MEM 333 - 001

Mechanical Behavior of Materials

Engineering Consulting Report:

JAGR Engineering Consulting Firm Members:

Gwyn Godin (grg47@drexel.edu) 25%

Adam Nork (arn53@drexel.edu) 25%

Jonah Roberts (jmr552@drexel.edu) 25%

Rhys Kawaguchi (rlk92@drexel.edu) 25%

Executive Summary

On November 1, 2007, a segment of a foot-long diameter pipeline owned by Dixie Pipeline Company ruptured in a rural area beside Carmichael Mississippi. At the time, the pipeline was transporting 1,405 pounds per square inch (psi) of liquid propane, an extremely flammable and hazardous liquid. Roughly over 10,200 barrels of propane were released and resulted in a large fire. The fire burned over 70 acres of grass and woodland and destroyed over four homes. Two people were killed and seven sustained injuries. An estimated $3.3 million damage was a product of this accident.

While some facts are known, there are still undeniable uncertainties circling this event. JAGR Engineering Consulting Group has taken initiative to conduct research and provide a meaningful explanation of the events that took place on November 1, 2007 as well as insight on metallic pipe failures. The following information will help pave an understanding of whether or not High-Density Polyethylene (HDPE) pipes can replace metallic pipes in engineering applications.

The anatomy of the accident is not completely straightforward, but it can be deconstructed into a series of events that lead to the catastrophe. A compilation of circumstances such as: a major oversight of the Pipeline and Hazardous Materials Safety Administration's policies, the adequacy of federal pipeline safety regulations, and simple failure mechanisms for low-frequency resistance welded pipes all contributed to the event. This event can be used as a tool for understanding the use of HDPE pipe and its practicality.

After a series of calculations using information provided by the National Transportation Safety Board (NTSB), we found it is more cost effective to remain with the X52 steel currently being used in the pipeline rather than switching over to HDPE. There is a variety of recycled HDPE that could be used as a PR booster after damages to the surrounding environment, but this would cost your company even more than what our calculations found.

Introduction

After reviewing the Dixie Pipeline Company's high pressure pipe catastrophe on November 1, 2007, JAGR Engineering Consulting Group received its first client that designs and manufactures High Density Polyethylene (HDPE) pipe. Interested in the failure, the client wants to learn about fracture in pipes as well as what causes failure. In an effort to determine whether HDPE pipe would be better than metallic pipe, the client hired JAGR to analyze the failure mechanics and types of failure in both metallic and HDPE pipes. Providing knowledge on longitudinal and hoop stress in piping that causes failure, JAGR will use both the National Transportation Safety Board's report on Dixie Pipeline Company's steel pipe failure and material behavior analysis techniques to conduct the engineering analysis. While the highlighted failure on November 1, 2007 involved a steel pipe, JAGR will use material property knowledge of not only steel but also HDPE and other metals used in piping to conduct the experiment. Because there may be no clear evidence that suggests the use of one material over another, JAGR will explore the safety factors involved in pipe fracture. By providing education on failure in both metallic pipes and HDPE pipes as well as safety standards and factors, JAGR plans to aid the client in determining which material will best suit future needs allowing companies to prevent future catastrophes.

The Incident

Around 10:30 am, the 12-inch diameter pipe carrying liquid propane burst, sending flames upwards of 200 feet in the air. The damaged pipe was 52 feet long and was part of the Dixie pipeline running from Apex, NC, to Mont Belvieu, TX. The sudden release of pressure led to an increased flow rate through the piping, from 5,952 barrels per hour to 7,354 gallons per hour, and caused 71.4 acres of habitat loss. In all, this incident killed two and injured seven others, and cost over $3 million in property damages and loss of product.

The pipeline transported exclusively propane, a highly volatile and hazardous liquid. The specifications of the pipe include a 395-mile by 12-inch-diameter pipe made of API grade X52 steel. The steel pipe had a 12.75 inch outer diameter accompanied by a 0.25-inch nominal wall thickness. The minimum yield strength of the X52 steel is 52,000 psi. The company, Lone Star Steel Company, built the pipe for Dixie Pipeline in 1961. Lone Star used a low-frequency electric welding process as well as a full-body normalizing treatment at 1,605 degrees fahrenheit. A shielded metal arc welding process was used to join the individual pipe components. The pipeline was coated with a coal tar enamel and felt wrap (often containing fiberglass, which protects against corrosion and isolates the pipeline from environmental elements). From the original 1961 construction, documents of welding specifications exist which contain weld tests and acceptance standards for the girth welds. Radiographic inspection of the pipe for field weld quality control is specified, but no documentation was found indicating which specific girth welds underwent a radiographic inspection. There were no construction x-rays found by Dixie either.

Annual external control surveys from 2005 and 2006 were reviewed and confirmed. The company that conducted yearly cathodic protection surveys for Dixie claimed that the system was in good operating condition. There was also no excavation activity in the area of the rupture that could have been a cause variable. On November 1, 2007, the highest recorded discharge pressure at Carmichael Station was found to be 1,417 psig. This was the apparent pressure at the time of the rupture.

Before it was placed in service in 1961, the Dixie pipeline segment was subjected to hydrostatic pressure testing. This test resulted in 13 pipe failures, ten of which categorized as seam splits or ruptures in the longitudinal weld seams, the rest being a pinhole, lamination, and undefined leak. Sixty longitudinal seam failures due to hydrostatic pressure testing appeared in 1983, 1984, 2001, 2002, 2004, 2006, and 2007 (May). The reasoning for the 1983 and 1984 testing was inconclusive. An analysis of the eight seam failures was completed for the 2004 hydrostatic pressure testing. All of the seam failures were due to manufacturing defects. All eight of the failures occurred at stress levels that exceeded 89.5 percent of the minimum material yield strength. In 2005, Dixie implemented a pipeline integrity repair program, subsequently removing 21 pipe joints which yielded reportable concerns.

The damage of the pipeline extended over a distance of 52 feet and 4.75 inches. A large portion of the fracture extended through the longitudinal ERW seam. The fracture faces that were along the seam weld had a layer of oxide that is consistent with fire exposure. There was no evidence of a pre-existing crack in the girth weld, but there was evidence of a 1-inch fracture portion of the downstream face of the girth weld. A void (metal discontinuity due to pollution or other conditions) was found in the upstream girth weld, which was about 0.05 inches in cross section with respect to the fracture surface. According to welding standards at the time (2007), any void smaller than 25 percent of the wall thickness, or 0.0625 inches in this case, is deemed acceptable. The void of the failure pipe was within the permissible size.

Various simulations were conducted to mimic the fractures. In the years 1988 and 1989, the Pipeline and Hazardous Materials Safety Administration (PHMSA) released two Alert Notices that all natural gas transmission operators and all liquid pipeline operators of hazardous liquids. PHMSA recommended: hydrostatically testing all liquid pipelines to 125 percent of the maximum allowable pressure; avoid increasing a pipeline's long standing operating pressure; confirm effectiveness of cathodic protection systems; and conduct metallurgical examinations in the event of a ERW seam failure.

The NTSB report suspected that the cause of failure was a faulty weld along the longitudinal seam (the weld done during manufacturing to join sheet metal together to create the circular pipe), a portion of the upstream girth weld (the weld that joins two pipes together at their circumference), and portions of the adjacent pipe joints. The burst pipe could be seen as a longitudinal fracture at the 12 o'clock position and ran the entire length of the seam. As can be seen in the report, the initial burst was upstream, and continued downstream. The upstream portion of the pipe had the largest separation of burst pipe, maxing out at 17 ⅞ inches (see Figure 1).

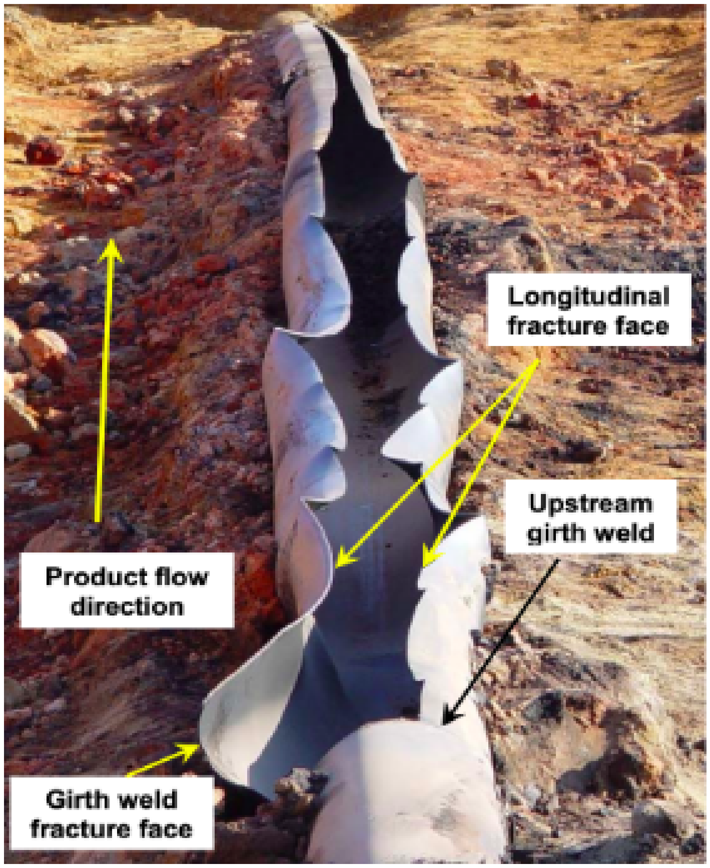

Figure 1: Ruptured Steel Pipe

During examination of the burst pipe, there were no outside dents, major scratches or gashes that would lead investigators to suspect a third party was involved in vandalising the pipe, leading to the explosion. There was no internal or external corrosion and fractographic examination showed there was no stress corrosion that would've led the pipe to fail. The pipeline controller working, reported the lead correctly and on time, and was not under the influence of any drugs or alcohol, so it wasn't a staff error. There was evidence of high standing pressure in the beginning of the 2007 calendar year, as well as evidence of a void, both deemed within acceptable limits. Finally, the pipeline was working under regular regulations, leading to the idea there was an error during the construction of the pipeline or the pipe itself that failed because of long term stress. However, the NTSB report provides any description on why the pipe at that point, other than long term stress over time.

Steel Pipe Failure Analysis

From the analysis of the November 1, 2007 steel pipeline failure case, we narrowed the probable cause down to the seams of the Dixie Pipeline. Using dimensions of the pipe, the provided minimum yield strength, and the pressure in the piping at the time of rupture, the principal normal stresses, principal shear stresses, and the average safety factor for the main body of the pipe as well as the seams were calculated.

$$\sigma_t = \frac{pr_1}{t} \qquad (1)$$

$$\sigma_x = \frac{pr_1}{2t} \quad (2)$$

$$\sigma_r = -p \qquad (3)$$

Eq. 1, 2, and 3 are the hoop, longitudinal, and radial stress, respectively. **Eq. 1** displays the relationship between pressure p , the inner radius r_1, and thickness t. **Eq. 2**, while almost identical Eq. 1 shows the slight difference as *t* is multiplied by 2. The radial stress in Eq.3 is equal and opposite to the pipe's gage pressure.

Because there is no mention of initial shear stress within the report, JAGR assumed that these three stresses provided the stress state of the pipe at any point in time. While there could be some shear stress as pressures vary within the pipe, JAGR took these shears into consideration with **Eq. 5.** The three stresses give us the following stress state in **Figure 2,** with the two stresses shown and another stress coming out of the page (not shown).

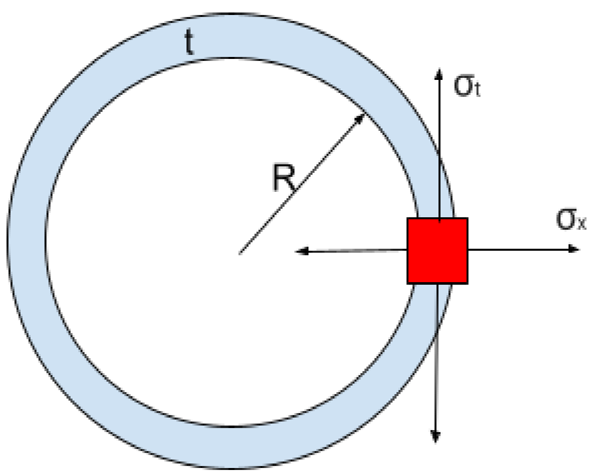

Figure 2: Stress state of the pipe at any given time

Using **Eq. 4, 5, and 6,** JAGR was able to determine the max normal and shear stresses of the pipeline at the time of fracture. **Eq. 4** gives the principal normal stresses while **Eq. 5 and 6** determine the principal shear stresses and max shear stress, respectively

$$\sigma_{1,2,3} = \sigma_{t,x,r} \tag{4}$$

$$\tau_{1,2,3} = \frac{\left|\sigma_2 - \sigma_3\right|}{2}, \frac{\left|\sigma_1 - \sigma_3\right|}{2}, \frac{\left|\sigma_1 - \sigma_2\right|}{2} \tag{5}$$

$$\sigma_s = MAX(\left|\sigma_1 - \sigma_2\right|, \left|\sigma_2 - \sigma_3\right|, \left|\sigma_3 - \sigma_1\right|) \tag{6}$$

Finally, with **Eq. 7, 8, and 9**, JAGR was able to determine the max normal stress fracture, the octahedral shear yield, and the safety factor for the pipeline (respectively).

$$\sigma_N = MAX(\left|\sigma_1\right|, \left|\sigma_2\right|, \left|\sigma_3\right|) \tag{7}$$

$$\sigma_H = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{8}$$

$$X_S = \frac{\sigma_0}{\sigma_s \, or \, \sigma_N \, or \, \sigma_H} \tag{9}$$

Taking the dimensions and actual values of the Dixie Pipeline pipe at the time of the rupture, JAGR used the above equations to yield hoop, longitudinal, and radial stress, seen in Table 1. Additionally, the principal shear stress was calculated, which is displayed in Table 2.

X52 Steel, Thin Walled Pipe	
Inner Radius	6.125 in
Outer Radius	6.375 in
Thickness	0.25 in
Pressure at Rupture	1405 psi

Min Shear	52 ksi
Safety Factor (X_s)	0.72

Table 1: Dixie Pipeline X52 Steel Pipe Parameters

	Inside radius	**Outside radius**
σ_1, σ_t (ksi)	34.423	34.423
σ_2, σ_x (ksi)	17.211	17.211
σ_3, σ_r (ksi)	1.405	0
τ_1(ksi)	9.308125	8.605625
τ_2(ksi)	17.91375	17.21125
τ_3(ksi)	8.605625	8.605625

Table 2: Dixie Pipeline X52 Steel Pipe Calculated Principal Normal Stresses and Shear Stresses

X52 Steel (Max Sheer, Max Normal, Octahedral Stress)	
σ_s $(max\ shear)$ (ksi)	35.8275
σ_N $(max\ normal)$ (ksi)	34.4225
σ_H $(octahedral\ shear\ yield)$ (ksi)	31.0855

Table 3: Dixie Pipeline X52 Steel Pipe Calculated Max Shear Stress, Max Normal Stress, and Octahedral Shear Yield

The average safety factor for the main pipe body was calculated by using the max shear stress yield, max normal stress fracture, and the max normal stress fracture to calculate three different safety factors, of which the average was taken. The average safety factor for the pipe seams was calculated using a minimum yield strength adjusted for the weaker seams. The seams had 44% less impact value than the baseline strength, and so the yield strength for the seams was 29.12 ksi. The average safety factor for the main pipe body was found to be 1.545833, however, the average safety factor for the pipe seams was found to be much lower at 0.86567. Table 4 exhibits the safety factor for the main pipe as well as the pipe seams.

Safety Factor	Whole pipe (no seams)	Pipe seams (44% less impact value)
$X_{S,S}$ ($max\ shear$)	1.45	0.812
$X_{S,N}$ ($max\ normal$)	1.51	0.846
$X_{S,H}$ ($octahedral\ shear\ yield$)	1.68	0.938
$X_{S,\ AVG}$ ($average\ safety\ factor$)	1.55	0.866

Table 4: Dixie Pipeline X52 Steel [Main Steel Pipe & Pipe Seams] Safety Factors

According to our calculations on the the average safety factors for the main pipe body and the pipe seams at the actual rupture pressure and the theoretical rupture pressure, we can ascertain that in order for the pipe to burst there must have been a deformity in the in the form of a crack in the seam ERW weld or a crack in the girth weld. This can be assumed because the pressure at the actual rupture was lower than the supposed theoretical minimum rupture pressure. Theoretically, without any prior deformity or fracture, the pipe would not have burst or at least not when it did.

HDPE Pipe Analysis:

According to Cornell Law school, the largest minimum safety factor for pipeline design is 0.72. Using this information, maintaining the inner diameter of the pipe as to not change the volume of product moving, and knowing the lower end yield strength for HDPE is 4351 psi, JAGR used maximum normal stress fracture criteria to determine the thickness of the HDPE pipe as 1.69 inches. Since the failure of the steel pipe was caused by an error in the weld and not the actual pipe itself, JAGR assumed that the HDPE pipe was to have the same strength. Therefore, JAGR compared the HDPE pipe to the steel pipe keeping the strength constant to determine the better material. However, when looking over the type of steel used and the minimum pressure that it failed at during testing, JAGR noticed a safety factor of about 1.25 was used. Using this value, JAGR determined the required thickness of the HDPE pipe, that would make its strength equivalent to that of the X52 steel, would have to be 2.94 inches.

The average price of HDPE in the United States is 38.81 cents per pound. Knowing the density of this plastic to be 59.9 pounds cubic feet, the cost of one foot of 1.69 inch thick pipe would be $11.95, and for one foot of 2.94 inch thick pipe would be $22.65. One issue with using the HDPE plastic is the fact that the pipes would have to be made specifically to the thickness and size desired, which will drastically increase the price. With the X52 steel, manufacturers already make pipe to the dimensions already in use. Furthermore, the X52 steel costs only about $12.51 per foot.

In terms of strength, the plastic pipe is a bit more elastic, which has both positives and negatives. As the plastic material becomes more flexible, installation will be easier; however, if the pressure is greatly increased and the HDPE plastic deforms, it will be detrimental to the function of the pipeline. Since JAGR did calculations to align with the current strength of the steel, the point of failure would be equivalent for the two materials.

Concluding Remarks:

JAGR recommends that the X52 steel continue to be used in all pipe design rather than the HDPE pipe. The strength of the steel compared to the HDPE is unmatched, and the steel is more reasonable financially. JAGR found that in order for the HDPE pipe to match the strength of steel pipe, the thickness of HDPE would have to be nearly 11 times that of steel. Also, a foot of HDPE pipe can cost about $10 more than a foot of X52 steel pipe. Because pipelines are not small, that extra $10 per foot can end up costing a company thousands by the end of installation. One benefit of the HDPE is that it can be more environmentally friendly being made out of recycled plastics. However, the environmentally friendly HDPE comes at a cost. A company might justify the usage of HDPE from an ethical standpoint rather than a financial one. Using HDPE pipe as a replacement for steel pipe might make sense for a company looking to recover from damage that it has caused to a particular environment or town. However, looking at numbers and functionality, X52 steel pipe is recommended. Overall, the steel will save a company money and time because it has already been used for the pipeline design and installation. Introducing a new material to pipeline design might cause the need for reevaluation of specifications and other logistical processes unnecessarily creating more work for a company.

JAGR does recommend checking all the welds connecting the pipe sections before making any decisions. If possible, JAGR recommends reinforcing the welds between pipe sections to further prevent any possible failures. The weld, in the section that bursted, failed because of long term stress on the manufacturing error, and JAGR believes it is possible that a similar accident could happen in the future. To prevent this from happening, JAGR suggests developing a replacement schedule schedule for high risk pipeline sections. High risk pipe sections are sections that have been in use for a long time and sections that frequently experience high volume displacement and pressure changes. Older sections and sections that are exposed to greater stress should be checked and replaced more often. In conclusion, X52 steel is the better material option; however, like any material, the steel can begin to fatigue over time, so companies should be proactive in locating high risk mains for replacements and reinforcements.

Works Cited

"Polyethylene (PE): LDPE, LLDPE and HDPE Properties Comparison." *HDPE LDPE LLDPE Comparison*, SpecialChem, omnexus.specialchem.com/plastics-and-elastomers/polyethylene-pe/hdpe-ldpe-lldpe-co Parison

Authors, Guest. "Markets Bring Higher Post-Consumer HDPE Prices." *Plastics Recycling Update*, Plastics Recycling Update, 14 Nov. 2018, resource-recycling.com/plastics/2018/11/14/markets-bring-higher-post-consumer-hdpe-p ices/.

Evian, Samantha. "49 CFR § 192.111 - Design Factor (F) for Steel Pipe." *Legal Information Institute*, Legal Information Institute, www.law.cornell.edu/cfr/text/49/192.111.

"API 5L Seamless Line Pipe: X52 Grade Steel Pipe: API5L Steel Pipe." *FedSteel.com*, Federal Steel Supply INC., www.fedsteel.com/api-5l-seamless-line-pipe/.

"API 5L X52 Pipe." *API 5L X52 Pipe Suppliers*, Neelcon Steel Industries, www.neelconsteel.com/api-5l-gr-x52-carbon-steel-pipes.html.

"Rupture of Hazardous Liquid Pipeline With Release and Ignition of Propane." *NTSB*, National Transportation Safety Board , 14 Oct. 2009, www.ntsb.gov/investigations/AccidentReports/Reports/PAR0901.pdf.