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

May 19, 2011

MATERIALS LABORATORY STUDY REPORT Report No. 11-057

A. ACCIDENT INFORMATION

Place	:	San Bruno, California
Date	:	September 9, 2010
Vehicle	:	Pacific Gas & Electric Natural Gas Transmission Pipeline
NTSB No.	:	DCA10MP008
Investigator	:	Ravi Chhatre

B. TOPICS ADDRESSED

Calculations to evaluate the pressure required to burst the pipe.

C. DETAILS OF THE STUDY

Burst pressures were evaluated for a pipe with no defect and for pipe with the observed weld seam with incomplete penetration found in Pups 1, 2, and 3. See NTSB (2011a-c) for details on the configuration of the pups and the examination of the ruptured pipe. The burst pressure of the pipes was estimated using two methods:

1) Net section yielding according to the Effective Area Method (RSTRENG) as described in ASME B31G–2009[1]
2) Propagation of a crack-like defect according to API 579-1/ASME FFS-1—Part 9 — Assessment of Crack-Like Flaws

1. ASME B31-G Approach

Burst pressure estimates were calculated for an assumed grade and geometry of a typical pipe and for the geometry found in Pups 1, 2, and 3. The burst pressure calculations are based on net section yielding and do not take into account the effect of the crack-like geometry along the Pups 1, 2, and 3 longitudinal seams. Also, the Effective Area Method incorporates a bulging factor (Folias factor), that may not apply to crack-like geometries. The KAPA2006 Microsoft Excel spreadsheet (downloaded from <http://www.kiefner.com>) was used to perform a Level 2 analysis using the Effective Area Method.

[1] 49 CFR, Section 192.7 does not incorporate RSTRENG via ASME B31G-2009, but rather by reference to Pipeline Research Council International (PRCI): AGA Pipeline Research Committee, Project PR-3-805, "A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe," December 22, 1989.

For a typical pipe with no defects, the following properties consistent with X42 pipe were assumed:

Diameter = 30 inch
t = Wall thickness = 0.375 inch
Specified minimum yield strength (SMYS) = 42 ksi

For a typical pipe with these parameters, the Effective Area Method predicted a burst pressure of 1,300 psig.

For Pups 1, 2, and 3, the wall thickness was reduced along the seam due to grinding on the outer surface. Therefore, the wall thickness was based on the average wall thickness data at the longitudinal seam from the lower rows of Table 1 in NTSB (2011c). For Pup 1, the wall thickness was based on the average wall thickness (0.309 inch) + half of the high/low offset across the longitudinal seam (0.015 inch) (NTSB, 2011a). Remaining wall thickness data used in the calculation were obtained from the welded depth measurements taken along the Pup 1, 2, and 3 longitudinal seams (NTSB, 2011a, c). The welds were fractured during the rupture, making direct yield strength and toughness measurements unobtainable. Therefore, an estimate of yield strength, σ_{ys}, was calculated from Vickers hardness data for Pups 1, 2, and 3 (NTSB, 2011c) using the following polynomial expression fit to yield strength data from tensile test data (NTSB, 2011b, c):

$$\sigma_{ys} = -1306638 + 35348.5HV - 344.877HV^2 + 1.46812HV^3 - 0.00227721HV^4$$

It should be noted that hardness is not a direct measure of yield strength, but rather a measure of flow stress at an average strain under an indenter. Although previous studies have indicated a correlation between hardness and yield strength for steels (Cahoon et al., 1971), (Pavlina and Van Tyne 2008), there may be some deviation between the estimated yield strength values and the actual yield strength values. The following data were used as inputs:

Pipe Length	Diameter, inch	t, inch	σ_{ys}, ksi
Pup 1	30	0.324	40.9
Pup 2	30	0.369	40.5
Pup 3	30	0.352	39.4

The estimated burst pressures were 594 psig, 668 psig, and 558 psig for Pups 1, 2, and 3, respectively.

2. API 579-1/ASME FFS-1 Approach

The method for estimating fracture toughness for historical grades of steel (including welds in steel), the stress intensity formula for an infinite longitudinal crack, and the stress intensity formula for an elliptical longitudinal surface crack from API 579-

1/ASME FFS-1 were used to estimate the burst pressure of the longitudinal seam for a crack-like defect. The steps were as follows:

1) Estimate lower bound fracture toughness, K_{IC}, and mean material fracture toughness, K_{mat}^{mean}, for unknown steel using API 579-1/ASME FFS-1—Annex F;
2) Compare to estimates of K_{IC} based on the thumbnail-shaped initiation site found along the Pup 1 longitudinal seam and a burst pressure of 386 psig using two approximate methods;
   a. An infinite longitudinal crack with the depth of the crack equal to the sum of the unwelded depth and an average crack depth measured in the welded region, an overly conservative worst-case scenario;
   b. An elliptical crack with the same area as the initiation site in a wall section equal to the average thickness of the welded region along Pup 1.[2]
3) Calculate the estimated burst pressure for an infinite longitudinal crack with the dimensions of the wall thickness and unwelded region along the Pups 1, 2, and 3 longitudinal seams using the K_{IC} estimates.

The lower bound fracture toughness, K_{IC}, was calculated based on the ASME Section XI Reference Curves. The seams were assigned to Curve A based on the vintage of the pipe and no evidence of normalizing heat treatment. K_{IC} was then calculated according to:

$$K_{IC} = 33.2 + 2.806 \cdot \exp\left[0.02\left(T - T_{ref} + 100\right)\right]$$

Where T = 50 °F and;

$$T_{ref} = C \cdot \operatorname{atanh}\left[\frac{\dfrac{\sqrt{5000 \cdot CVN \cdot E_y}}{1000 \cdot \sigma_{ys}} - 1.7}{1.7 - \dfrac{27}{\sigma_{ys}}}\right] + T_0$$

Where C = 66 °F, CVN (Charpy V-Notch energy) = 15 ft-lb, and T_0 = 114 °F are given in API 579-1/ASME FFS-1—Annex F, σ_{ys}, is given in the table above, and Young's modulus, E_y = 30,000 ksi. The calculated lower bound fracture toughness, K_{IC}, for Pups 1, 2, and 3 were 45.5 ksi$\sqrt{\text{in}}$, 45.4 ksi$\sqrt{\text{in}}$, and 44.9 ksi$\sqrt{\text{in}}$, respectively.

[2] The fourth-order polynomial stress distribution method was considered, in order to account for the stress concentration effect caused by the unwelded portion of the seam. However, the stress distribution applied to the entire pipe circumference (not just to the crack plane), resulting in an overestimate of the required fracture toughness.

In API 579-1/ASME FFS-1—Annex F, the mean material fracture toughness, K_{mat}^{mean}, can then be calculated according to:

$$K_{mat}^{mean} = K_{IC}\left[\frac{1}{B_0 + B_1\left(T - T_{ref}\right) + B_2\left(T - T_{ref}\right)^2 + B_3\left(T - T_{ref}\right)^3 + B_4\left(T - T_{ref}\right)^4 + B_5\left(T - T_{ref}\right)^5}\right]$$

Where B_0 through B_5 are given in API 579-1/ASME FFS-1—Annex F. The calculated values for K_{mat}^{mean} were 88.6 ksi$\sqrt{\text{in}}$, 88.2 ksi$\sqrt{\text{in}}$, and 86.9 ksi$\sqrt{\text{in}}$.

K_{IC} and K_{mat}^{mean} were compared to estimates of the Pup 1 fracture toughness derived from stress intensity solutions in API 579-1/ASME FFS-1—Annex C for simplified geometries of the initiation site. Two geometries were considered:

1) A uniform crack depth, *a*, of infinite length was calculated from the sum of the unwelded depth and the average crack depth in the welded region, as shown in Figure 1. This is an upper bound estimate of K_{IC}, as the crack at the initiation site was 2.4 inch in length and not of infinite length.
2) The initiation site was modeled as an elliptical crack in a cylindrical shell with an effective wall thickness equal to the average thickness of the welded region.

The uniform crack depth was calculated using remaining intact wall thickness measurements for the initiation site in Appendix A of NTSB Materials Laboratory Report 11-056 (NTSB, 2011c), excluding two wall thickness values at either end. The average intact wall thickness, t_{intact}, was estimated to be 0.091 inch. The calculated crack length was:

$a = t - t_{intact}$
$= 0.324$ inch – 0.091 inch = 0.233 inch

The fracture toughness associated with a crack of this depth, of infinite length, and a burst pressure of 386 psig was estimated from the solution in API (2007), C.5.4 for Cylinder – Surface Crack, Longitudinal Direction – Infinite Length, Internal Pressure, Inside Surface:

$$K_I = \frac{pR_0^2}{R_0^2 - R_i^2}\left[2G_0 - 2G_1\left(\frac{a}{R_i}\right) + 3G_2\left(\frac{a}{R_i}\right)^2 - 4G_3\left(\frac{a}{R_i}\right)^3 + 5G_4\left(\frac{a}{R_i}\right)^4\right]\sqrt{\pi a}$$

Where R_o is the outer diameter radius, R_i is the inner diameter radius (R_0 – *t*), and *p* is the internal pressure. The coefficients, G_0 through G_4, were listed in Table C.10 and were a function of t/R_i (calculated as 0.022). Coefficients were taken from the row for $t/R_i = 0.025$. K_I was calculated for each value of *a*/*t* in the table (0, 0.2, 0.4, 0.6, and 0.8) and a fourth-order polynomial was fit to the data giving:

$$K_I = 843.55\left(\frac{a}{t}\right)^4 - 700.36\left(\frac{a}{t}\right)^3 + 205.34\left(\frac{a}{t}\right)^2 + 35.154\left(\frac{a}{t}\right)$$

For a/t = 0.72, the calculated fracture toughness was 96.6 ksi$\sqrt{\text{in}}$. By comparison, K_{mat}^{mean} for Pup 1 was 88.6 ksi$\sqrt{\text{in}}$. The K_{mat}^{mean} values correspond to burst pressure estimates for the Pup 1, 2, and 3 longitudinal seams between 833 psig and 1099 psig, above that for net section yielding according to the Effective Area Method.

The elliptical crack calculation was performed by constructing an elliptical crack with an equivalent area as the pre-existing crack at the initiation site. The area of the elliptical crack was calculated according to:

$$A_{crack} = A_0 - A_{intact}$$

Where A_{crack} is the circumscribed area of an elliptical surface crack with width, $2c$ = 2.4 inch, and depth, a (to be determined), A_0 is the cross sectional area of the section without any crack, and A_{intact} is the cross sectional area of the remaining intact wall at the initiation site in the presence of the crack. A_0 was calculated using the data in Appendix A of NTSB (2011c) as the average weld depth at the initiation site in Pup 1 (0.165 inch) multiplied by the length of the crack (2.4 inch). A_{intact} was calculated from the remaining wall thickness data in Appendix A (NTSB, 2011c) as a piecewise sum of trapezoidal area measurements along the seam (trapezoidal rule). The depth of the elliptical crack, a, was:

$$a = \frac{2(A_0 - A_{intact})}{\pi c}$$

Where A_0 = 0.397 inch^2, A_{intact} = 0.228 inch^2, and a = 0.090 inch. The crack was assumed to be in a cylindrical shell with wall thickness equal to the average weld depth at the initiation site along the Pup 1 longitudinal seam, t = 0.165 inch. The fracture toughness was calculated according to:

$$K_I = \frac{pR_o^2}{R_o^2 - R_i^2}\left[2G_o - 2G_1\left(\frac{a}{R_i}\right) + 3G_2\left(\frac{a}{R_i}\right)^2 - 4G_3\left(\frac{a}{R_i}\right)^3 + 5G_4\left(\frac{a}{R_i}\right)^4\right]\sqrt{\frac{\pi a}{Q}}$$

Where p = the internal pressure of the pipe at rupture (386 psig), R_0 = the outer radius of the pipe (15.000 inch), R_i = the inner radius of the pipe = ($R_0 - t$) = 14.835 inch and at the deepest point of the crack, for $\varphi = \pi/2$:

$$G_0 = A_{0,0} + A_{1,0}\beta + A_{2,0}\beta^2 + A_{3,0}\beta^3 + A_{4,0}\beta^4 + A_{5,0}\beta^5 + A_{6,0}\beta^6$$

$$G_1 = A_{0,1} + A_{1,1}\beta + A_{2,1}\beta^2 + A_{3,1}\beta^3 + A_{4,1}\beta^4 + A_{5,1}\beta^5 + A_{6,1}\beta^6$$

$$\beta = \frac{2\varphi}{\pi} = \frac{2}{\pi}\left(\frac{\pi}{2}\right) = 1$$

$$G_2 = \frac{\sqrt{2Q}}{\pi}\left(\frac{16}{15} + \frac{1}{3}M_1 + \frac{16}{105}M_2 + \frac{1}{12}M_3\right)$$

$$G_3 = \frac{\sqrt{2Q}}{\pi}\left(\frac{32}{35} + \frac{1}{4}M_1 + \frac{32}{315}M_2 + \frac{1}{20}M_3\right)$$

$$G_4 = \frac{\sqrt{2Q}}{\pi}\left(\frac{256}{315} + \frac{1}{5}M_1 + \frac{256}{3465}M_2 + \frac{1}{30}M_3\right)$$

$$M_1 = \frac{2\pi}{\sqrt{2Q}}(3G_1 - G_0) - \frac{24}{5}$$

$$M_2 = 3$$

$$M_3 = \frac{6\pi}{\sqrt{2Q}}(G_0 - 2G_1) + \frac{8}{5}$$

$$Q = 1.0 + 1.464\left(\frac{a}{c}\right)^{1.65}$$

The coefficients, $A_{0,0} \cdots A_{6,0}$ and $A_{1,1} \cdots A_{6,1}$ are given in API (2007), Table C.12 and are a function of t/R_i, a/c, and a/t. Rows in the table were selected for t/R_i = 0.01 (actual value = 0.011) and a/c = 0.0625 (actual value = 0.075). K_I was calculated for each value of a/t in the table (0, 0.2, 0.4, 0.6, and 0.8) and a fourth-order polynomial was fit to the data giving:

$$K_I = -216.15\left(\frac{a}{t}\right)^4 + 444.79\left(\frac{a}{t}\right)^3 - 220.1\left(\frac{a}{t}\right)^2 + 98.458\left(\frac{a}{t}\right)$$

For t = 0.165 inch and a = 0.090 inch, the calculated fracture toughness was K_{IC} = 41.0 ksi$\sqrt{\text{in}}$, less than but close to the lower bound fracture toughness of 45.5 ksi$\sqrt{\text{in}}$ for Pup 1 based on the ASME Section XI Reference Curves.

The lower bound fracture toughness, K_{IC}, for Pups 1, 2, and 3 was used to estimate the burst pressure for the Pup 1, 2, and 3 longitudinal seams using the stress intensity formula for a Cylinder – Surface Crack, Longitudinal Direction – Infinite Length, Internal Pressure, Inside Surface as above, solving for the pressure, p. The formula assumes the inner surface is a perfect cylinder and does not account for weld misalignment effects. The following parameters were used:

Pipe Length	***t*, inch**	***a*, inch**	**K_{IC}, ksi$\sqrt{\text{in}}$**
Pup 1	0.324	0.162	45.5
Pup 2	0.369	0.174	45.4
Pup 3	0.352	0.190	44.9

The values for t and a were from Table 1 in NTSB (2011c). Other assumed or calculated values included:

R_o = 15.000 inch
$R_i = R_o - t$

The coefficients, G_0 through G_4, were listed in Table C.10 and were a function of t/R_i (calculated as 0.022, 0.025, and 0.024 for Pups 1, 2, and 3, respectively). Coefficients were taken from the row for t/R_i = 0.025. K_I/p was calculated for each value of a/t in the table (0, 0.2, 0.4, 0.6, and 0.8) and a fourth-order polynomial was fit to the data giving:

$$\frac{K_I}{p} = 2.1854\left(\frac{a}{t}\right)^4 - 1.8144\left(\frac{a}{t}\right)^3 + 0.532\left(\frac{a}{t}\right)^2 + 0.0911\left(\frac{a}{t}\right)$$

For Pups 1, 2, and 3, the burst pressures estimated from API 579-1/ASME FFS-1 were 515 psig, 574 psig, and 430 psig, respectively.

D. REFERENCES

ASME. (2009). *ASME Standard B31G, 2009, Manual for Determining the Remaining Strength of Corroded Pipelines*. New York: American Society of Mechanical Engineers.
API. (2007). *API 579-1/ASME FFS-1, 2007, Fitness-for-Service*. Washington, DC: American Petroleum Institute.
Cahoon, JR, Broughton, WH, and Kutzak AR. (1971). *Metall. Trans.*, 2, p. 1979.
NTSB. (2011a). *Docket Number SA-534 — Exhibit No. 3-A — Metallurgical Group Chairman Factual Report*, Washington, DC: National Transportation Safety Board.
NTSB. (2011b). *Docket Number SA-534 — Exhibit No. 3-B — Metallurgical Group Chairman Factual Report*, Washington, DC: National Transportation Safety Board.
NTSB. (2011c). *Materials Laboratory Factual Report 11-056*. Washington, DC: National Transportation Safety Board.
Pavlina, EJ and Van Tyne, CJ. (2008). *J. Mater. Engng. Perf.*, 17(6), p. 888.

Donald Kramer
Materials Engineer

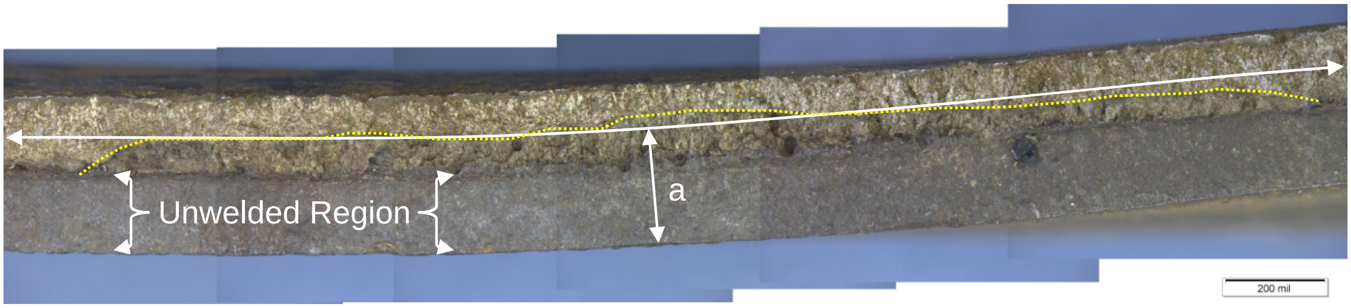

Figure 1: Longitudinal cross section of the Pup 1 longitudinal seam. The boundary of the initiation site is indicated by a yellow-dashed line. In one scenario, the burst pressure of Pup 1 was estimated assuming the presence of an infinitely long crack of uniform depth at the average depth of the initiation site boundary, indicated by the white line.