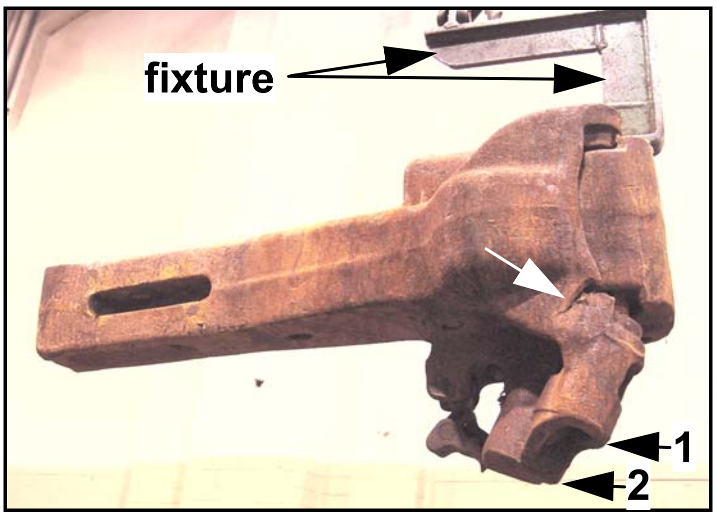


Figure 10. Closer view of the lower shelf showing deformation at the lower corner of the pin protector, indicated by arrow "1", and deformation at the lower corner of the lower shelf, indicated by arrow "2".



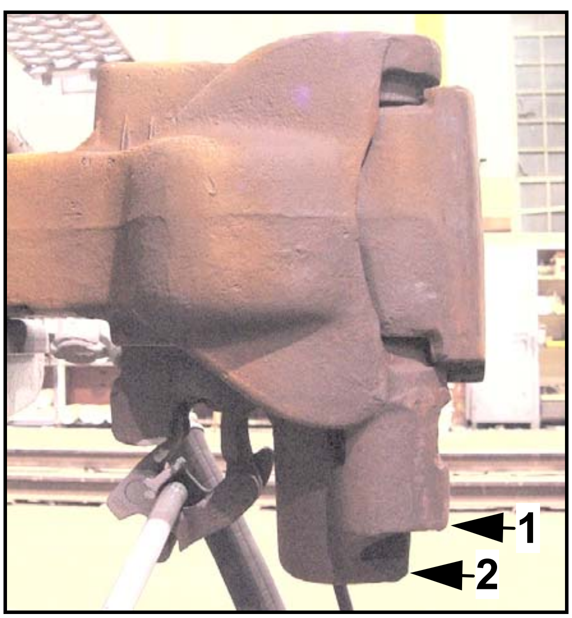
ImageNo:0502A00862, Project No:2005020010

Figure 11. Left side of the coupler assembly at the "B" end showing a gaping crack, indicated by arrow, in the area above the pin protector.



ImageNo: 0502A00900, Project No:2005020010

Figure 12. Left side of the coupler assembly after disassembly. Arrow indicates the location of a gaping crack.



ImageNo:0502A00862, Project No:2005020010

Figure 13. Left side of a coupler assembly from a flatbed car that was not involved in the accident. Shown for comparison purpose. Arrow "1" indicates the location of the lower corner of the pin protector, and arrow "2" indicates the location of the lower corner of the lower shelf.

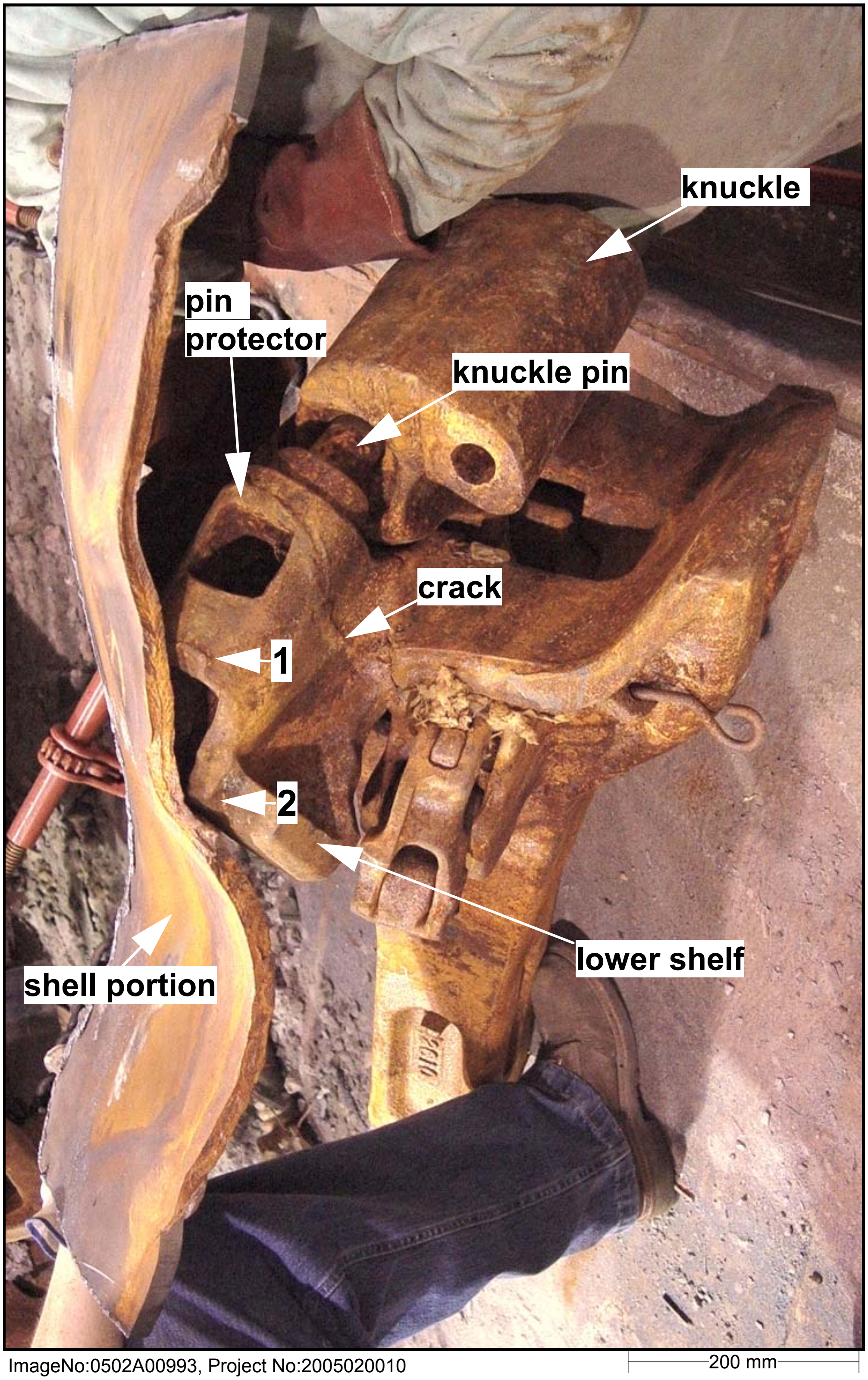
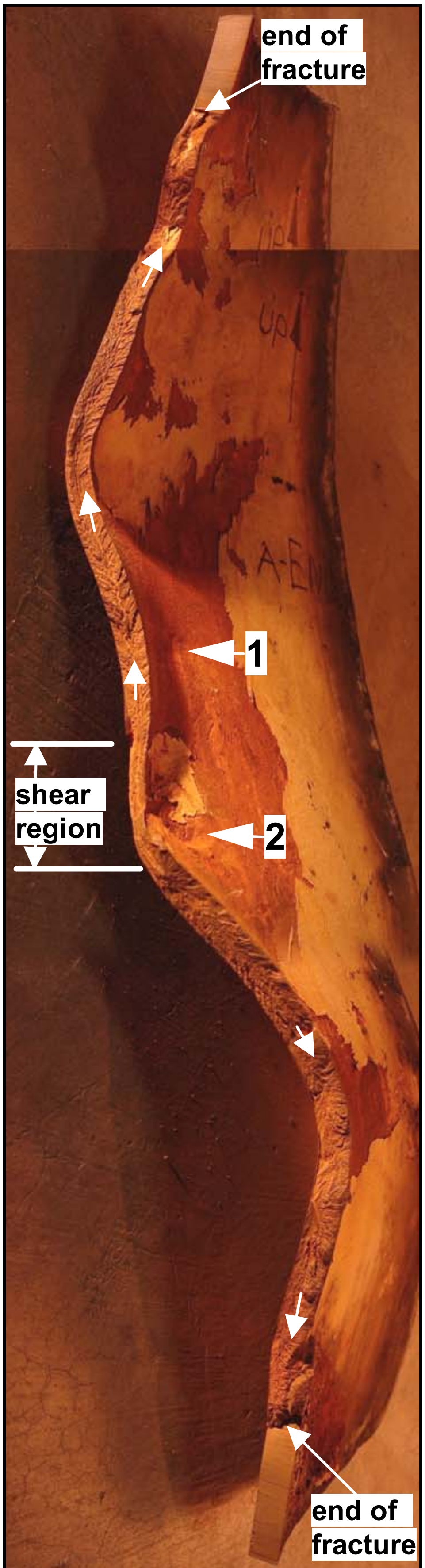


Figure 14. Fit-up test showing the coupler assembly (right side of photgraph) as it was placed against the external face of the shell portion (left side of photograph) that contained the "A" end of the fracture. Deformation at the lower corner of the pin protector, arrowed "1", and at the lower corner of the lower shelf, arrowed "2", corresponded with impression marks found at the external face of the shell, indicated by arrows "1" and "2" in figures 4 and 5, respectively.

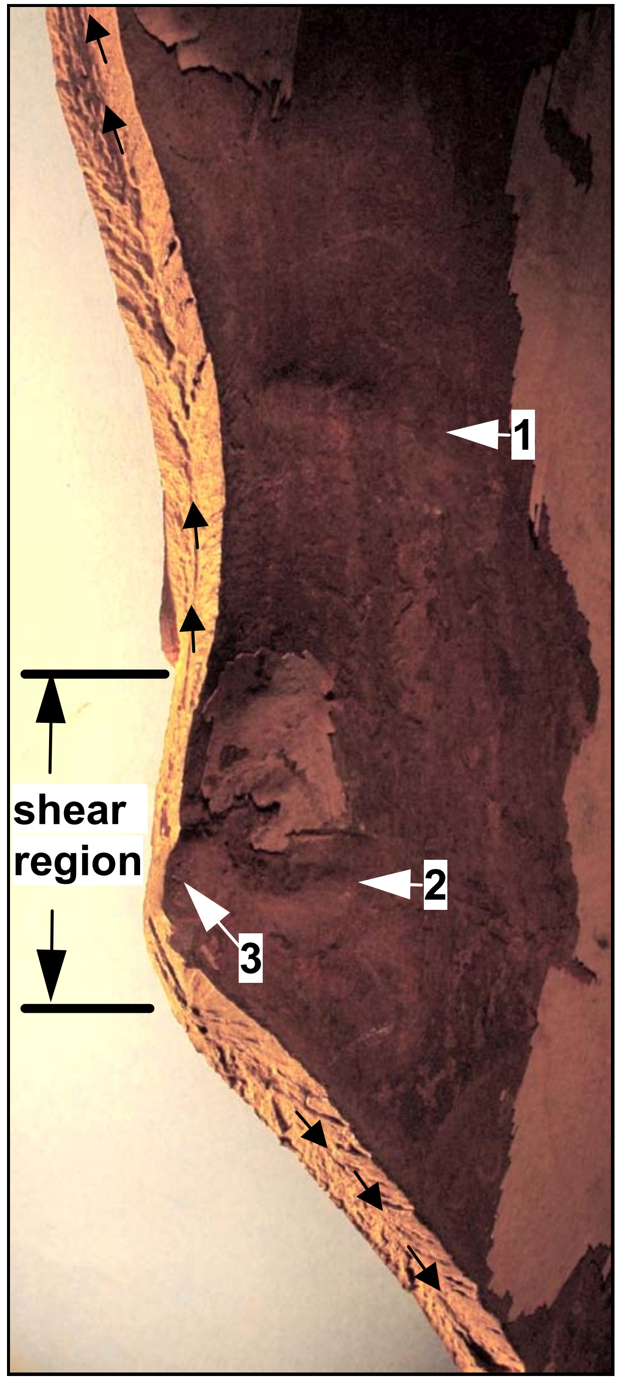
ImageNo:0503A00406, Project No:2005020010

500 mm

Figure 15. Excised shell coupon (upper left corner); head coupon (upper right corner), and mating fractures of the shell (lower side of photograph) showing the external faces.

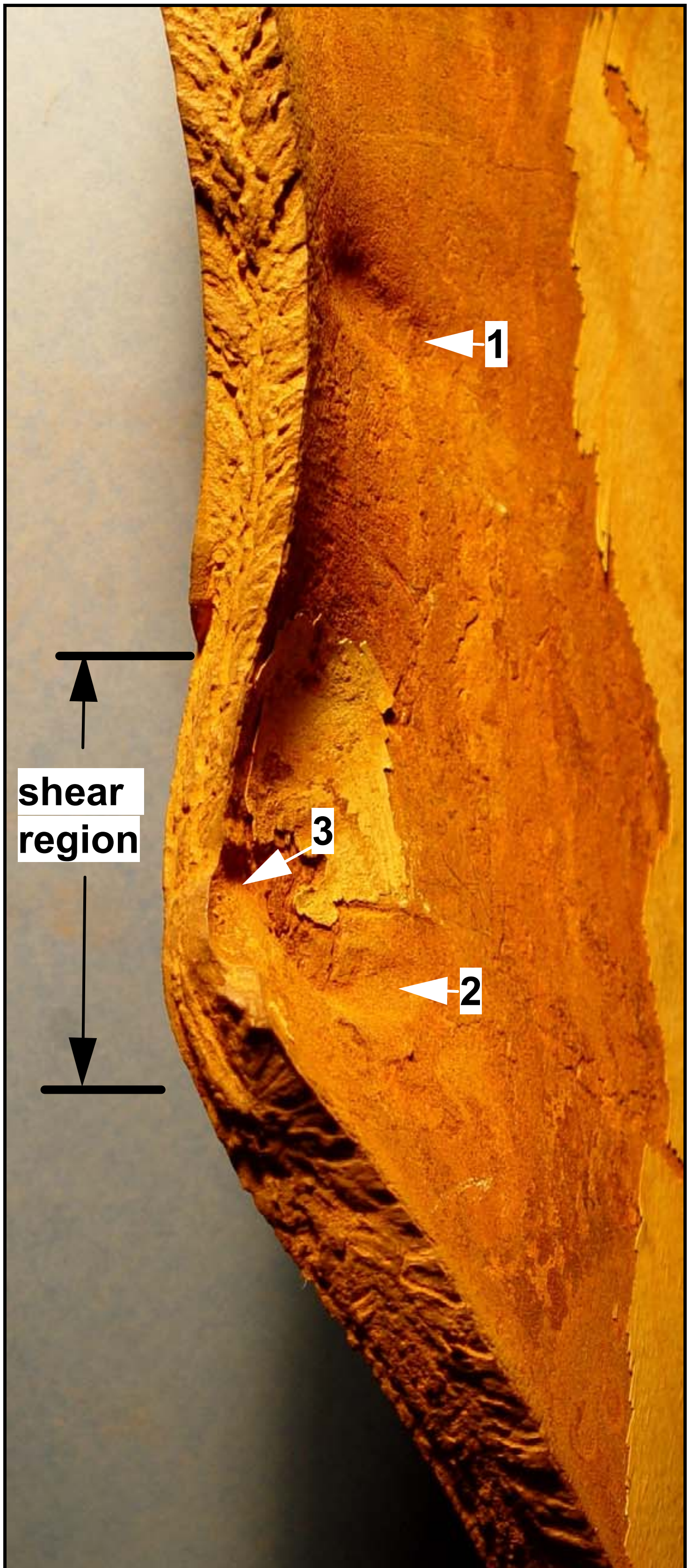


ImageNo:0503A00622, Project Nc 200 mm

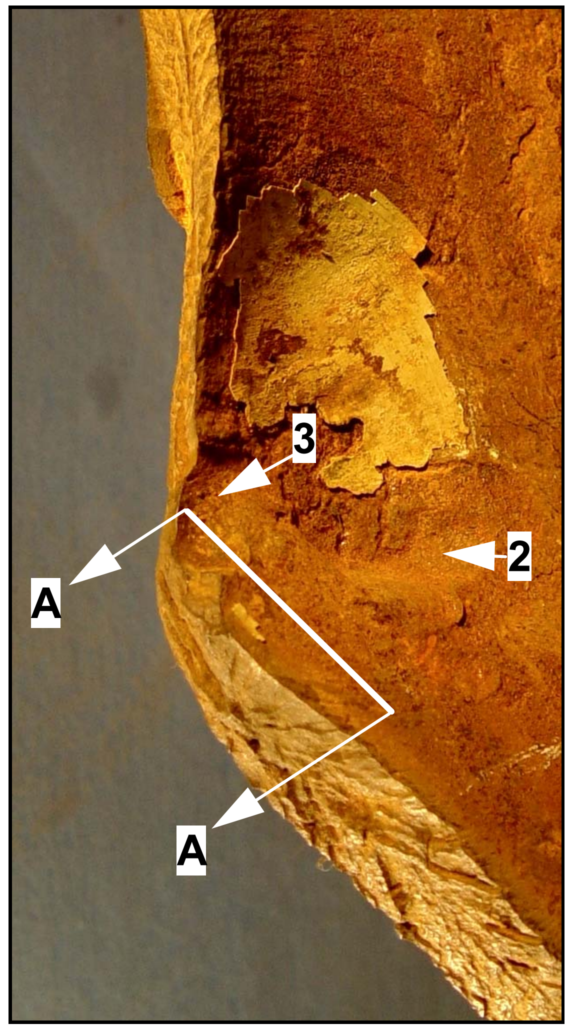


ImageNo: 0503A00486, Project No:2005020010

Figure 16. Composite photograph of the shell fracture on the "A" end (left side of the page) and a higher magnification photograph of the shear fracture region (right side of page). Arrows indicate direction of fracture propagation.

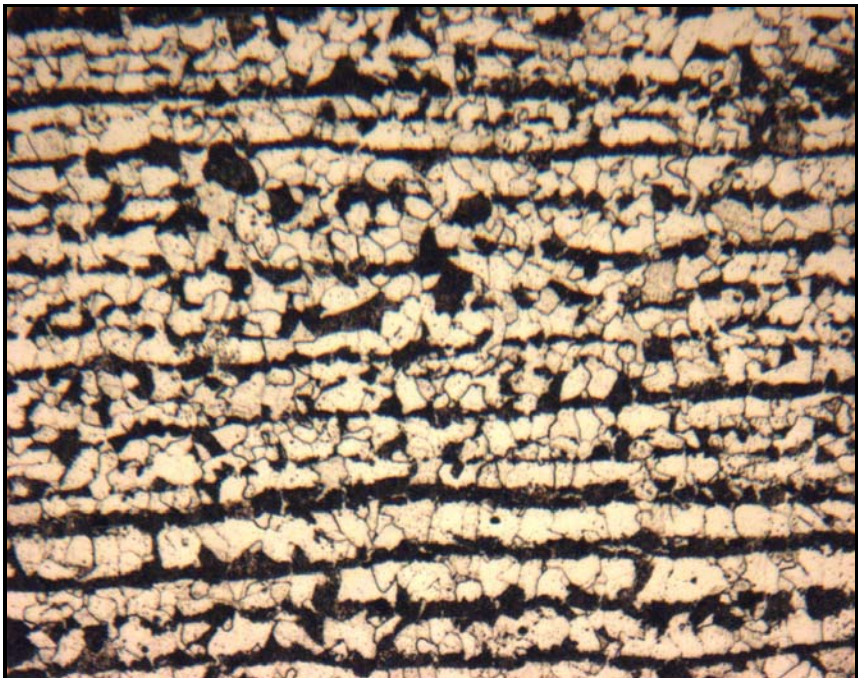


ImageNo:0503A00492, Project No:2005020010



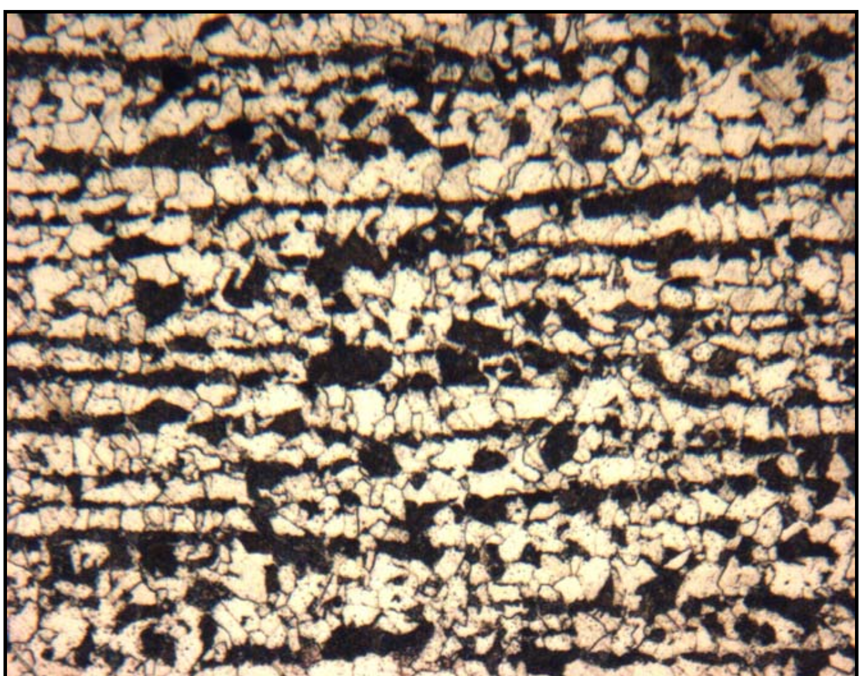
ImageNo: 0503A00465, Project No:2005020010

Figure 17. Close-up views of impression marks "1" and "2" and the shear fracture region.



ImageNo:0503A00544, Project No:2005020010 100 µm

Figure 18. Microstructure of the shell showing the plane that was parallel to the circumference of the tank car. This is the plane that was parallel to the rolling direction determined for the steel plate.



ImageNo: 0503A00550, Project No:2005020010 100 µm

Figure 19. Microstructure of the shell showing the radial plane that was longitudinal to the tank car. This is the plane that was perpendicular to the rolling direction determined for the steel plate.

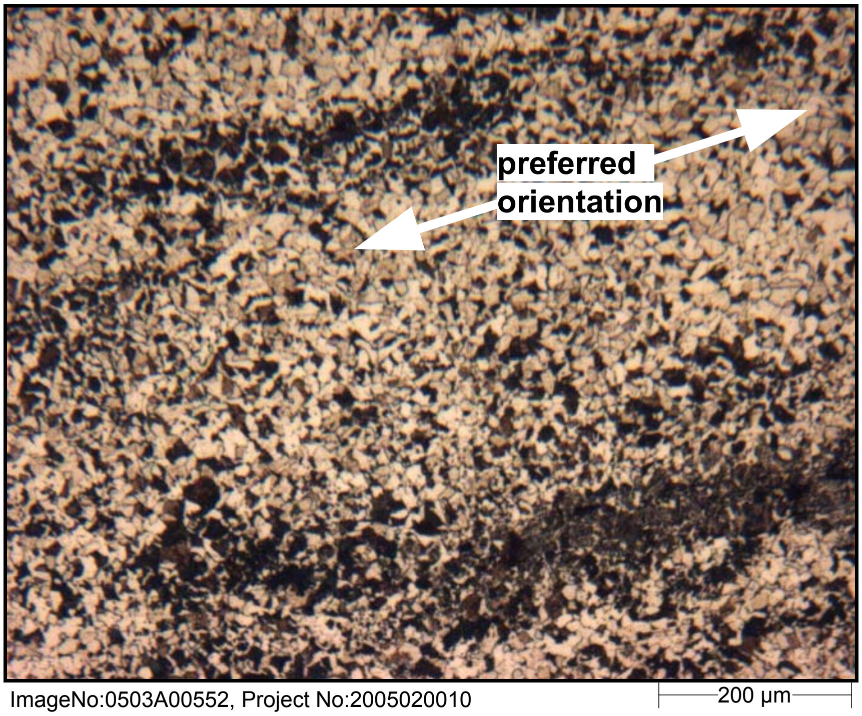


Figure 20. Microstructure of the shell showing the plane that corresponds to the surface that was located midway between the shell's interior and exterior surface. The pearlite colonies (appear dark) follow a preferred orientation indicated by arrows.

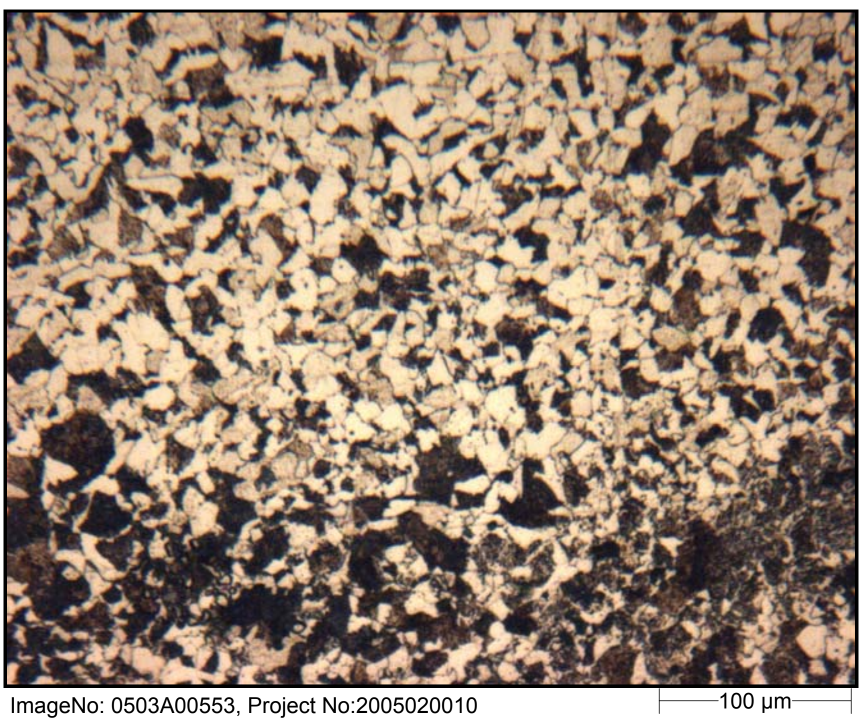
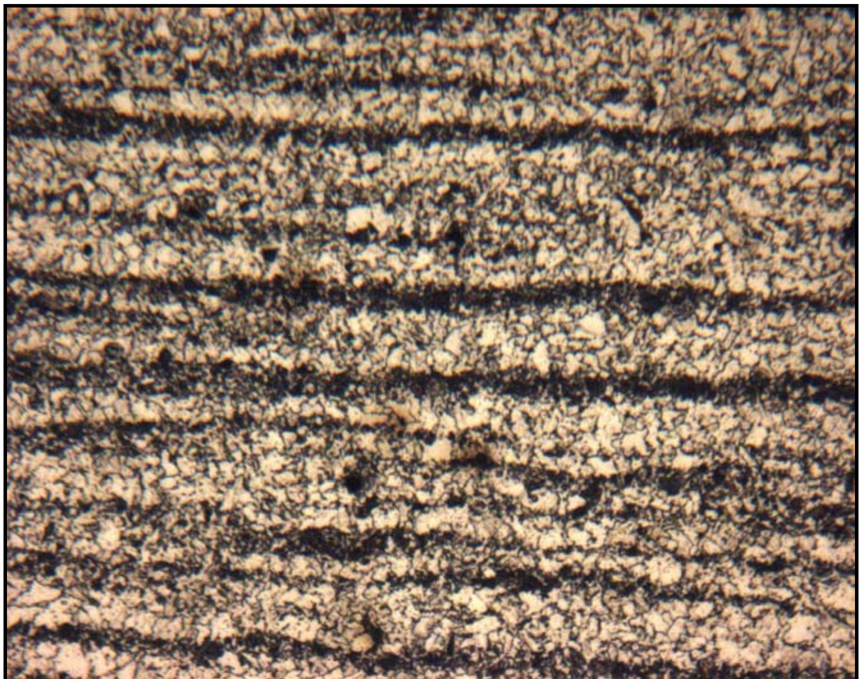
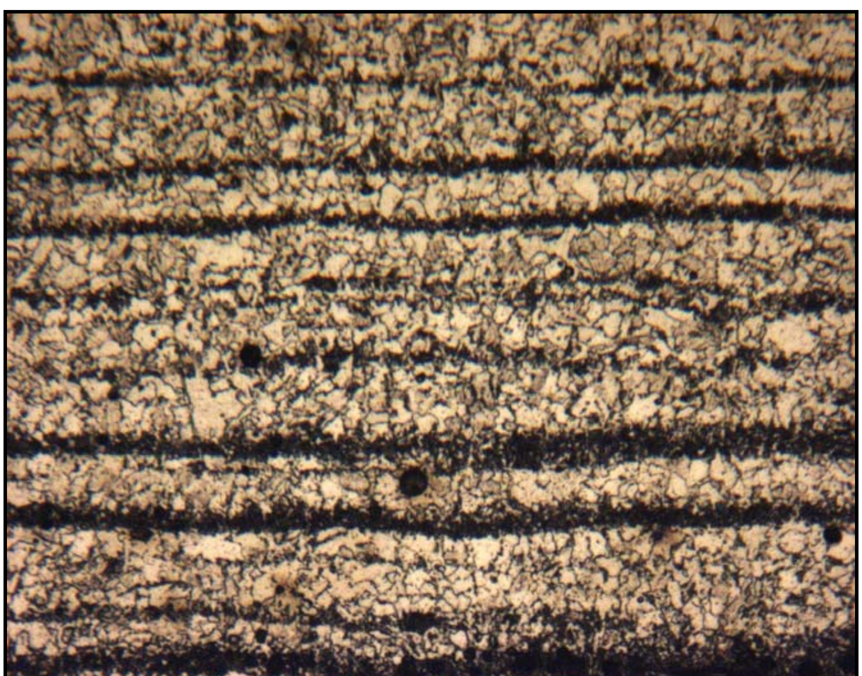


Figure 21. Microstructure of the shell showing the plane that corresponds to the surface that was located midway between the shell's interior and exterior surface. Same as in figure 20 except at higher magnification.



ImageNo:0503A00558, Project No:2005020010 100 µm

Figure 22. Microstructure of the head that was through the thickness of the steel plate. This plane was parallel to the preferred orientation.



ImageNo: 0503A00562, Project No:2005020010 100 µm

Figure 23. Microstructure of the head showing the plane that was perpendicular to the orientation of the pearlite colonies.

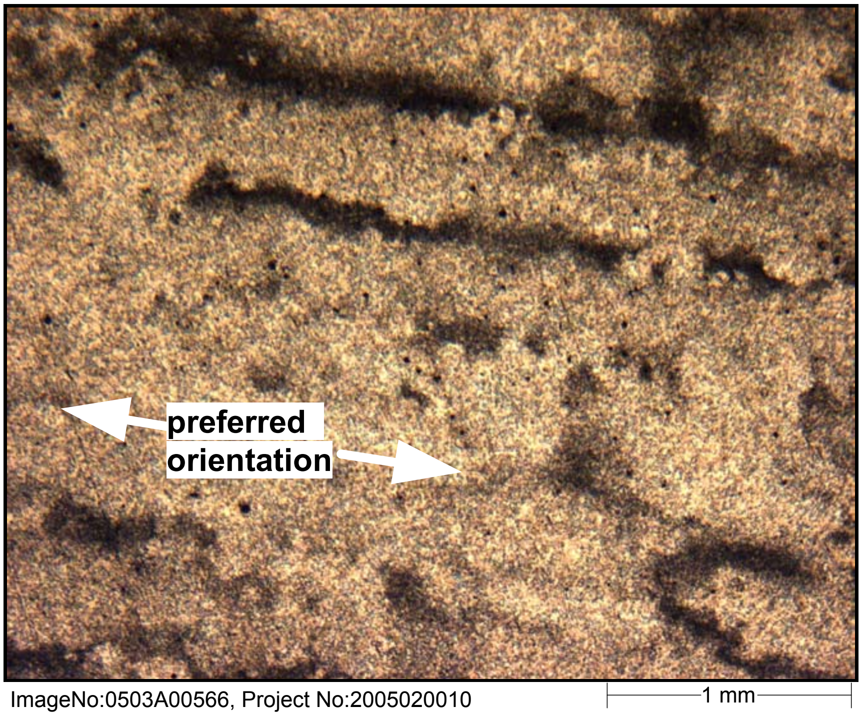


Figure 24. Microstructure of the head showing the plane that corresponds to the surface that was located midway between the head's interior and exterior surface. The pearlite colonies (appear dark) follow a preferred orientation indicated by arrows.

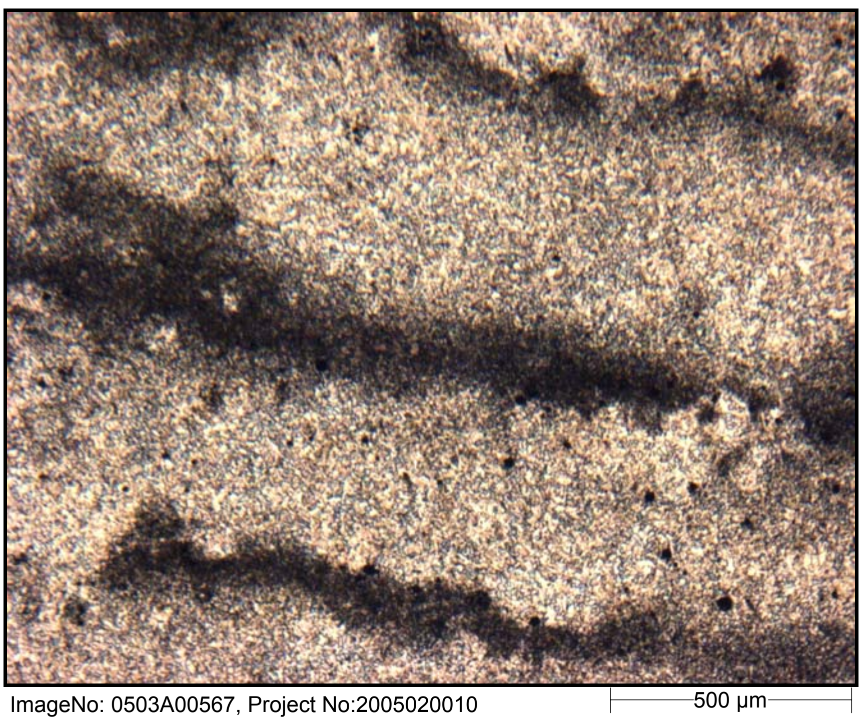
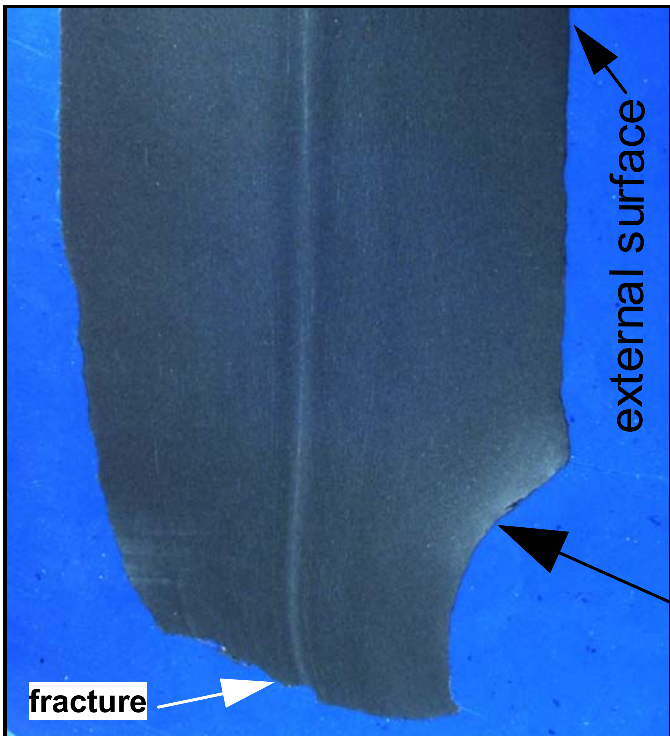
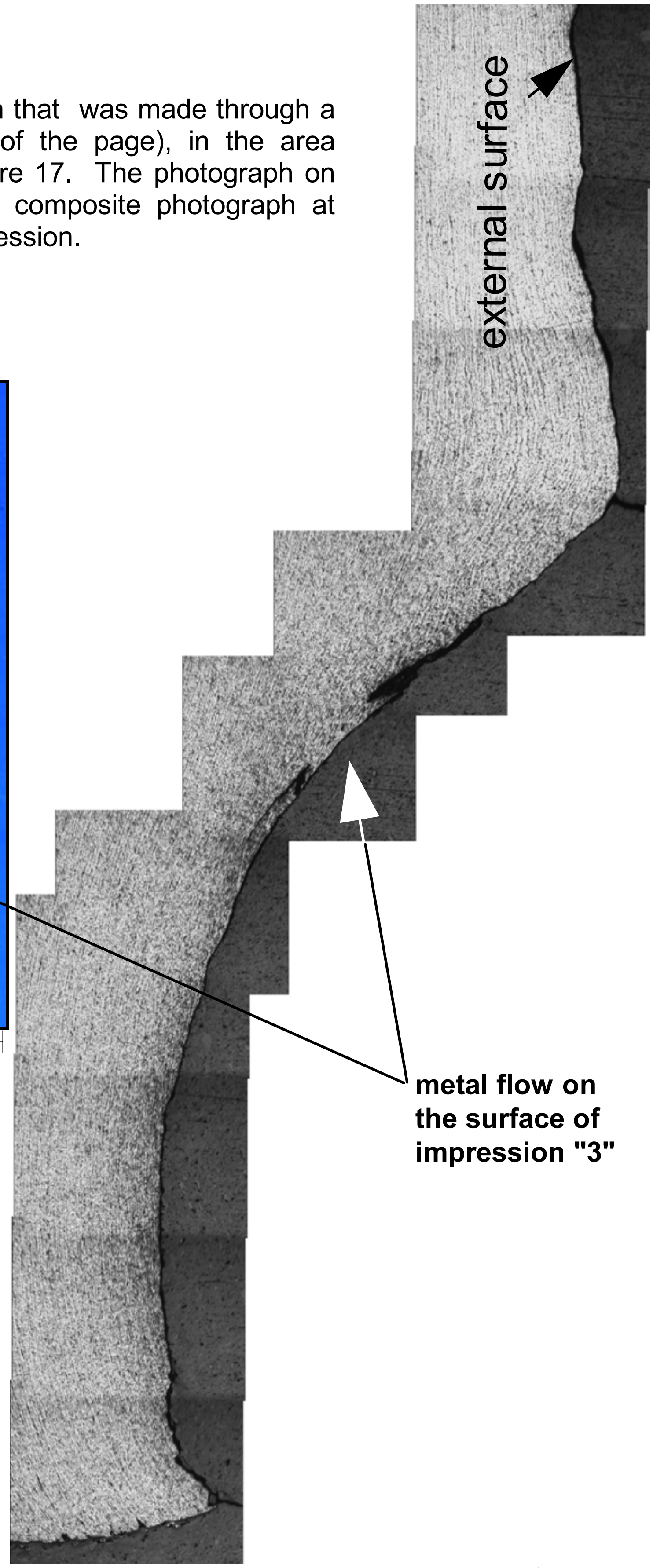


Figure 25. Microstructure of the head showing the plane that corresponds to the surface that was located midway between the head's interior and exterior surface. Same as in figure 24 except at higher magnification.

Figure 26. Metallurgical cross section that was made through a portion of impression "3" (left side of the page), in the area indicated by section line "A-A" in figure 17. The photograph on the right side of the page shows a composite photograph at higher magnification of the same impression.



ImageNo:0503A00842, Project No:2005020010



ImageNo: 0503A00869, Project No:2005020010