CHARACTERISTICS OF OIL AND GAS PIPELINE ACCIDENTS CAUSED BY CLIMATE CHANGE INTENSIFIED HURRICANES

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Abstract

Scientist now believe with more confidence that human activities contribute substantially to the observed upward trend in hurricane activity. An occasional casualty of hurricanes is energy infrastructure like hazardous liquid and gas pipelines. The objective of this study is to use pipeline accident data from the Pipeline and Hazardous Material Safety Administration (PHMSA) to search for the characteristics indicative of the most severe pipeline accidents caused by hurricanes. Using a multivariable regression analysis, this study demonstrates a weak relationship between hurricane damages and offshore gas pipelines' pressure, size, and strength. The data for hazardous liquid and onshore gas pipelines was too limited to draw any definite conclusions. In regions susceptible to hurricanes, policy makers who govern areas near offshore gas pipelines, or companies who move product via offshore pipeline of significant pressure, size, and strength may want to consider the implications of these findings when evaluating risks to energy infrastructure.

Contents

Introduction

As climate change becomes more severe due to the increased concentrations of greenhouse gasses in the atmosphere, extreme weather events, such as heat waves, extreme cold, wildfires, storms and flooding from increased precipitation, are likely to become more severe and more frequent.[1] An occasional casualty of extreme weather is energy infrastructure such as hazardous liquid and gas pipelines that transport fossil fuels. When pipelines break, the environmental consequences can be dire. In one significant incident, the Silvertip pipeline owned by ExxonMobil, ruptured near Laurel, Mont., on July 2011. Prolonged flooding conditions caused debris to catch the pipeline and cause excessive stress until it eventually burst.[2] This event released an approximate 63,000 gallons of oil, affecting approximately 85 miles of the Yellowstone River and its associated floodplain.[3] In another accident extreme flooding occurred in 1994 in the State of Texas, leading to the failure of eight pipelines and the release of more than 35,000 barrels of hazardous liquids into the San Jacinto River. Some of that released product also ignited, causing minor burns and other injuries to nearly 550 people.[4] As recently as November 16th, 2017, the TransCanada's Keystone pipeline spilled 210,000 gallons after an improperly installed small diameter threaded pipe connection leaked.[5]

While these events are rare, pipelines impacted by weather events, such as hurricanes, can spill their contents polluting the environment, impacting public health, and damaging ecosystems and property. In 2016, the U.S. pipeline system contained 296,918 miles on-shore

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[1] Field et al., "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation."
[2] Pipeline and Hazardous Materials Safety Administration, "ExxonMobil Silvertip Pipeline Crude Oil Release into the Yellowstone River in Laurel, MT on 7/1/2011."
[3] "ExxonMobil Pipeline To Pay $12M Over 2011 Spill Into Yellowstone River - Lexis Legal News."
[4] Pipeline and Hazardous Materials Safety Administration, Pipeline Safety: Safety of Hazardous Liquid Pipelines; Proposed Rule.
[5] Mufson and Mooney, "Keystone Pipeline Spills 210,000 Gallons of Oil on Eve of Permitting Decision for TransCanada."

transmission lines, 2,209,349 miles of service and distribution lines, and 211,150 miles of hazardous liquid lines.[6]

Figure 1 and Figure 2 map hazardous liquid and gas pipelines across the U.S. As illustrated by these figures pipelines are highly concentrated in southern coastal states commonly impacted by hurricanes. Scientist now believe with more confidence that human activities contribute to the observed upward trend in hurricane activity. [7] As hurricane activity increases, storms are likely to pose a greater threat to gas and liquid pipelines. The objective of this study is to use pipeline accident data from the Pipeline and Hazardous Material Safety Administration (PHMSA)[8] to search for the characteristics indicative of the most severe pipeline accidents caused by hurricanes. By understanding the characteristics indicative of high-damage accidents, policy makers and pipeline operators can better anticipate threats and take the necessary steps to prevent spills.

[6] Pipeline and Hazardous Materials Safety Administration, "Accident Incident and Mileage Summary Statistics."
[7] Kossin et al., "Extreme Storms."
[8] Pipeline and Hazardous Materials Safety Administration, "Hazmat Incident Report Search"; Pipeline and Hazardous Materials Safety Administration, "Distribution, Transmission & Gathering, LNG, and Liquid Accident and Incident Data."

Figure 1: Gas Transmission Pipeline in the U.S.[9]

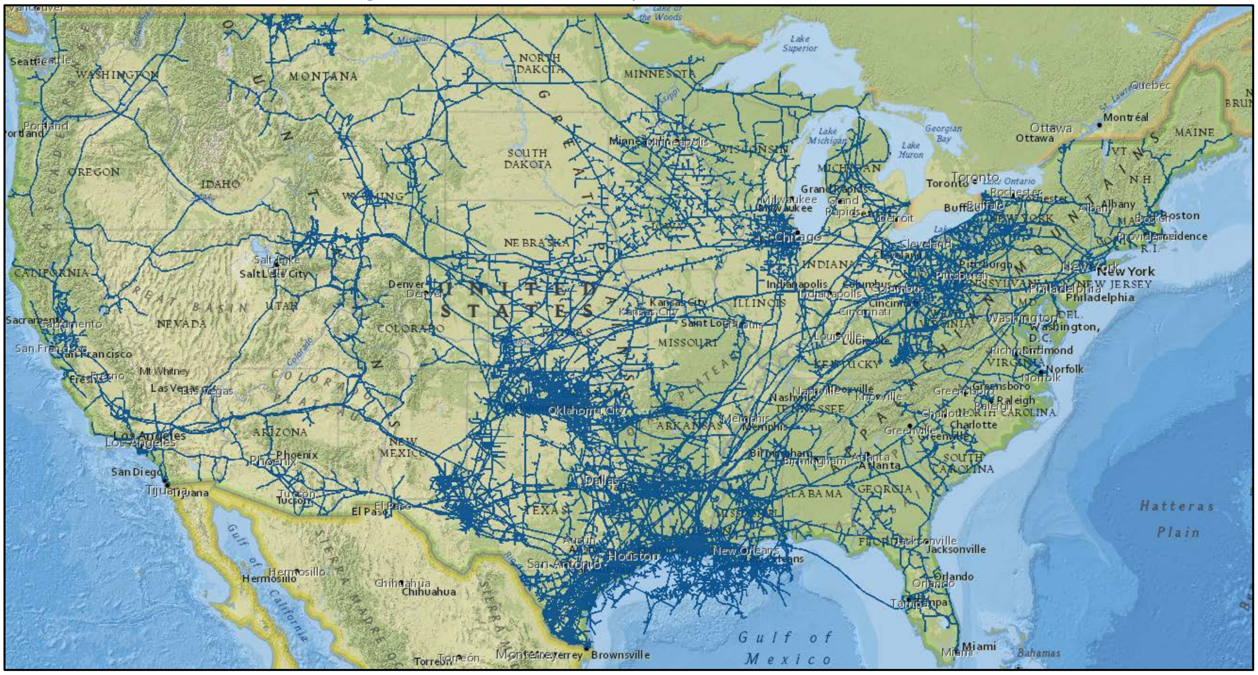
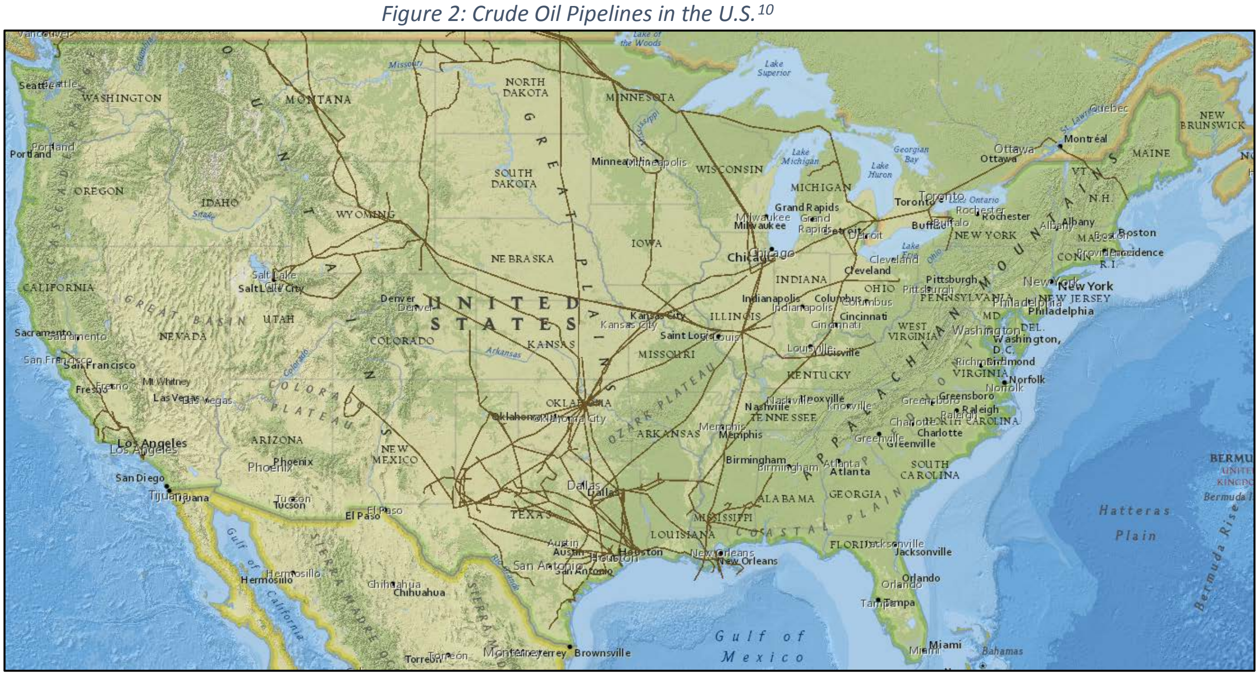


Figure 2: Crude Oil Pipelines in the U.S.[10]



Background

Despite this study's focus on hurricane induced incidents, threats to hazardous gas and liquid pipelines may come from a variety of origins. Other types of extreme weather recorded

[9] Energy Information Administration, "U.S. Energy Mapping System."
[10] Energy Information Administration.

damaging pipelines include tornadoes, thunderstorms, high winds, extreme precipitation and temperatures. More specifically pipelines may burst, leak or explode because of

- Material and construction defects, e.g. defective longitudinal pipe seam, pipe body or joint welds;
- Mechanical damage from construction, maintenance or third-party excavation;
- Incorrect operation;
- Corrosion, creep and cracking mechanisms; and,
- Device failures and malfunctions. [11]

For example, radical temperature swings have caused pipelines to freeze, expand and rupture."[12] In another example, sub-zero temperatures caused water trapped in pipeline valves to freeze, crack, and release product.[13] Incidents with heavy rains and fierce winds historically knocked over trees and broken above ground pipes.[14] In addition, flooded soil moved above or below ground pipelines causing them to rupture and burst.[15]

With the exception of temperature swings, many types of phsyical damage and equipemnt failure may occur during a hurricane. In one particuarlly theatrical incident, Hurricane Andrew dragged four, 30,000 pound anchors, attached to an oil rig by 3 foot thick chain, across an oil pipeline cutting three large grooves in a transmission pipe.[16] In another incident, Hurricane Gustav created underwater mudslides which destroyed an oil pipeline.[17] Hurricane related accidents are not always as theatrical as the two above. In one accident,

[11] Kishawy and Gabbar, "Review of Pipeline Integrity Management Practices."
[12] Hazardous Liquid Incident Report Number #20020405
[13] Hazardous Gas Transmission Incident Report Number #20090118
[14] Hazardous Gas Transmission Incident Number #20040010
[15] Hazardous Gas Transmission Incident Number #20040059
[16] Hazardous Liquid Incident, Report Number #19920157
[17] Hazardous Liquid Incident, Report Number 20080304

blackouts cased by Hurricane Sandy forced pipeline operators loose communication with a compressor station in West Virginia causing leaks.[18]

Despite some scientific disagreements on the connection between hurricanes and climate change, there is a consensus on a few important trends. Scientist suggests tropical cyclone number and intensity will increase on a warmer plant. In the Atlantic and Pacific, hurricanes' precipitation rates are expected to increase with high confidence and intensity with medium confidence [19] Scientist believe with medium confidence that human activities contribute substantially to the observed ocean–atmosphere variability in the Atlantic Ocean and medium confidence that this observed ocean–atmosphere variability changes contributed to the observed upward trend in North Atlantic hurricane activity since the 1970s.[20] There is some disagreement as to the relative magnitude of human influences. However, there is broad agreement human factors are responsible for a measurable impact on hurricane activity impacted by observed oceanic and atmospheric variability in the North Atlantic.[21]

Previous research explored the relationship between extreme weather, climate change and pipelines. Krausman and Cruz identified how climate changes may impact oil and gas extraction, transportation, processing, and delivery, and how these energy industries may adapt or mitigate adverse impacts.[22] The paper recommended oil and gas facilities and infrastructure in low-lying coastal areas (such as pipelines) subject to severe weather will be vulnerable to climate change. In addition, that climate change and extreme weather events represent a real physical threat to infrastructure in the oil and gas sector.

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[18] Hazardous Gas Incident, Report Number #20120118
[19] Kossin et al., "Extreme Storms."
[20] Kossin et al.
[21] Kossin et al.
[22] Cruz and Krausmann, "Vulnerability of the Oil and Gas Sector to Climate Change and Extreme Weather Events."

In 2008, Restrepo et al. analyzed data from 1,582 accidents related to hazardous liquid pipelines for the period 2002–2005 but included 25 different causes of accidents, not only extreme weather events.[23] Restrepo et al. determined with a least squares regression model important association between distinctive characteristics of the accidents and the consequences including product lost; public, private, and operator property damage; and cleanup, recovery, and other costs.

The following year, Krausman identified over 600 hazardous-materials releases from offshore platforms and pipelines triggered by Hurricanes Katrina and Rita. This study identified from these two hurricanes, only 3–6 releases of 1000 barrels or more. However, the authors emphasize from their finding the importance of improving the existing systems for incident reporting, analysis and documentation. Hazmat releases reported following these two hurricanes was slow and in some cases, appeared incomplete. Operators took up to two years after the hurricane to report some incidents. The fact that hazmat releases were being reported through 2005, 2006 and 2007, indicates that there were little preparations or standard procedures for hazmat release identification, analysis, and clean up.[24]

In 2010, Kishway and Gabbar reviewed pipeline integrity management practices and engineering systems that prevent damage from extreme weather but do not include climate change in the discussion. [25] The authors simply outline procedures and policies to help prevent pipeline disasters.

[23] Restrepo, Simonoff, and Zimmerman, "Causes, Cost Consequences, and Risk Implications of Accidents in US Hazardous Liquid Pipeline Infrastructure."
[24] Cruz and Krausmann, "Hazardous-Materials Releases from Offshore Oil and Gas Facilities and Emergency Response Following Hurricanes Katrina and Rita."
[25] Kishawy and Gabbar, "Review of Pipeline Integrity Management Practices."

Lastly, Girgin and Krausmann analyzed 7,000 incidents from 1986 to 2012, 3,800 of which were regarded as significant based on their consequences. They found 5.5% of all and 6.2% of the significant incidents caused by natural hazards resulted in a total hazardous substance release of 317,700 bbl. Furthermore, the total economic cost of significant natural hazard was $597 million USD, corresponding to about 18% of all incident costs in the same period. More than 50% of this cost was due to meteorological hazards, mainly tropical cyclones.[26]

Methodology

The following Methodology section is divided into three parts, Data, Procedures, and Analysis.

Data

The data in this analysis is derived from a PHSMA's database on pipeline accidents. This data is obtained by pipeline operators who are required by Title 49 of the Code of Federal Regulations (49 CFR Parts 191, 195) to submit incident reports within 30 days of a pipeline incident or accident. The CFR defines pipeline accidents and the criteria for submitting reports to the Office of Pipeline Safety. Specific information includes the time and location of the incident(s), number of any injuries and/ or fatalities, commodity spilled/gas released, causes of failure and evacuation procedures.[27] Specifically, according to the 49 CFR § 195.50a hazardous liquid accident is defined as a pipeline a release where:

- An explosion or fire occurred unintentionally;
- An incident released 5 gallons (19 liters) or more, except if less than 5 barrels (795 liters) spilled during a pipeline maintenance activity;
- Death of any person;

[26] Girgin and Krausmann, "Historical Analysis of U.S. Onshore Hazardous Liquid Pipeline Accidents Triggered by Natural Hazards."
[27] Pipeline and Hazardous Materials Safety Administration, "Distribution, Transmission & Gathering, LNG, and Liquid Accident and Incident Data."

- Personal injury necessitating hospitalization; and,
- Estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, exceeding $50,000. [28]

According to § 191.3 of the federal CFR, a gas pipeline incident is an event where gas released from a pipeline results in one or more of the following consequences:

- A death, or personal injury necessitating in-patient hospitalization;
- Estimated property damage of $50,000 or more, including loss to the operator and others, or both, but excluding cost of gas lost;
- Unintentional estimated gas loss of three million cubic feet or more; or,
- An event that is significant in the judgment of the operator.[29]

It should be noted, studies show operators under report this information to PHSMA. Furthermore, operators sometimes under report natural hazards as the incident case and when they do, the incident report may lack completeness.[30] However, for this study the operator submission report are assumed to be accurate and complete.

Lastly, some incidents may be misreported. For example, the data reported for Gas Transmission Incident #20050123 listed the pipe as 500 inches or 42 feet thick. These incidents with reported data that contained obvious errors were excluded from the analysis. Additionally, the database sometimes filled in "0" where the data was blank. Since these are measurements, a pipeline cannot be zero inches thick or zero pressure. Zeroes were omitted and assumed to be missing data.

[28] Pipeline and Hazardous Materials Safety Administration, Reporting Accidents.
[29] Pipeline and Hazardous Materials Safety Administration, Definitions.
[30] Girgin and Krausmann, "Historical Analysis of U.S. Onshore Hazardous Liquid Pipeline Accidents Triggered by Natural Hazards."

The dependent variable "damages" was reported by the pipeline operators in the accident year dollars and was converted to current dollars (US $2016) using the Gross Domestic Price (GDP) Implicit Price Deflator. This index is a measure of the ratio of the current-dollar value of GDP, to its corresponding chained-dollar value, multiplied by 100.[31] Operator reported damages include:

- All relevant costs available at the time of report submission including costs due to property damage to the operator's facilities and to the property of others, facility repair and replacement, and environmental cleanup and damage;
- Public and non-operator private property damage estimates from sites not owned or operated by the operator;
- Operator's property including physical damage to the property of the pipeline operator or owner company such as the estimated installed or replacement value of the damaged pipe, coating, component, materials, or equipment due to the incident.
- Cost of gas released unintentionally, intentional, and/or from a controlled blowdown
- Estimated cost of operator's emergency response expenses; and,
- Any other associated costs not specified.[32]

Procedures

To understand the relationship between pipe characteristics and the severity of an accident, the analysis used a multivariable regression model. A multivariable regression model attempts to discover and test relationships between a dataset of historical dependent and independent variables. The linear regression model used in this analysis is presented below. The

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[31] U.S. Bureau of Economic Analysis, "GDPDEF."

[32] Pipeline and Hazardous Materials Safety Administration, "Instructions For Form PHMSA F 7100.2 (Rev. 06-2011) Incident Report – Natural And Other Gas Transmission And Gathering Pipeline Systems"; Pipeline and Hazardous Materials Safety Administration, "Instructions For Form PHMSA F 7000-1 (Rev. 10-2011) Accident Report – Hazardous Liquid Pipeline Systems."

equation represents the best-fit curve assuming each variable is independent of the predictor variable and the errors are normally distributed around each regressor.[33]

$$Y = B_0 + B_1X_1 + B_2X_2 + \ldots + B_nX_n$$

The significance of independent variables is evaluated through F-test. In the pipeline integrity management literature, an acceptable level of risk for an F-test result should be less than or equal to the 5%-level. Accordingly, if the F-test result for each variable is less than the amount of alpha then that variable is significant; otherwise, the variable is often removed. Additionally, R-squared is a measure of the efficiency of a regression model to predict the true result. Correlations in the Results describe the ability of this regression model to estimate the damages because of hurricanes. [34] Therefore, low alphas indicate the regression is efficient at predicting true damages with knowledge of pipeline characteristics.

The data was downloaded from PHSMA's website cleaned and organized in Microsoft Excel. The data was then uploaded into a statistical program, R, where the multivariable regression was estimated. R is a free, open-sourced, software used for statistical computing and graphics. Since offshore and onshore pipelines are regulated differently and exposed to different natural elements of a hurricane, both types of pipes were analyzed separately. Therefore, the data was broken into four smaller datasets, offshore liquid, offshore gas, onshore liquid and onshore gas.

Analysis

Pipeline operators claimed all the incidents resulted from hurricane or tropical storm induced natural forces. Some summary information on this data is presented in Table 1. The

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[33] Parvizsedghy and Zayed, "Developing Failure Age Prediction Model of Hazardous Liquid Pipelines."
[34] Wang, Zayed, and Moselhi, "Prediction Models for Annual Break Rates of Water Mains"; Parvizsedghy and Zayed, "Developing Failure Age Prediction Model of Hazardous Liquid Pipelines."

average incident's damages fall in the 64th – 78th percentile, which shows the skewness of the incident data. Several extremely damaging accidents skew the average incident to the point where in some cases the median incident can be several orders of magnitude less than the average. If the data was normally distributed, the average incident would be near or at the 50th percentile.

Table 1: Summary Information Hurricane Incidents 1985 - 2012

(US $2016)	All Incidents		Offshore		Onshore	
Damages	Liquid	Gas	Liquid	Gas	Liquid	Gas
Mean	$8,188,968	$7,833,865	$5,006,201	$8,291,365	$14,554,502	$5,500,616
Median	$1,018,722	$1,044,066	$2,790,369	$2,169,510	$108,892	$138,365
Max	$181,687,522	$106,462,022	$30,005,502	$99,902,828	$181,687,522	$106,462,022
Number	51	122	34	102	17	20
Mean's Percentile Rank	78%	77%	64%	74%	76%	66%

Of all the incidents, the largest accident caused $182 million in damage. This incident was a pipeline terminal damaged by high winds during Hurricane Katrina.[35] Figure 3 and Table 2 show the total damage to pipeline infrastructure by hurricanes. There are some years the damages barely surpass a million dollars and other years, such as 2005 and 2008, where the damage amounts to hundreds of millions. It also is no coincidence, these years of high damage correspond to the years that famous hurricanes Ike, Katrina, Gustav, and Rita landed on United States' coast.

[35] Hazardous Liquid Incident, # 20050287

Figure 3: Total Hurricane Damage to Pipeline Infrastructure per Year (US $2016)

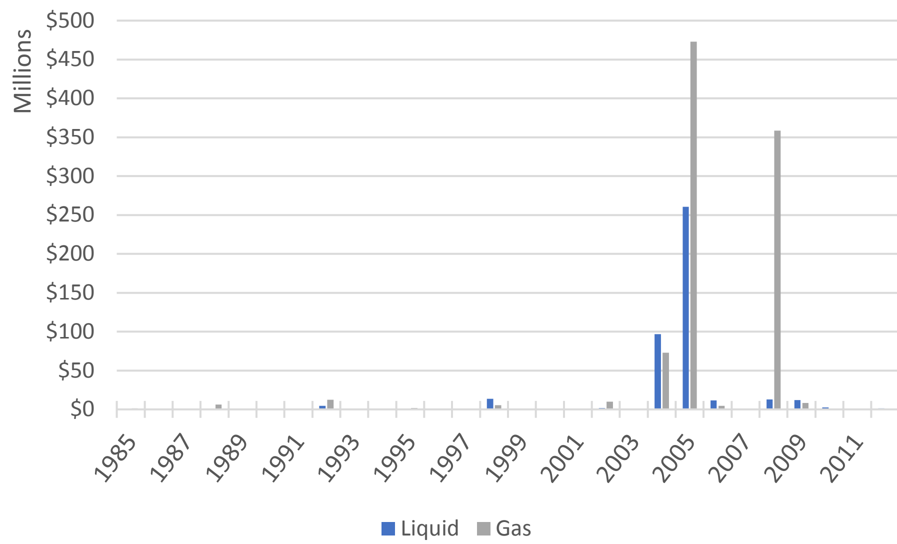


Table 2: Total Hurricane Damage to Pipelines per Year

Year	Liquid	Gas	Major Named Hurricanes[36] **
1985	$0	$1,459,903	Gloria, Juan, Kate
1986	$0	$0	
1987	$0	$0	
1988	$0	$6,092,479	Florence
1989	$0	$0	Chantal, Hugo, Jerry
1990	$0	$0	
1991	$0	$0	
1992	$4,507,699	$12,443,143	Andrew
1993	$0	$0	
1994	$0	$0	
1995	$739,581	$1,523,537	Erin, Opal
1996	$0	$72,633	Bertha, Fran
1997	$0	$107,115	
1998	$13,817,885	$5,368,913	Bonnie, Earl, Georges
1999	$0	$0	
2000	$0	$0	
2001	$0	$0	
2002	$1,506,665	$10,008,788	Lili
2003	$0	$0	
2004	$96,785,440	$72,809,425	Alex, Charley, Gaston, Frances, Ivan, Jeanne
2005	$260,554,441	$473,028,713	Cindy, Dennis, Katrina, Rita, Wilma
2006	$11,383,180	$4,451,334	
2007	$187,884	$387,931	Humberto

[36] Chris Landsea, "FAQ E23) What Is the Complete List of Continental U.S. Landfalling."

2008	$12,717,490	$358,685,610	Dolly, Gustav, Ike
2009	$11,946,709	$8,285,310	
2010	$2,422,980	$0	
2011	$0	$541,173	Irene
2012	$1,067,403	$465,532	Isaac, Sandy
** Note this list is not comprehensive and just includes ***major*** "named" hurricanes.			

Results

This section presents the multivariable regression results for each data subset. Table 3 shows the Pearson correlation results for each individual independent variable against the dependent variable "Damages". The Pearson correlation coefficient is a measure of the linear correlation between two variables. As seen from Table 3 some of the variable are better at explaining the relationship between damages than other variables. Explanations of the pipeline characteristics are listed in Table 3 and in the following paragraph. These characteristics are used to regulate pipelines in federal and state regulatory codes. Often, changes to monitored pipe characteristics inform pipeline operators when safety procedures need to be initiated to prevent and accident. For example, if pipe corrosion reduces the wall thickness to less than that required to maintain the maximum operating pressure, operators are required to submit a report to PHMSA and repair the pipeline.[37]

SMYS is the specific minimum yield strength of the pipe. It is an indication of the minimum stress a steel pipe may experience before its permanently deforms. It is calculated from internal pressure, wall thickness and outside diameter and measured as a pressure. Age is the estimated age of the part or pipe using the part's installation year. The parts range from new to some parts installed in the first half of the 20th century. Wall thickness refers to the thickness of the pipe. Pipes are commonly less than an inch thick. Pipe size refers to the pipe's overall diameter. Most oil and gas pipe diameters usually range between 4 and 48 inches. Max

[37] Pipeline and Hazardous Materials Safety Administration, "Safety-Related Condition Reports (SRCRs)."

pressure, also commonly referred to as max allowable pressure (MAOP), is the maximum pressure in which a pipeline may be safely operated. While accident pressure is the pressure in which the pipeline operated at before the accident occurred, sometimes this data point may be referred to as "estimated pressure."

Table 3: Pearson Correlation Coefficient Results with Dependent Variable Damages

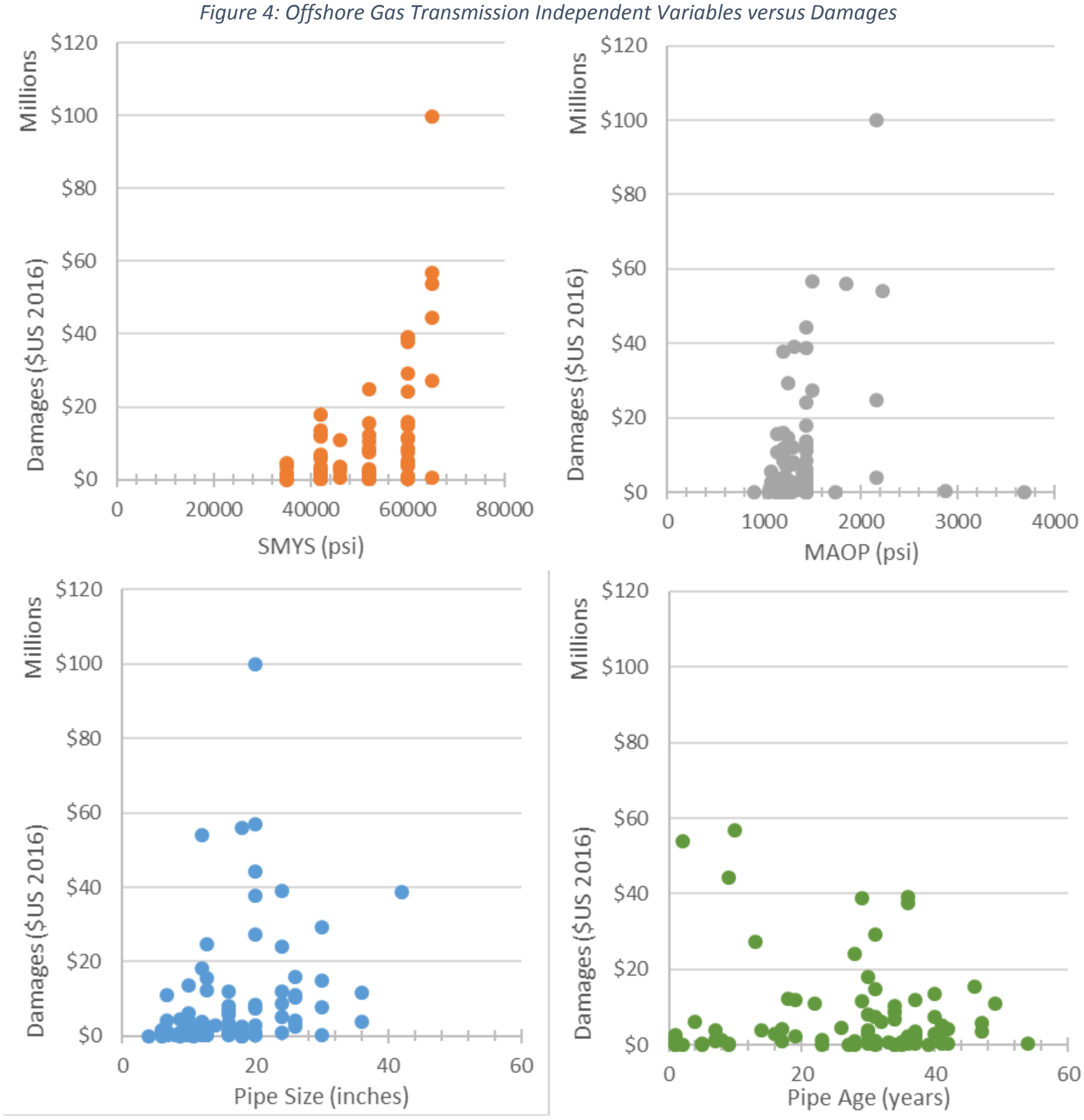
Variable	Offshore Liquid	Onshore Liquid	Offshore Gas	Onshore Gas
Accident Pressure	-0.48	0.12	0.10	-0.25
Max Pressure (MAOP)	0.00	-0.20	0.27	-0.34
Pipe Diameter (Pipe Size)	0.19	0.29	0.32	-0.20
Wall Thickness	0.26	-0.38	0.29	-0.10
SMYS	-0.01	-0.32	0.49	-0.24
Age	-0.12	0.63	-0.09	0.60

- SMYS - the specified minimum yield strength (SMYS) for steel pipe is a common term used in the oil and gas industry as an indication of the minimum stress a pipe may experience that will cause plastic (permanent) deformation.
- Accident Pressure – sometimes referred to as "estimated pressure", the pipe pressure at the time of accident
- Max Pressure – sometimes referred to as Maximum Allowable Operating Pressure (MAOP), this pressure is the pipes max allowable pressure
- Pipe Diameter (Pipe Size) - the pipe's diameter, sometimes referred to as pipe size. Pipe diameters usually range between 4 and 48 inches.
- Wall Thickness - thickness of the pipe's wall
- Age - estimated age of the pipe using installation its year

In total, there are four modeled categories, offshore liquid, offshore gas, onshore liquid, and onshore gas. The two or three variables with the strongest relationship for each dataset were chosen for the multivariable regression model. For example, the offshore liquid model used accident pressure (-.48) and wall thickness (.26). Each of the following sub sections lists specific regression results. Of the tested regressions, only the results from offshore gas pipelines were significant. The remaining regressions did not have enough complete and comprehensive data to produce meaningful results. Figure 4 shows four pipeline characteristics for offshore gas transmission lines and their relationship to damages. Three of these characteristics, MAOP, Pipe

Size, and SMYS, strongly explained the relationship to damages. While the fourth characteristics, Age, poorly explained pipeline damages.

Figure 4: Offshore Gas Transmission Independent Variables versus Damages



Offshore Hazardous Liquid Pipelines

The limited amount of observations likely explains why none of the variables with strong Pearson Correlations explained the relationship between damages and pipe characteristics in offshore liquid pipelines. For example, the model deleted 17 observations in some cases due to incomplete data. The p-values of the estimated coefficients indicate none of the variables are significant or explain the relationship between damages and pipelines characteristics. Perhaps a further analysis with more complete data may find a stronger relationship.

Table 4: Regression Results for Accident Pressure and Pipe Wall Thickness

	Estimate	Std. Error	T value	Pr(>|t|)
(Intercept)	-4486158	12781786	-0.351	0.7308
Accident Pressure	-9317	4919	-1.894	0.0791
Wall Thickness	33789822	26426454	1.279	0.2218

Residual standard error: 7496000 on 14 degrees of freedom
(17 observations deleted due to missing data)
Multiple R-squared: 0.3089, Adjusted R-squared: 0.2101
F-statistic: 3.128 on 2 and 14 DF, p-value: 0.07532

Table 5: Regression Results for Pipe Wall Thickness and Size

	Estimate	Std. Error	T value	Pr(>|t|)
(Intercept)	-4083450	6228499	-0.656	0.517
Wall Thickness	15702085	13800668	1.138	0.265
Pipe Size	179029	266390	0.672	0.507

Residual standard error: 6937000 on 28 degrees of freedom
(3 observations deleted due to missing data)
Multiple R-squared: 0.08298, Adjusted R-squared: 0.01748
F-statistic: 1.267 on 2 and 28 DF, p-value: 0.2974

Table 6: Regression Results for Pipe Size and Accident Pressure

	Estimate	Std. Error	T value	Pr(>|t|)
(Intercept)	5254502	5466626	0.961	0.3528
Pipe Size	548258	412650	1.329	0.2052
Accident Pressure	-12245	5017	-2.441	0.0285 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*'
Residual standard error: 7465000 on 14 degrees of freedom
(17 observations deleted due to missing data)
Multiple R-squared: 0.3146, Adjusted R-squared: 0.2167
F-statistic: 3.213 on 2 and 14 DF, p-value: 0.07107

Onshore Hazardous Liquid Pipelines

For hazardous liquid pipelines, the limited number of complete observations possibly indicates why none of the variables with strong Pearson Correlations explained hurricane damages in onshore liquid pipelines. All the estimated coefficients are insignificant when the relationship between damages and pipelines characteristics was tested. In addition, the regressions deleted 12-13 observations due to missing data.

Table 7: Regression Results for Pipe Size and Age

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2916854	9433058	-0.309	0.786
Pipe Size	130082	470968	0.276	0.808
Age	208936	188506	1.108	0.383
Residual standard error: 8855000 on 2 degrees of freedom (12 observations deleted due to missing data) Multiple R-squared: 0.4035, Adjusted R-squared: -0.1929 F-statistic: 0.6765 on 2 and 2 DF, p-value: 0.5965				

Table 8: Regression Results for Wall Thickness and Age

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	103966489	50379360	2.064	0.287
Wall Thickness	-195364950	92934468	-2.102	0.283
Age	-818073	515113	-1.588	0.358
Residual standard error: 5460000 on 1 degrees of freedom (13 observations deleted due to missing data) Multiple R-squared: 0.8787, Adjusted R-squared: 0.636 F-statistic: 3.621 on 2 and 1 DF, p-value: 0.3483				

Offshore Transmission Gas Pipelines

For offshore transmission gas pipelines four different regressions analyzed some combination of the most statistically significant variables, maximum operating pressure, pipe size, and SMYS. Each regression varied in its statistical significance and ability to predict the severity of incident damages.

The best result in Table 10 show the regression with lowest error. In this regression all variables were significant to at least the .1% level and the regression explained 20% of the variability of accidents. These results are expected, indicating the largest, highest pressure pipes, that transport the most gas, weakly explain the most severe pipeline accidents measured in terms of damages caused by hurricanes. Given the skewed distribution of pipeline accidents, these pipes are the primary contenders to cause a the most damages during a hurricane. Table 12 results contained the largest R-squared explaining 28% of the variable in damages, however these results are slightly less significant. The Table 12 regression compared pipe strength and pressure to damages.

Table 9: Regression Results for MAOP, Pipe Size and SMYS

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.085e+07	9.194e+06	-4.443	2.66e-05 ***
MAOP	8.337e+03	4.108e+03	2.029	0.045542 *
Pipe Size	1.024e+04	2.806e+05	0.036	0.970974
SMYS	7.693e+02	2.254e+02	3.414	0.000983 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*'
Residual standard error: 13440000 on 85 degrees of freedom
(13 observations deleted due to missing data)
Multiple R-squared: 0.2809, Adjusted R-squared: 0.2555
F-statistic: 11.07 on 3 and 85 DF, p-value: 3.318e-06

Table 10: Regression Results for MAOP and Pipe Size

Coefficients:	Estimate.	Std. Error	t value	Pr(>|t|)
(Intercept)	-22186148	6937974	-3.198	0.001887 **
MAOP	13736	4104	3.347	0.001175 **
Pipe Size	748504	192460	3.889	0.000188 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*'
Residual standard error: 14320000 on 94 degrees of freedom
(5 observations deleted due to missing data)
Multiple R-squared: 0.1989, Adjusted R-squared: 0.1818
F-statistic: 11.67 on 2 and 94 DF, p-value: 2.979e-05

Table 11: Regression Results for SMYS and Pipe Size

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-3.255e+07	8.382e+06	-3.883	0.000202 ***
SMYS	8.917e+02	2.210e+02	4.034	0.000118 ***
Pipe Size	-1.599e+05	2.726e+05	-0.586	0.559114

Signif. codes: 0 '***' 0.001 '**' 0.01 '*'
Residual standard error: 13680000 on 86 degrees of freedom
(13 observations deleted due to missing data)
Multiple R-squared: 0.246, Adjusted R-squared: 0.2285
F-statistic: 14.03 on 2 and 86 DF, p-value: 5.32e-06

Table 12: Regression Results for SMYS and MAOP

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.093e+07	8.895e+06	-4.601	1.44e-05 ***
SMYS	7.755e+02	1.482e+02	5.232	1.17e-06 ***
MAOP	8.292e+03	3.898e+03	2.127	0.0362 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*'
Residual standard error: 13360000 on 86 degrees of freedom
(13 observations deleted due to missing data)

Multiple R-squared: 0.2809,   Adjusted R-squared: 0.2642
F-statistic: 16.79 on 2 and 86 DF, p-value: 6.96e-07

Onshore Transmission Gas Pipelines

The results for onshore pipelines' analysis were inconclusive. For example, while these regression in Table 14 explained 55% variation in damages these results were insignificant. In addition, the regression resulted in a p-value of .19. Results of the regression analysis in Table 13 and Table 15 are equally as insignificant and did not show a strong relationship between pipeline characteristics and damages. Since 7 to 13 observations we omitted because of missing operator data depending on the regression. The inconsistent results can likely be accredited to the incredibly small sample size of onshore gas transmission lines damages caused by Hurricanes.

Table 13: Regression Results for Pipe Size and MAOP

	Estimate	Std. Error	T value	Pr(>|t|)
(Intercept)	337577.6	116673.8	2.893	0.016*
Pipe Size	-2910.5	5339.3	-0.545	0.598
MAOP	-100.1	121.0	-0.827	0.427

Signif. codes: 0 '***' 0.001 '**' 0.01 '*'
Residual standard error: 172100 on 10 degrees of freedom
(7 observations deleted due to missing data)
Multiple R-squared: 0.1013,   Adjusted R-squared: -0.07848
F-statistic: 0.5634 on 2 and 10 DF, p-value: 0.5864

Table 14: Regression Results for Pipe Size and Age

	Estimate	Std. Error	T value	Pr(>|t|)
(Intercept)	108237	121190	0.893	0.4223
Pipe Size	-6817	7172	-0.951	0.3957
Age	6705	3076	2.180	0.0948

Residual standard error: 144900 on 4 degrees of freedom
(13 observations deleted due to missing data)
Multiple R-squared: 0.5547,   Adjusted R-squared: 0.332
F-statistic: 2.491 on 2 and 4 DF, p-value: 0.1983

Table 15: Regression Results for Pipe Size and SMYS

	Estimate	Std. Error	T value	Pr(>|t|)
(Intercept)	572063.07	700132.15	0.817	0.460

Pipe Size	7639.11	24207.53	0.316	0.768
SMYS	-10.99	23.19	-0.474	0.660
--- Residual standard error: 203000 on 4 degrees of freedom (13 observations deleted due to missing data) Multiple R-squared: 0.07834, Adjusted R-squared: -0.3825 F-statistic: 0.17 on 2 and 4 DF, p-value: 0.8495				

Discussion

The results from this analysis are not conclusive for all pipeline types. The analysis only shows a conclusive but weak relationship between incident damages and offshore gas pipeline characteristic. Table 9 through Table 12 show that high-pressure, large, and strong pipes may produce the most serious accidents when damaged by hurricanes. The lack of conclusive results is likely due to the insufficient observations and missing information pervasive through the operator accident reports. If this analysis is conducted again after more data on hurricane induced pipeline accidents is available, conducting this analysis may result in more conclusive results for other types of pipelines.

Furthermore, there is the opportunity to do a similar analysis for other types of weather events that may increase in severity due to climate change. PHSMA's database contains information on pipelines accidents caused by floods, extreme temperatures, thunderstorms, windstorms, and lightning. These types of weather events may also demonstrate relationships between pipeline characteristics and damages.

Similar studies demonstrated stronger relationships, but used different combinations of independent and dependent variables, more observations, or different databases entirely. Using age of failure as the dependent variable, and maximum pressure, diameter, thickness, and SMYS as the independent variables, Parvizsedghy and Zayed built a model that explained 86% of the variation in the age of failure using pipe characteristics of hazardous liquid accident. However, since these authors studied corrosion instead of extreme weather, they had over 2000 records.[38]

Senouci et al.'s model explained 83% of the failure type in oil pipelines (natural hazard, corrosion, etc.) using a multivariable regression. Their model used pipe location, type of product, age, land use, and diameter as their independent variables.[39] Both models were statistically significant at the 5% level.

Restrepo et al.'s analysis of hazardous liquid pipeline accidents used a least squares regression to identify significant variables that explain damages from accidents. Their analysis included gallons of oil lost, pipe offshore, ignition of pipe oil, and corrosion. These variables were all significant at the 5% level.[40]

Conclusion

This analysis demonstrates a weak relationship between hurricane damages and offshore gas pipelines' pressure, size, and strength. Policy makers who govern areas near offshore gas pipelines or companies who move product via pipeline of significant pressure, size, and strength in hurricane prone regions may want to consider the implications of these finding when evaluating risks associates with hurricanes to pipeline infrastructure. However, the imperfect results of this study make is impossible to draw more certain conclusions about hurricane induced damages for other types of pipelines. Further analysis on this topic could take two routes. Searching for relationships between other types of weather events and pipeline damages or collecting more incident data to demonstrate more conclusive relationships between hurricane damaged pipeline characteristics.

[38] Parvizsedghy and Zayed, "Developing Failure Age Prediction Model of Hazardous Liquid Pipelines."
[39] Senouci et al., "A Model for Predicting Failure of Oil Pipelines."
[40] Restrepo, Simonoff, and Zimmerman, "Causes, Cost Consequences, and Risk Implications of Accidents in US Hazardous Liquid Pipeline Infrastructure."

Appendix: Data Tables

The following section lists the final datasets for both gas and liquid pipelines used in this analysis. This data reflects the final datasets after the cleaning for typos.

Table 16: Hazardous Gas Pipeline Hurricane Accident Data

Accident Year	ID Number	Damages	Pipe Size	SMYS	Age	Wall Thickness	Estimated Pressure	Max Pressure	Offshore?
1985	19850293	$1,459,903	10.75	42000	8	0.44	1125	1400	Yes
1988	19880208	$6,092,479	10	42000	4	0.5	1050	1440	Yes
1992	19920139	$2,526,206	16	42000	1	0.5		1069	Yes
1992	19920147	$2,368,318	18		19	0.5	600	1148	Yes
1992	19920148	$0			23		900	1200	Yes
1992	19920149	$48,945	10	35000	4	0.37	166	250	No
1992	19920151	$1,184,159			17		1000	1250	Yes
1992	19920152	$6,315,515			32		970		Yes
1995	19950141	$73,958	18		2	0.5	650	1238	Yes
1995	19950146	$1,449,579	6	35000	7	0.43	660	1440	Yes
1995	19950150	$0	4	35000	1	0.44	90	3680	Yes
1995	19960052	$0	8.63		34				Yes
1996	19960168	$72,633	18		1	0.5	870	1200	Yes
1997	19970105	$107,115	6.63	35000	39	0.25	900	1050	Yes
1998	19980221	$4,238,615	26	60000	17	0.63	750	1440	Yes
1998	19980223	$70,644	10.75	52000	9	0.5	1000	1730	Yes
1998	19980224	$70,644	10.75	42000	40	0.31	900	1060	No
1998	19980225	$141,287	10	35000	28	0.37	1015	1440	Yes
1998	19980255	$847,723	20	52000	1	0.5	700	1182	Yes
2002	20020077	$531,440	6			0.31	900	1357	Yes
2002	20020085	$6,820,147	16	42000	34	0.38	850	1235	Yes
2002	20020086	$2,657,200	26	52000	30	0.56	887	1250	Yes
2004	20040084	$287,375	16	42000	48	0.25	150	200	No

2004	20040090	$3,803,493	26	60000	30	0.49	1138	1440	Yes
2004	20040091	$3,803,493	36	60000	14	0.6	1000	1200	Yes
2004	20040092	$11,072,392	26	60000	22	0.75	900	1440	Yes
2004	20040093	$8,621,251	24	60000	34	0.5	1100	1200	Yes
2004	20040094	$845,221	24	60000	33	0.5	1100	1200	Yes
2004	20040100	$44,376,200	20	65000	9	0.5	901	1440	Yes
2005	20050028	$1,555,864	12.75	52000	1	0.38	980	1138	Yes
2005	20050094	$15,946,784	26	60000		0.49	900	1200	Yes
2005	20050095	$90,076	8.63	35000		0.5	715	1125	Yes
2005	20050096	$106,462,022							No
2005	20050099	$265,838	1				348	442	No
2005	20050100	$455,113	0.25				720	982	No
2005	20050101	$3,603,053	12	42000	37	0.5	1100	1235	Yes
2005	20050102	$307,491	0.5				77	480	No
2005	20050103	$4,143,511	10	35000	42	0.37	1000	1440	Yes
2005	20050104	$90,076					1100	1150	No
2005	20050105	$818,876	18	52000		0.5	1150	1200	Yes
2005	20050106	$90,076	12.75	52000	35	0.5	1100	1200	Yes
2005	20050107	$98,265	26	60000		0.38	1100	1273	No
2005	20050109	$98,265	20	60000		0.63	1200	1440	Yes
2005	20050111	$1,637,751	12	52000	37	0.38	922	1206	Yes
2005	20050112	$163,775	20						Yes
2005	20050117	$56,805,986	20	65000	10	0.5	901	1500	Yes
2005	20050118	$163,775	8	52000		0.41	1000	1440	Yes
2005	20050120	$327,550	12.75	52000		0.5	1050	1300	Yes
2005	20050121	$163,775	6.63	35000		0.31	1000	1150	Yes
2005	20050123	$3,678,244	12	46000	41		950	1440	Yes
2005	20050124	$24,811,932	12.75	52000		0.56	1280	2160	Yes
2005	20050125	$12,037,472	24	52000	37		1100	1250	Yes
2005	20050131	$81,889							No
2005	20050133	$154,695			54		280	805	No

2005	20050135	$2,947,952	14	42000	37	0.5	895	1200	Yes
2005	20050136	$98,265					850	1200	No
2005	20050139	$8,434,419	20	52000		0.5	750	1440	Yes
2005	20050140	$14,821,649	30	60000	31	0.6	1000	1250	Yes
2005	20050141	$247,300	12		9	0.38	1250	1440	Yes
2005	20050143	$327,550	12	42000		0.38	1000	1250	Yes
2005	20050148	$245,663	26	52000	34	0.5	1000	1247	No
2005	20050149	$3,460,568	16	35000	47	0.5	865	1168	Yes
2005	20050150	$1,105,482	16	52000	31	0.5	1000	1440	Yes
2005	20050154	$53,960,930	12	65000	2	0.5	1060	2220	Yes
2005	20050155	$99,902,828	20	65000		0.55	1080	2160	Yes
2005	20050156	$2,538,514	12.75	46000	37	0.38	1200	1300	Yes
2005	20050157	$417,627	12	42000	41		993	1440	Yes
2005	20050158	$18,015,264	12	42000	30	0.38	1000	1440	Yes
2005	20050159	$561,749	12	52000	36	0.31	900	1300	Yes
2005	20050160	$423,604	6	42000	37	0.28		1200	Yes
2005	20050161	$24,041,760	24	60000	28	0.5	1150	1440	Yes
2005	20050162	$932,449	12	52000	28	0.38	950	1440	Yes
2005	20050163	$856,218	12	52000	35	0.38	930	1250	Yes
2005	20050164	$131,020			15		925	1056	No
2005	20050172	$982,651	8.63	35000	7	0.32	1250	1440	Yes
2005	20050178	$1,228,313	6.63	42000	23	0.31	1100	1200	Yes
2005	20050182	$2,976,154	12	42000	16	0.5	950	1250	Yes
2006	20060051	$2,859,929	20	52000	40	0.5	1050	1440	Yes
2006	20060059	$397,212	10	42000	54	0.5	870	1440	Yes
2006	20060069	$95,331	10.75	35000	27	0.31	650	1440	Yes
2006	20060074	$120,778	6.63	42000	31	0.25	400	1280	Yes
2005	20060075	$318,628	10.7	42000	30	0.28	400	1280	Yes
2006	20060087	$978,083	10.7	42000	31	0.28	400	1280	Yes
2007	20070080	$387,931	2		40		980	1000	No
2008	20080087	$10,867,473	6.63	46000	49	0.5	900	1130	Yes

2008	20080088	$5,160,532	24	60000	41	0.5	1168	1393	Yes
2008	20080089	$13,525,147	10	42000	40	0.5	750	1440	Yes
2008	20080091	$112,528	1			0.22	750	1100	No
2008	20080092	$7,049	1			0.22	750	1100	No
2008	20080096	$55,885,526	18			0.5	850	1850	Yes
2008	20080097	$4,037,357	6.63	35000	7	0.43	750	2160	Yes
2008	20080098	$27,256,415	20	65000	13	0.5	900	1500	Yes
2008	20080099	$4,705	6			0.25	50	900	Yes
2008	20080101	$8,007,931	16	52000	30	0.5		1300	Yes
2008	20080103	$422,646	16	65000	5	0.81	765	2875	Yes
2008	20080104	$11,973,952	16	42000	19	0.5		1300	Yes
2008	20080105	$7,589,018	30	60000	40	0.5		1300	Yes
2008	20080106	$145,709	2.38	35000	3	0.15	980	1440	No
2008	20080107	$10,452,671	26	52000	34	0.5	980	1200	Yes
2008	20080108	$11,687,087	36	60000	29	0.6	980	1200	Yes
2008	20080109	$15,557,486	12.75	52000	46	0.38	900	1138	Yes
2008	20080111	$38,786,089	42	60000	29	0.81	800	1440	Yes
2008	20080113	$227,671	16	52000		0.5	1250	1440	Yes
2008	20080114	$5,691,763	16	42000	47	0.41	900	1069	Yes
2008	20080115	$39,126,633	24	60000	36	0.5		1306	Yes
2008	20080116	$956,216	16	60000	36	0.5	895	1306	Yes
2008	20080117	$956,216	6	35000	36	0.31	895	1250	Yes
2008	20080118	$29,268,664	30	60000	31	0.63		1250	Yes
2008	20080120	$713,368	10.75	35000	30	0.31		1300	Yes
2008	20080122	$37,688,428	20	60000	36	0.47	895	1200	Yes
2008	20080123	$7,422,059	20	52000	31	0.47	895	1219	Yes
2008	20080124	$2,079,391	10	52000	36	0.37	985	1200	Yes
2008	20080126	$645,066	20	60000	35	0.5	1150	1250	Yes
2008	20080127	$106,246	10		5		920	1440	Yes
2008	20080133	$12,218,318	12.75	42000	18	0.5	980	1440	Yes
2008	20080136	$106,246	30	60000	34	0.6	850	1250	Yes

2009	20090014	$2,259,630	12.75	42000	36	0.5	850	1250	Yes
2009	20090036	$4,519,260	8.63	35000	26	0.5	800	1440	Yes
2009	20090127	$1,506,420	6	35000		0.43	1150	1173	Yes
2011	20110370	$541,173	6	35000	50	0.219	450	565	No
2012	20120095	$444,913	16	46000	42	0.5	938	1440	Yes
2012	20120118	$20,619			14		718	1000	No

Table 17: Hazardous Liquid Hurricane Pipeline Accident Data

Year	ID Number	Damages	Accident Pressure	Max Pressure	Pipe Size	Wall Thickness	SMYS	Age	Offshore?
1992	19920157	$1,349,941	900	1440	20	0.41	52000	16	Yes
1992	19920163	$3,157,757		1440	10	0.5	42000	14	Yes
1995	19950182	$739,581		1440	12	0.41	52000	27	Yes
1998	19980156	$395,604	1440	1440	13	0.41	52000	30	Yes
1998	19980160	$4,238,615		1440	10	0.5	42000	6	Yes
1998	19980163	$9,183,666	139	1440	10	0.5	35000	18	Yes
2002	20020392	$327,536	375	1440	8	0.5	42000	25	Yes
2002	20020410	$1,179,129	400	1440	6.63	0.31	42000		Yes
2004	20040270	$7,720,101			20	0.38	56000	7	Yes
2004	20040273	$4,877,104			0.5				Yes
2004	20040274	$18,287,451							No
2004	20040290	$5,252,169			18	0.56	65000	1	Yes
2004	20040299	$22,004,101	100	1950	18	0.56	60000	8	Yes
2004	20040317	$30,005,502	125	1440	10.75	0.5	35000		Yes
2004	20040336	$8,639,012			18	0.5	65000	2	Yes
2005	20050278	$18,423,115	180	832	20	0.25	52000	47	No
2005	20050279	$22,741,214							No
2005	20050284	$6,198			1.32	0.18	35000		Yes
2005	20050285	$4,210,984	14	720					No
2005	20050286	$375							No
2005	20050287	$181,687,522							No
2005	20050288	$1,018,722	250	1180	12	0.31	46000	49	No
2005	20050289	$30,475							No
2005	20050290	$0							No
2005	20050302	$14,423,809		1440	8.63	0.5	42000	33	Yes
2005	20050322	$61,774		1440	6.63	0.43	35000		Yes
2005	20050332	$100,292	300	1440	6.63	0.43	35000	22	Yes
2005	20050333	$7,634,741	350	1440	12.75	0.41	52000		Yes
2005	20050361	$3,233,981	78	1440	8.63	0.38	52000	33	Yes

2005	20060007	$6,980,512	200	1440	12.75	0.41	52000	37	Yes
2005	20060010	$727		2312	18	0.69	42000	9	Yes
2006	20060048	$9		1440	8.63	0.38	52000	34	Yes
2006	20060049	$9		1440	8.63	0.38	52000	34	Yes
2006	20060195	$219,799		835	2			1	No
2006	20060346	$11,163,362	70	1440	12.75	0.56	46000	27	Yes
2007	20070201	$78,992	340	1440	8	0.22	52000		No
2007	20080005	$108,892		250	8	0.28			No
2008	20080211	$566		2160	10	0.5	60000		Yes
2008	20080304	$4,712,779	500	1440	10	0.5	52000	25	Yes
2008	20080305	$3,368	670	2160	20	0.56	60000	13	Yes
2008	20080307	$56,127	50	2183					No
2008	20080308	$7,696	75	1950	24	0.5	65000	12	No
2008	20080313	$22,941	70	1250	24	0.5	70000	4	No
2008	20080324	$56,239	1050	1440	10	0.5	42000		Yes
2008	20080337	$7,857,773		2160	6	0.63	52000	2	Yes
2009	20090235	$11,946,709	750	1440	20	0.41	52000	33	Yes
2010	20100045	$2,422,980	400	1407	18	0.406	52000	42	Yes
2012	20120258	$1,175							No
2012	20120263	$531,048	5	285				4	No
2012	20120281	$497,694		1200				4	Yes
2012	20120344	$37,486							Yes

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