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

April 20, 2012

MATERIALS LABORATORY STUDY Report No. 12-046

A. ACCIDENT INFORMATION

Place	:	Marshall, Michigan
Date	:	July 25, 2010
Vehicle	:	30-inch diameter crude oil pipeline
NTSB No.	:	DCA10MP007
Investigator	:	Matt Nicholson, RPH-20

B. COMPONENTS EXAMINED

2 lengths of 30-inch diameter pipe from Enbridge Line 6B.

C. DETAILS OF THE STUDY

A number of remaining strength calculations of crack features were performed based on data from corrosion and crack features that were reported at the location of deepest crack penetration (the primary origin site) on the rupture. The remaining strength calculations were performed using CorLAS software by Det Norske Veritas (DNV), Houston, Texas. Various parameters were entered for crack depth, crack length, crack shape, pipe wall thickness, and pipe material properties, and the predicted failure pressure for the 30-inch-diameter pipe was determined. The data included in this study were (1) corrosion features that PII Pipeline Solutions (PII) reported at the rupture site in the 2004 GE Oil & Gas UltraScan™ wall measurement (USWM) tool report, (2) crack features PII reported at the rupture site in the 2005 GE Oil & Gas UltraScan™ crack detection (USCD) tool report, (3) measurements of the extent of corrosion and cracking determined during post-accident laboratory examination of the fracture surface, (4) PII's post-accident analysis of the 2005 USCD data, (5) minimum value material properties used for fitness-for-purpose calculations, and (6) material properties determined from post-accident tensile and Charpy impact tests of specimens from the ruptured joint.

Variables for crack depth included depth with and without tool tolerance added, profile maximum crack depth versus bin maximum crack depth,[1] and crack depth with corrosion depth added to the tool-reported depth. Crack shape was considered as a rectangular shape or a semi-elliptical shape. Crack length was varied between the total length of the crack-like feature reported in the 2005 USCD report and a shorter length

[1] For the 2005 USCD report, crack depths were reported within a depth range called a bin. At Enbridge's request, PII reanalyzed selected features to obtain a more precise depth, called the profile depth.

based on post-accident analysis of the data. Wall thickness varied among the tool-reported value, nominal thickness, and the post-accident NTSB Materials Laboratory measurements. Material properties were varied between conservative values used for fitness-for-purpose calculations and properties determined from post-accident testing of material from the ruptured joint.

1. Summary of Data Sources

The PII report for the 2004 USWM tool run listed a metal loss feature measuring 18.5 inches long, 2.1 inches wide, and up to 0.087 inch deep at the location corresponding to the rupture primary origin site. In the vicinity of the rupture, the local wall thickness measured by the 2004 USWM tool was 0.252 inch.

The PII report for the 2005 USCD tool run listed a 51.6-inch-long crack-like feature with a bin maximum depth of 0.071 inch (25% of a 0.285-inch-thick wall) at the location corresponding to the rupture primary origin site. The USCD tool has a reported tolerance of ±0.020 inch in depth sizing. The 2005 USCD tool reported the thickness of the rupture joint to be 0.285 inch.

A profile of the corrosion depth and crack penetration measured across the face of the rupture was obtained as shown in Materials Laboratory Factual Report 11-055. The deepest crack penetration was 0.213 inches relative to the original wall surface. At the location of deepest crack penetration, the corrosion depth measured approximately 0.030 inch. (The deepest corrosion pit measured in the vicinity of the deepest crack penetration but not intersecting the fracture surface measured 0.078 inch deep.) The local wall thickness in an areas appearing free from wall metal loss near the area of deepest crack penetration was 0.254 inches. (The pipe wall was generally thicker near the upstream end of the joint where a wall thickness of up to 0.283 inch was measured.)

The crack feature corresponding to the rupture origin location was listed in the 2005 USCD report as a 51.6-inch-long crack-like feature with a maximum depth of 0.071 inches. In a post-accident analysis of the 2005 USCD data, PII found that the 51.6-inch-long feature was misclassified as a crack-like feature in 2005. The 51.6-inch-long feature was reanalyzed by PII using current techniques,[2] and using current techniques the feature would likely be reported as 3 separate features consisting of a crack-like feature on the longitudinal seam, a crack field feature clockwise from the seam,[3] and another crack field feature counterclockwise from the seam.[4] The location of the rupture origin would have corresponded to the location of the crack field at the clockwise side of the longitudinal seam. When this crack field feature at the rupture

[2] Changes to PII's analysis processes made since the 2005 USCD ILI but prior to the accident include improvements in the feature identification process and changes to the algorithm for calculating the estimated depth of a crack field feature.

[3] Unless stated otherwise, all clock references are as viewed looking downstream along the axis of the pipe.

[4] Inspection data is subject to human interpretion, so while rules have changed since PII issued the 2005 report, there is a possibility that the data could be interpreted differently depending on the analyst doing the interpretation.

origin was sized using the current sizing algorithm for crack field features, the maximum depth for this feature (using the 2005 USCD data) was 0.079 inch.

The 51.6-inch-long feature corresponding to the rupture origin was also analyzed as a crack-like feature using algorithms in place in 2005. The profile maximum depth of the 51.6-inch-long feature was 0.063 inch (22% of the reported 0.285 inch wall thickness) using the 2005 sizing algorithm for a crack-like feature.

Minimum value material properties for base metal manufactured to the API[5] Standard 5LX *Specification for High-Test Line Pipe* X52 specification steel used in the ruptured joint were yield stress equals 52,000 pounds per square inch, tensile stress equals 66,000 pounds per square inch, flow stress equals 62,000 pounds per square inch, and Charpy impact energy equals 20 pound feet.

Materials properties determined from post-accident testing of specimens from the ruptured joint were yield strength equals 61,400 pounds per square inch and tensile strength equals 82,400 pounds per square inch. Flow stress was calculated as the average of the difference between the tensile stress and the yield stress, or 71,900 pounds per square inch. Charpy impact tests were conducted at various temperatures on specimens from the rupture joint using subsize specimens due to wall thickness limitations. The upper shelf Charpy impact energy measured for the subsize specimen was 19.5 pound feet. For purposes of further analysis, the Charpy impact energy of the subsize specimen was converted to a full-size specimen value using API Standard 579-1/ASME Standard FFS-1, 2007.[6] Using the procedure in that standard, the upper shelf Charpy impact energy for a full size specimen was calculated to be 39 pound feet. At 70 ºF, the reported pipeline temperature at rupture, the Charpy impact energy for the full size specimen was calculated to be 30 pound feet.

2. Remaining Strength Calculations with Data Available in 2005

The remaining strength in terms of internal pressure was calculated using CorLAS software for the 51.6-inch-long crack-like feature listed in the 2005 USCD report, and results are listed in table 1. For these calculations, the crack shape is defined as a rectangular shape with the length equal to the length of the entire feature and the depth as listed in table 1. The depth of the crack was varied to represent the bin maximum crack depth reported in the 2005 USCD report with and without tool tolerance added. Crack depth was also varied to show the profile maximum crack depth (determined using the 2005 sizing algorithm) with and without tool tolerance added. In addition, the crack depth was varied to show the bin maximum and profile maximum crack depths from the 2005 USCD tool data with maximum corrosion depths from the 2004 USWM tool report added to the crack tool-reported depth. The wall thickness was varied as listed in table 1 to represent the 2004 USWM tool-reported thickness, the 2005 USCD tool-reported thickness, or the nominal thickness. Materials

[5] American Petroleum Institute, New York, New York.
[6] API Standard 579-1/ASME Standard FFS-1, 2007, American Petroleum Institute (2007) Appendix F.4.3.2.d.

properties used in these calculations were the minimum material properties for the API Standard 5LX X52 pipe material.

Results listing the predicted failure pressure for the 51.6-inch-long crack with the inputs described in the previous paragraph are summarized in table 1. The results were compared to the maximum operating pressure (MOP) and the hydrostatic test pressure of the ruptured joint. According to data provided by Enbridge, the MOP and hydrostatic test pressure for the ruptured joint were 624 psig and 796 psig, respectively. In table 1, predicted failure pressures less than hydrostatic pressure are listed in blue (second through sixth data rows), and predicted failure pressures less than MOP are listed in red (last two data rows).

Table 1. Remaining Strength Calculations for the 51.6-inch-long Feature

Wall Thickness (inch)	**Crack Depth (inch)**	**Predicted Failure Pressure (psig)**	**Comments**
0.285	0.071	858	Baseline: USCD tool-reported wall thickness and bin maximum crack depth
0.25	0.071	718	Nominal wall thickness, USCD bin maximum crack depth
0.25	0.063	748	Nominal wall thickness, USCD profile maximum crack depth
0.25	0.089	649	Nominal wall thickness, USCD profile maximum crack depth plus tool tolerance
0.285	0.097	759	USCD tool-reported wall thickness, bin maximum crack depth plus tool tolerance
0.285	0.089	790	USCD tool-reported wall thickness, profile maximum crack depth plus tool tolerance
0.252	0.158	372	USWM tool-reported wall thickness, USCD bin maximum crack depth plus USWM maximum corrosion depth
0.252	0.150	407	USWM tool-reported wall thickness, USCD profile maximum crack depth plus USWM maximum corrosion depth

In summary, the following results are determined from the remaining strength calculations of the 51.6-inch-long crack-like feature using data available after the 2005 USCD tool run with conservative estimates for crack shape and material properties:

- Using nominal wall thickness instead of the 2005 USCD tool-reported wall thickness resulted in predicted failure pressures for the 51.6-inch-long feature that were less than the hydrostatic test pressure, even with a crack depth equal to the profile maximum depth.

- Adding tool tolerance to the crack depth resulted in predicted failure pressures for the 51.6-inch-long feature that were less than hydrostatic pressure, even with a crack depth equal to the profile maximum depth.

- If the maximum corrosion depth reported from the 2004 USWM tool was added to either the bin maximum crack depth or the profile maximum crack depth for the rupture feature, the predicted failure pressure was less than the MOP. (The predicted failure pressure was also less than 486 psig, which was the recorded pressure at the time of the pipeline rupture.)

3. Estimated Crack Size in December, 2005

Estimates of the crack length and depth of the rupture feature at the time of the last crack tool inspection are presented in this section. There were no features on the fracture surface or microstructure that could be used to mark the crack position relative to any particular load excursion such as a hydrostatic test or change in environmental condition such as variations in water level. The estimates are derived from crack tool data from 2004 and 2005 and laboratory measurements of the condition at the time of rupture. These estimates are subject to the tolerances and limitations associated with the USWM and USCD tools and to variations in the corrosion and crack tip morphology that would have occurred since the last crack tool inspection in 2005. However, this study of crack size is provided to facilitate calculations of the possible pipe remaining strength at last inspection and the crack growth rate since that time.

As discussed above, the 2005 USCD tool-reported depth of the rupture feature when sized as a crack field feature using the current sizing algorithm was 0.079 inch. However if metal loss had occurred at the time of the crack tool measurement, this depth is the depth relative to the existing wall surface, not the original wall surface. The effect of metal loss must be accounted for to estimate the total crack depth relative to the original wall surface.

The 2004 USWM showed wall metal loss (corrosion) was present in the area of the rupture origin in 2004, and the maximum depth for the metal loss feature was 0.087 inch. However, post-accident measurements of corrosion depth indicate that in areas where crack features intersected corrosion in the area of deepest crack penetration, the depth of the corrosion was approximately 0.030 inch. Assuming that the area of deepest penetration on the fracture surface corresponds precisely with the deepest signal response in the 2005 USCD data, the corrosion depth associated with the feature generating the deepest-crack signal response would be no greater than 0.030 inch.

Assuming that the change in corrosion depth since the 2005 inspection is negligible in the area of deepest crack penetration, the total crack depth would correspond to the tool-measured crack depth using today's sizing algorithm plus the lab-measured corrosion depth where the cracks intersected the exterior surface. Thus the estimated maximum crack depth relative to the original local wall surface (crack plus corrosion) as it existed in December, 2005, is 0.109 inch.

The length of the crack feature as it existed in 2005 is estimated based on a preliminary profile of the rupture feature that PII provided Enbridge shortly after the rupture using data from the 2005 USCD tool run and on the 2004 USWM data. The profile is used for crack-like features showing depth as a function of position along the length of the pipe. The profile has not been included in public documents since the accuracy of the result when applied to a crack field feature has not been determined. However, the profile does show relative depths of signal returns along the length of the pipe. The profile shows a continuous length of cracking along a distance of 18.7 inches at the location of the rupture origin. In addition, the profile also matches well to the relative depths of the cracks measured on the rupture fracture surface. On the fracture face, a continuous series of linked preexisting cracks were present up to 10.8 inches upstream and 7.9 inches downstream of the area of deepest penetration for a total length of 18.7 inches. Finally, this length also corresponds well with the length of the 18.5-inch-long wall metal loss feature detected by the 2004 USWM tool. Based on this information, the effective length of the crack for this study is estimated to be 18.7 inches.

4. Estimated Average Annual Crack Growth Rate since December, 2005

The average annual crack growth rate is estimated from the depth measured in the area of deepest penetration on the fracture surface relative to the estimated maximum crack depth at the time of the 2005 USCD inspection as described in the previous subsection of this study. Based on these results, the crack grew in depth an estimated 0.104 inch in the 4.6 years between the 2005 USCD tool run and the time of the accident, corresponding to an average annual rate of 0.0226 inch per year (0.574 millimeter per year). A report from the Canadian Energy Pipeline Association (CEPA) states that growth rates in lab tests which attempt to simulate field operating conditions provide a distribution of growth rates for SCC ranging from approximately 0.06 millimeter per year to 0.88 millimeter per year (0.0024 inch per year to 0.035 inch per year).[7] Enbridge has indicated that their maximum assumed SCC growth rate on Line 6B is 0.38 millimeter per year (0.015 inch per year).

5. Predicted Failure Pressure for the Joint in December, 2005

An estimate of the failure pressure for the crack feature at the rupture origin at the time of the 2005 USCD ILI run was calculated using CorLAS software. The crack was estimated as a semi-elliptical shape with length and depth of 18.7 inch and 0.109 inch, respectively, as discussed in subsection C.3 of this study. Wall thickness was set to 0.254 inch as measured in the NTSB Materials Laboratory in the vicinity of the rupture origin. The materials properties were measured and calculated from mechanical tests of the pipeline material as described in subsection C.1. The calculation showed a predicted failure pressure for the crack feature at the rupture origin as it possibly existed during the 2005 USCD tool run was 869 psig.

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[7] *Stress Corrosion Cracking Recommended Practices*, 2nd Edition, Canadian Energy Pipeline Association (2007).