ABSTRACT

Title of Thesis:	A PROBABILISTIC RISK ASSESSMENT BASED APPROACH TO UNDERSTANDING AND MANAGING RISKS OF NATURAL GAS DISTRIBUTION PIPING IN THE UNITED STATES
	Sara Lyons, Master of Science, 2020
Thesis Directed By:	Professor Mohammed Modarres Department of Mechanical Engineering

Two hundred sixty-nine regulated pipeline system accidents caused fatalities and/or injuries in the United States between 2010 and 2018, resulting in 106 fatalities and 599 injuries requiring hospitalization. About 84% of these serious accidents occurred on gas distribution systems, which primarily transport natural gas. This study adapts probabilistic risk assessment (PRA) methods which are used predominantly in the space and nuclear industries to gas distribution systems in the U.S. Nationwide system and accident data are used to evaluate natural gas distribution system risks, estimate how many additional resources the public would be willing to dedicate to reduce or eliminate these risks, and determine which improvement areas warrant further evaluation. Recommendations regarding the overall PRA-based framework, as well as the scope, quality, and level of detail of the underlying data, are provided.

A PROBABILISTIC RISK ASSESSMENT BASED APPROACH TO UNDERSTANDING AND MANAGING THE RISKS OF NATURAL GAS DISTRIBUTION PIPING IN THE UNITED STATES

by

Sara Lyons

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2020

Advisory Committee:
  Professor Mohammad Modarres, Chair
  Professor Katrina Groth
  Professor Jeffrey Herrmann

Preface

I began my career shortly after the Space Shuttle Columbia accident took the lives of seven astronauts in 2003. With a Bachelor's degree in Mechanical Engineering and very little practical experience, I moved from my hometown in South Florida to work at the Michoud Assembly Facility in New Orleans, Louisiana. For the next five years, I learned from some of the country's most talented engineers, as we collectively worked toward reducing the risks of space flight for future astronauts. While my responsibilities focused on materials testing and analysis, I gained some exposure to the world of risk management that stayed with me in the years to come.

In 2008, my personal life led me to look for career opportunities in Denver, Colorado, and I found a great position with the Pipeline and Hazardous Materials Safety Administration (PHMSA). While there, I studied their pipeline accident data and learned from their pipeline accident investigators in support of various data-driven initiatives the agency was pursuing at the time. I was convinced that further analysis of available accident data could help drive significant safety improvements, but I did not have a strong enough background in reliability engineering to demonstrate the value.

A few years later, a position with the Nuclear Regulatory Commission (NRC) motivated me and my family to move to the D.C. area. The NRC provided many opportunities for me to learn more about reliability engineering, risk management, probabilistic risk assessment, public perception of risk, and a seemingly endless list of related intricacies and nuance in application. I learned a great deal about these topics from the staff at the NRC, especially while supporting response efforts following the tragic events that occurred at the Fukushima Daiichi nuclear power plant in 2011.

As my understanding and curiosity grew, I realized that I needed to look to academia to learn more. In 2017, I began studying reliability engineering part-time at the University of Maryland with the goal of building the skills needed to inspire safety improvements through the application of these methods. As my thesis project, I have decided to take another look at the work I attempted while studying accident data for PHMSA. Now, with an additional decade of experience, related graduate-level coursework, and the advisement of Dr. Modarres, I hope that I have laid out a framework that can be built upon and improved by others. As I have recently joined the National Transportation Safety Board as a Pipeline Accident Investigator, I fully expect to be able to contribute to this effort myself in coming years.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ASME	American Society of Mechanical Engineers
CCF	common cause failure
CDF	cumulative distribution function
CFR	Code of Federal Regulations
DOT	U.S. Department of Transportation
ILI	in-line inspection
INPO	Institute of Nuclear Power Operations
LDC	local distribution company
LEL	lower explosive limit
MAIS	maximum abbreviated injury scale
NRC	U.S. Nuclear Regulatory Commission
NTSB	National Transportation Safety Board
PDF	probability density function
PE	polyethylene
PHMSA	Pipeline and Hazardous Materials Safety Administration
PRA	probabilistic risk assessment
PRCI	Pipeline Research Committee International
PSMS	pipeline safety management systems
PVC	polyvinylchloride
SAPHIRE	systems analysis programs for hands-on integrated reliability evaluations
SCADA	supervisory control and data acquisition

UEL	upper explosive limit
VSL	value of a statistical life

Chapter 1: Introduction

When compared to other available transportation methods, pipelines offer a relatively safe alternative for transporting hazardous materials to downstream customers. However, there are accidents and incidents[1] associated with these pipelines each year, some of which impact public safety and result in significant unexpected costs. About 84% of serious pipeline accidents – accidents which involve fatalities and/or injuries requiring hospitalization – reported to the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) since 2010 have occurred on gas distribution systems (Table 1). The costs associated with these accidents can be substantial, exceeding a billion dollars in some cases [1]. This thesis will focus on adapting the probabilistic risk assessment (PRA) approach practiced mostly by the nuclear and space industries to the assessment of gas distribution systems risks. It will provide a method for evaluating these risks, estimate how many additional resources the public would be willing to dedicate to reduce or eliminate them, and recommend areas which warrant further evaluation.

Table 1. Serious Accidents by System Type (2010-2018) [2]

	Gas Distribution	**Gas Transmission**	**Hazardous Liquid**	**LNG**	***Total***
Number of Serious Accidents	226 (84%)	26 (10%)	16 (6%)	1 (<1%)	***269***
Fatalities	72 (68%)	24 (23%)	10 (9%)	0 (0%)	***106***
Injuries	471 (79%)	101 (17%)	26 (4%)	0 (0%)	***599***

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[1] There are various definitions of the terms "accident" and "incident" associated with the transportation of hazardous materials by pipeline. The term "accident" will be used throughout this paper to indicate an unplanned event which occurred on a hazardous material pipeline system.

Section 1.1: Background

Natural gas pipeline technology has evolved since the Chinese introduced it in 900 BC. At that time, the Chinese used bamboo tubes to transport natural gas over short distances to supply heat and light [3]. The first commercial use of natural gas occurred in 1802 when the Scottish engineer William Murdoch transported gas to the James Watt factory for lighting. Four years later, in 1806, the first gas mains ever laid in a public street were manufactured from sheet lead and installed in London, England. The first city in the U.S. to install gas pipelines was Baltimore, Maryland in 1817 [4]. Significant technological advancements have taken place since this time, improving materials, design and construction methods, data management, and measurement techniques. World War II brought advances in metallurgy, welding techniques and pipe rolling [3]. Around the same time, in 1945, Polyvinylchloride (PVC) plastic pipe was developed. After World War II, there was accelerated growth in pipeline construction [5].

Most customers receive natural gas from a local distribution company (LDC), a utility that can either be owned by investors or local governments. LDCs typically transport natural gas to households and businesses through thousands of miles of small-diameter distribution pipelines. The point where the natural gas is transferred from a transmission pipeline to the LDC is often termed the city gate. The natural gas is typically depressurized, scrubbed, filtered, and odorized near the city gate. The odorant, typically mercaptan, aides in the detection of natural gas, an otherwise odorless and colorless gas. The natural gas is periodically compressed to ensure pipeline flow. Supervisory control and data acquisition (SCADA) systems are sometimes used to provide a comprehensive measurement and control system for the LDC [6].

Current methods used to model the risk of gas pipelines varies from company to company and sector of the industry. Methods include the use of quantitative risk analysis (QRA), accident consequence analysis (ACA), and qualitative risk assessment methods using indices [7], [8], [9], [10], [11]. In some cases, techniques parallel those used in process safety management [12]. Some studies use nationwide PHMSA data to underpin the analysis [13]. These existing methods typically incorporate a combination of subject matter expert opinion and statistical analysis assumptions that are not thoroughly justified. The results do not support comparison with nationwide risk acceptance criteria or specific risk insights needed protect against catastrophic events. This study lays out a framework that would support comparison with nationwide risk acceptance criteria and allow for additional risk insights to be gleaned upon further development as described herein.

Section 1.2: Safety

The safety of natural gas distribution systems has improved in the last 200 years. Accidents that have occurred as the industry matured have shaped both company and government policies. One of the most catastrophic accidents occurred when the London Junior-Senior High School in New London, Texas, exploded on March 19, 1937. The school board in the affluent town of New London had voted to have a plumber illegally tap into a residue gas line of a local oil company to save money. The gas line connection leaked, filling the school's basement with natural gas which eventually ignited, taking about 300 lives [14].

The responsibility for gas pipeline safety was assigned to the DOT by statute in 1968 [15]. Under the current structure, PHMSA, a DOT agency, is responsible for ensuring adequate protection against risks to life and property posed by pipeline transportation of natural gas [16], [17]. The regulations governing natural gas distribution systems are codified in Title 49 of the Code of Federal Regulations (CFR) Parts 190, 191, 192, 196, and 199. Through a partnership with PHMSA, some states assume regulatory and enforcement responsibility for the regulation of gas distribution systems.

Although pipeline safety has significantly improved over the years, catastrophic accidents continue to occur. In the nine years that this analysis period includes, there were three significant gas distribution accidents that resulted in five or more fatalities each [18], [19], [20].

Chapter 2: PRA Methodology

The safety risks presented by gas distribution systems have been a topic of national interest for many decades, in part due to catastrophic accidents that have occurred in our country's history. The accidents that have occurred in the recent past can be used to help understand current safety risks. Risk can be defined as a measure of the probability and severity of adverse events. Risk assessments often consist of answering the following questions [21]:

(1) What can go wrong?

(2) How likely is this to happen?

(3) If it does happen, what are the consequences?

In this study, risks associated with the nation's current gas distribution system infrastructure will be identified and assessed. Management of these risks will be discussed. The risk identification phase will include system characterization and threat identification. The risk assessment phase will include estimating the likelihood and consequences of those threats that could lead to hazard exposure, quantifying the associated risk, evaluating uncertainties, and analyzing the sensitivity of various assumptions and importance of various risk contributors. The framework developed as proposed in this thesis for presenting this information is shown in Figure 1.

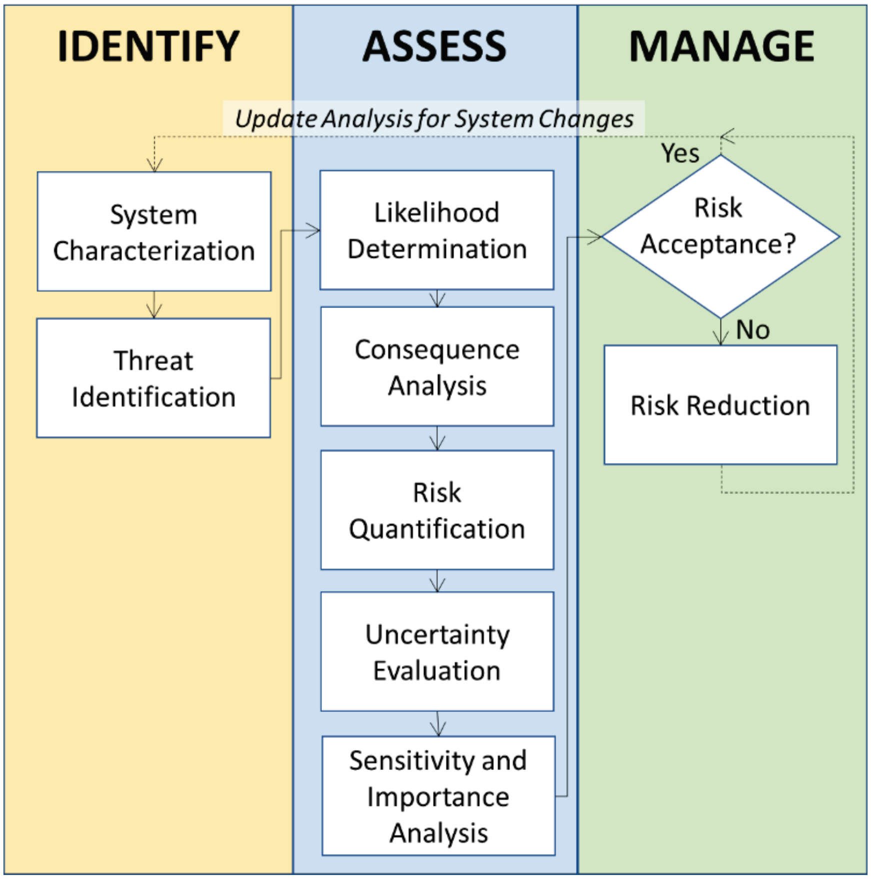

Figure 1. Methodology Flowchart

Section 2.1: Gas Distribution System Characterization

The natural gas distribution infrastructure in the U.S., which primarily transports natural gas, has evolved. Technological advancements have led to improvements in all aspects of these systems (e.g., materials, design, construction and maintenance practices, safety requirements). An example illustrating potential differences in the design is shown in Figure 2 [22]. The low-pressure distribution system (shown on the top) has various regulator stations that reduce the pressure of gas coming from the city gate. Downstream of the regulator stations, natural gas is provided to many customers at very low pressures.

If any regulator station fails to perform its function, all areas downstream of the regulator station can be over-pressurized, potentially leading to widespread catastrophic consequences. The high-pressure distribution system (shown on the bottom) regulates pressure near each structure and has a diverse safety device, an excess flow valve, to protect each customer from experiencing an over-pressurization event. In the unlikely event that both the excess flow valve and regulator associated with a residence fail, the single customer would potentially suffer consequences. There is also a possibility that multiple excess flow valves or multiple regulators could fail by a common cause (e.g., manufacturing or construction deficiencies). The likelihood of this occurrence is relatively small when diverse safety devices are used.

In this assessment, gas distribution risks will be estimated across the nation as a whole. Detailed design information is not available for all of the nation's gas distribution systems that contribute to the overall risk. However, there is information that is available on a nationwide basis from PHMSA's annual reporting forms, which will be summarized [2]. PHMSA annual report data were summarized based on mileage, decade installed, the material of construction, and repairs completed in a given year using a script that was developed in the statistical computing language and software environment, R, to support this study [23]. This data, which was reported in terms of miles of main and number of service lines, was combined after first converting the number of service lines to miles of service lines based on the average service length indicated on each report.[2] To establish

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[2] *Main* refers to a distribution line that serves as a common source of supply for more than one service line. *Service line* refers to a distribution line that transports gas from the main to customers as specified in 49 CFR § 192.3.

consistent data within the reporting period, pipelines that were reported to be fabricated from reconditioned cast iron were included as having "Other" material.

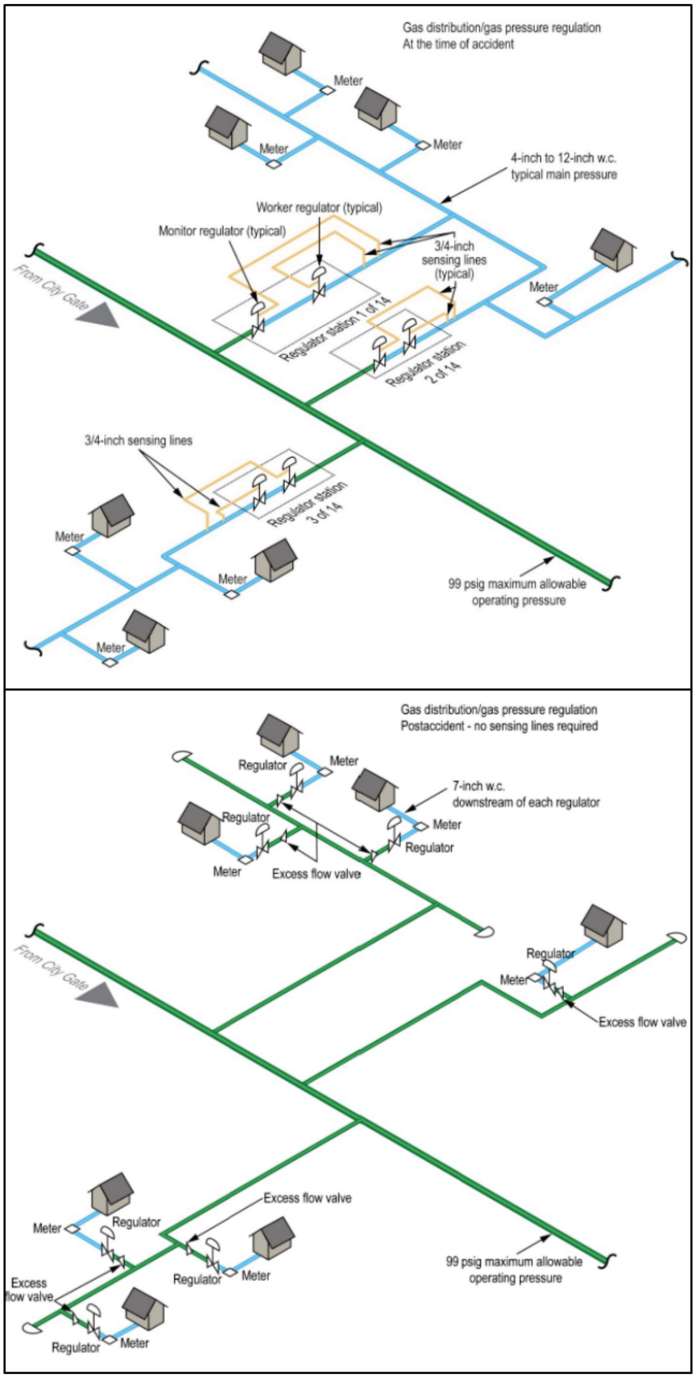


Figure 2. Example Natural Gas Distribution System Designs. Top: Low-Pressure Distribution System. Bottom: High-Pressure Distribution System. [22]

Section 2.2: Threat Identification

In order to identify threats to the system, it is necessary to answer the first question in the risk triplet: What can go wrong, or what can go wrong that could lead to hazard exposure? When the specific pipeline system information is known, the system can be evaluated to determine those threats that could result in hazard exposure. For example, the natural gas distribution systems shown in Figure 2 could be evaluated by considering the failure of any of the various subcomponents (e.g., failure of the pipe, a regulator station, or an excess flow valve). This can be done by evaluating the associated piping and instrumentation diagrams and identifying threats to the overall system performance. For example, failure of any regulator station in the low-pressure distribution system shown in Figure 2 (top) in the open position, would be identified as a safety threat to all downstream residences. If the regulator stations failed in the closed position, there could also be a safety risk associated with natural gas curtailment if the failure occurred during very cold weather.

Since specific pipeline system information is not available for this nationwide assessment, system reliability will be modeled based on failure cause. This is useful because pipeline safety programs are often established to address particular failure causes. For example, One-call programs (e.g., 8-1-1) target excavation accident prevention, whereas, in-line inspection (ILI) assessments target prevention of accidents from the particular failure mechanism(s) they can detect (e.g., cracks, corrosion, dents). Causes and failure modes of the gas distribution pipeline need to be assessed to define those threats that will be considered in this evaluation.

Section 2.3: Likelihood Determination

The likelihood that each of the identified threats will lead to hazard exposure will be estimated. To support this evaluation, those scenarios that result in a significant PHMSA reportable event should be considered to have led to hazard exposure. System reliability will be assessed as it relates to each threat.

Reliability typically refers to the probability that a component or system will function as expected for a predetermined amount of time when exposed to actual use, or operating, conditions. Various functions can be used to describe the reliability of a system, including the cumulative distribution, probability density, reliability, and hazard functions.

The cumulative distribution function (cdf) describes the probability that the component or system will fail before specified time, t. The probability density function (pdf) describes the relative likelihood that the component or system will fail at a time, t, and is defined as the derivative of the cdf. The reliability function describes the probability that the component or system will survive beyond time t.

The hazard function describes the propensity to fail in the next small interval, given survival up to that point. Mathematically, the hazard function is represented by:

$$h(t) = \lim_{\tau \to 0} \frac{1}{\tau} \frac{F(t+\tau) - F(t)}{R(t)} = \frac{f(t)}{R(t)} \qquad \text{(Eq. 1)}$$

The hazard function is important because it shows changes in the probability of failure over the lifetime of a component. For large samples, a nonparametric estimate of the reliability function can be calculated by:

$$\hat{R}(t_i) = \frac{N_S(t_i)}{N} \qquad \text{(Eq. 2)}$$

where $N_s(t_i)$ is the number of surviving components at a time, t_i, and N is the total number of components. A nonparametric estimate of the pdf can be calculated by:

$$\hat{f}(t_i) = \frac{N_f(t_i)}{N\Delta t} \qquad \text{(Eq. 3)}$$

where $N_f(t_i)$ is the number of failures observed in the interval $(t_i,\, t_i + \Delta t)$. From Equations 2 and 3, the hazard rate (or failure rate) can be estimated:

$$\hat{h}(t_i) = \frac{N_f(t_i)}{N_s(t_i)\Delta t} \qquad \text{(Eq. 4)}$$

In Equation 4, $\frac{N_f(t_i)}{N_s(t_i)}$ estimates the probability that a component will fail in the given interval, provided it survives up to time, t_i. Dividing by Δt estimates the failure rate (probability of failure per unit time) for interval Δt [24].

This concept allows for the development of life tables, which are used to describe human mortality and life expectancy. In this application, there are two types of life tables. The first type of life table is the cohort life table, which is developed by following a particular birth cohort throughout their life. This life table takes many years to develop and the development is sometimes not possible due to unavailable or incomplete data. The second type of life table is the period life table, which represents a hypothetical cohort that is alive during a specific period. For example, the period life table that was developed for the year 2015 “assumes a hypothetic cohort that is subject throughout its lifetime to the age-specific death rates prevailing for the actual population in 2015” [25].

When the human mortality hazard rate is plotted, it illustrates how the hazard rate changes with age for the hypothetical cohort, decreasing very early in life, remaining relatively constant, and increasing later in life during the “degradation” period (Figure 3). This typical shape is often described as a “bathtub curve.”

A similar "hypothetical cohort" approach will be used to evaluate the hazard rate of gas distribution systems. In this study, hazard rate curves (reported in the number of failures per mile per year) will be developed for each threat based on an analysis of available historical data. If this analysis demonstrates that the hazard rate is constant, the exponential distribution will be used to estimate the likelihood that the threat will challenge the system and lead to a reportable event. If the hazard rate is not constant for a particular threat, methods for addressing higher hazards at the beginning or end of life will be discussed.

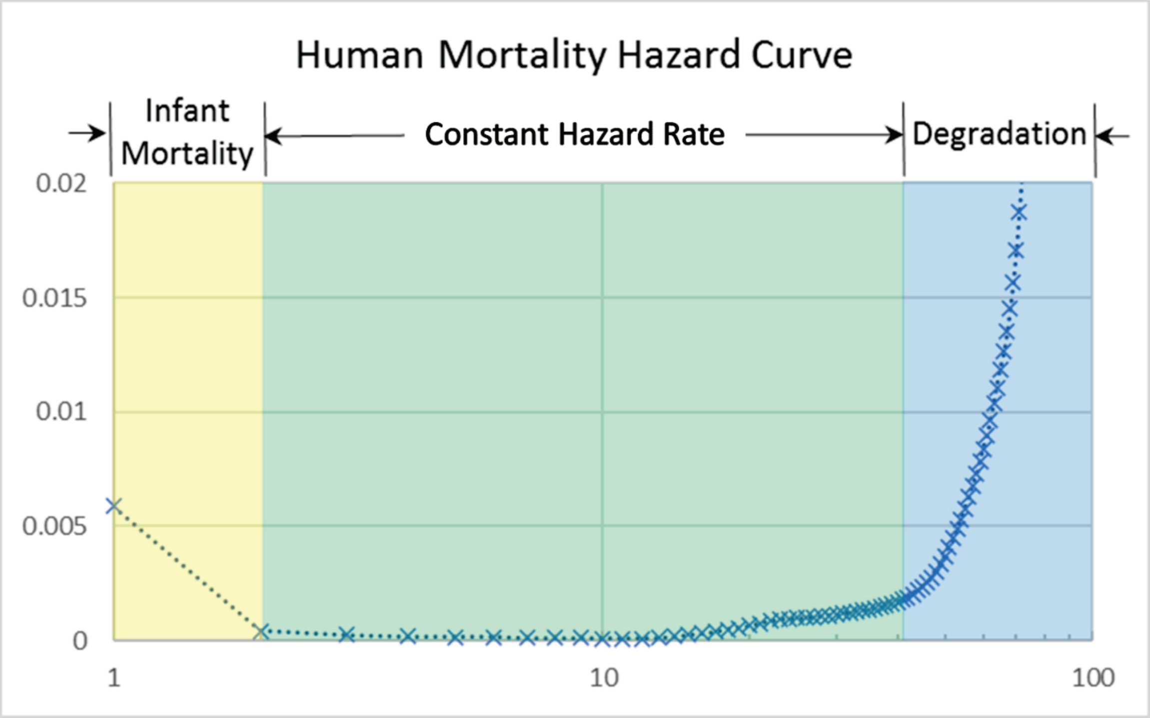


Figure 3. Bathtub Curve of Human Mortality [25]

Section 2.4: Consequence Analysis

Natural gas can form an explosive mixture when combined with air in concentrations between 5% (the lower explosive limit, or LEL) and 15% (the upper explosive limit, or UEL) natural gas in the air. In a typical gas distribution system accident sequence, there is the potential for very serious consequences, including fatalities, injuries, and extensive property damage. It is also possible that the consequences are relatively minor (e.g., venting gas to the atmosphere, cost of lost product and repairs). It is often convenient to model consequence scenarios using event tree models. In the simplified, notional event tree shown in Figure 4, the initiating event is assumed to be a PHMSA reportable gas distribution accident. If this initiating event occurs, there are a series of pivotal events (also called top events) that determine the associated consequences. In the notional event tree shown, the pivotal events include:

- Evacuation: Success of this top event is defined as a timely evacuation which is completed prior to the gas presenting a hazard to any person whose safety may be compromised (e.g., ignition/explosion or asphyxiation). The probability of success will depend on the specific scenario (potential consequences; available response time; ability to detect, diagnose, and appropriately evacuate). If the scenario does not present a hazard to any person, success is guaranteed.
- Protection and Response: Success of this top event occurs when gas vents to atmosphere without reaching flammable concentrations (i.e., 5-15% natural gas in air) in the vicinity of an ignition source. The probability of success will depend on the specific scenario (potential for gas to reach an ignition

source, ability to detect, diagnose, safely extinguish all ignition sources, and isolate the gas leak promptly). If a leak persists, natural gas vapors may travel to an ignition source and flashback, potentially increasing the potential consequences.

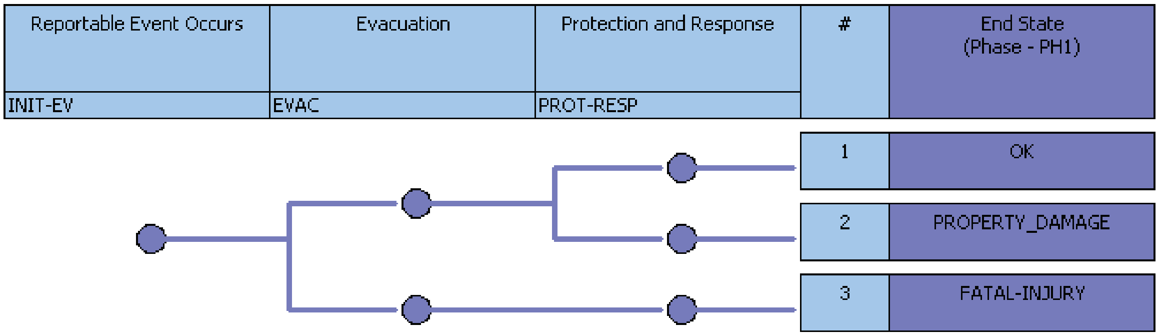


Figure 4. Simple, Notional Gas Distribution Accident Event Tree (Branching Convention: Success Path is Up, Failure is Down)

Instead of attempting to classify accident sequences based on their potential to result in a fatality, injury, or property damage, a single consequence measure will be used. Consequences will be assessed based on the statistical value of the accident, which is an estimate of the amount the public would have been willing to pay to prevent the fatalities and injuries that occurred as a result of the accident, plus the actual cost incurred. To support this portion of the analysis, a concept broadly used in regulatory cost-benefit analyses – the value of a statistical life (VSL) – will be used. "The Value of a Statistical Life (VSL) is defined as the additional cost that individuals would be willing to bear for improvements in safety (that is, reductions in risks) that, in the aggregate, reduce the expected number of fatalities by one. What is involved is not the valuation of life, but the valuation of reductions in risks" [26]. The VSL has been estimated based on existing guidance to adjust for inflation and real incomes since the guidance was developed. Using this procedure, the VSL was updated from \$9.6 million in 2016 and rounded to \$10 million in 2019. For this analysis, since injury severity information is generally not available, it is assumed that all reported injuries had a severity of the Maximum Abbreviated Injury Scale (MAIS) 3 or serious. This corresponds to a fraction of VSL of 0.105 for the purposes of statistical value calculations [26].

The statistical value is intended to estimate the total amount that the public would have been "willing to pay" for safety enhancements that would have prevented a given accident. The statistical value of each accident will be calculated based on the sum of:

- additional costs that individuals would have been willing to bear for improvements in safety to prevent the accident (i.e., VSL), and
- actual costs related to property damage, repairs, emergency response, clean-up, and lost product

Note that the statistical value does not include costs associated with lost productivity or psychological consequences which can result from a major accident or evacuation.

Section 2.5: Risk Quantification

Risk estimation is used to interpret the various contributors to risk. Because all sequences will be defined to be mutually exclusive, the risk can be calculated by Equation 5.

$$R = \sum_i F_i \times C_i \qquad \text{(Eq. 5)}$$

where F_i is the frequency or likelihood of sequence *i* occurring, and

C_i is the consequence of sequence *i*

The risk will be estimated for each threat.

Section 2.6: Uncertainty Evaluation

Risk assessments, like all engineering analyses, involve assumptions that are made to support the analyses. There are three types of epistemic uncertainty that typically need to be addressed directly, including completeness, parameter, and model uncertainty. Completeness uncertainty is either known or unknown, but not modeled. If known, it can be addressed by conservative or bounding analysis; if unknown, it can be addressed by the addition of safety margins or defense-in-depth. Parameter uncertainty is typically propagated through the probabilistic model. Model uncertainty occurs when there are multiple modeling approaches and no consensus model exists. Model uncertainty can be addressed by making assumptions, determining which are important to the decision, and quantitatively or qualitatively justifying them [27], [28]. The completeness, parameter, and model uncertainty that may be important to decisions that involve a risk assessment of gas distribution pipeline systems will be tabulated and discussed.

Section 2.7: Sensitivity and Importance Analysis

Sensitivity analysis will be performed, as needed, based on the results of the uncertainty evaluation. Importance analysis will be performed to assess the relative risk contribution of each threat. This is useful to understand which safety improvement areas have the most significant potential risk benefit.

Section 2.8: Risk Acceptance

Federal guidelines will be reviewed to determine the level of risk that is tolerable as it relates to gas distribution systems. Risk acceptance thresholds are used in several industries. One example is the commercial nuclear industry. The Nuclear Regulatory Commission (NRC) has two safety goals, one that relates to the risk of prompt fatality to an individual and one that relates to the societal risk of cancer fatalities [29]. The safety goal related to individual risk is:

> Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operations such that individuals bear no significant additional risk to life and health.

This safety goal has a corresponding quantitative objective:

> The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1 percent) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed.

A comparable framework is necessary to evaluate gas distribution system risk acceptability.

Section 2.9: Risk Reduction

The estimated risk will be compared to the acceptance threshold. If the current risks are not within the acceptable range, approaches to reduce these risks will be identified for further study.

Chapter 3: Results

This case study focuses on adapting PRA methods to the U.S. gas distribution system to help understand and manage risks. There are some challenges with this application that do not exist in other industries where PRA is more widely used. When contrasted with the nuclear and space industries, natural gas distribution systems:

- traverse broad, often populated areas that are not under the direct control of the operator,
- may have unknown configurations and materials of construction, especially for older systems,
- have limited experience data, and
- have not been studied as extensively with the intent of establishing the bases for assumptions that are needed to support a PRA

Despite these challenges, the structure that PRAs offer to support risk management are valuable and can be applied to other technologies, including gas distribution systems, to further advance safety performance. The results presented below show how this structure can be applied, given the currently available information.

Section 3.1: Gas Distribution System Characterization

The current U.S. gas distribution system primarily transports natural gas. Natural gas distribution systems include a network of piping that supply gas to various consumers. According to data provided by PHMSA, there are over two million miles of main and service lines which distribute gas to customers across the country.

The gas distribution infrastructure includes pipelines of various ages. Distribution pipelines that have known ages were installed between the start of the twentieth century and today, but the age of some gas distribution pipelines is unknown (Figure 5).

There are several materials that have been used to construct these pipelines, with the majority being from polyethylene (PE) or coated, cathodically protected (CP) steel. Most newly constructed gas distribution pipelines are fabricated from PE (Table 2).

The diameter of pipelines used in gas distribution systems varies. The majority have a diameter of 2-inches or less (Figure 6).

Gas distribution operators track and report leaks that are repaired in a given year by leak cause (Table 3). The repairs are considered to be associated with a "hazardous" leak if the operator determines that the leak requires an immediate response. Most repairs are attributed to equipment failure, corrosion, or excavation damage; most hazardous repairs are attributed to corrosion, natural force damage, or excavation damage.

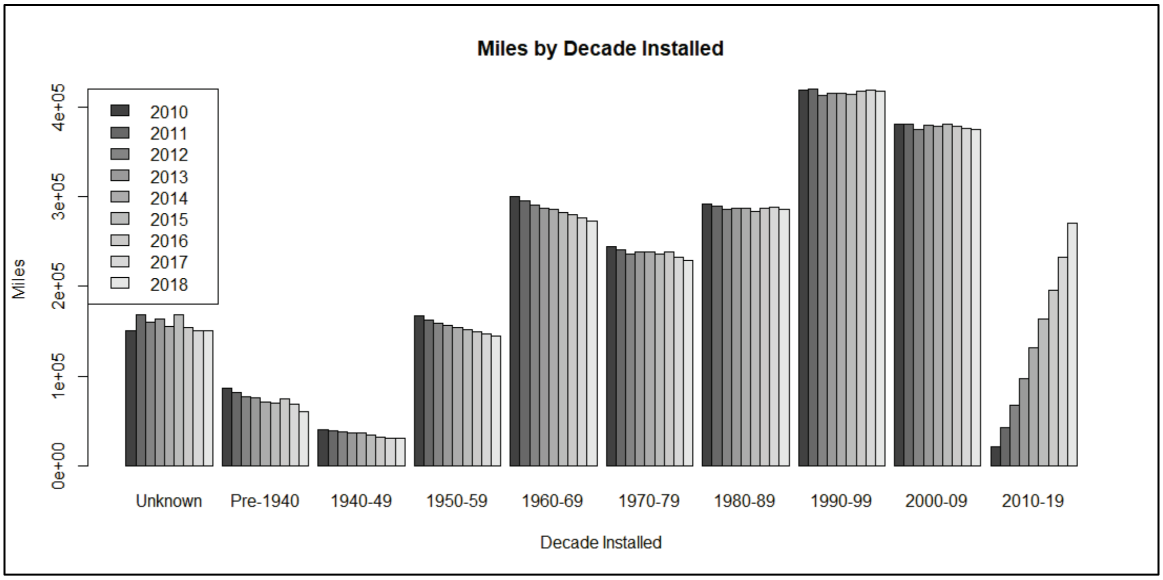


Figure 5. U.S. Gas Distribution Systems – Miles of Main and Service Lines by Decade Installed [2]

Table 2. U.S. Gas Distribution Systems – Miles of Main and Service Lines by Material [2]

	2010	**2018**
Polyethylene (PE)	1,201,543	1,424,057
Steel, Cathodically Protected (CP), Coated	668,072	636,457
Steel, Unprotected, Bare	78,826	50,307
Steel, Unprotected, Coated	37,387	36,549
Other	23,431	23,493
Cast/Wrought Iron	34,807	22,952
Steel, CP, Bare	21,058	15,936
Polyvinyl Chloride (PVC)	14,949	11,672
Copper	13,835	9,390
Other Plastic	3,258	4,312
Acrylonitrile-Butadiene-Styrene (ABS)	3,595	2,957
Ductile Iron	796	516
TOTAL	**2,101,556**	**2,238,597**

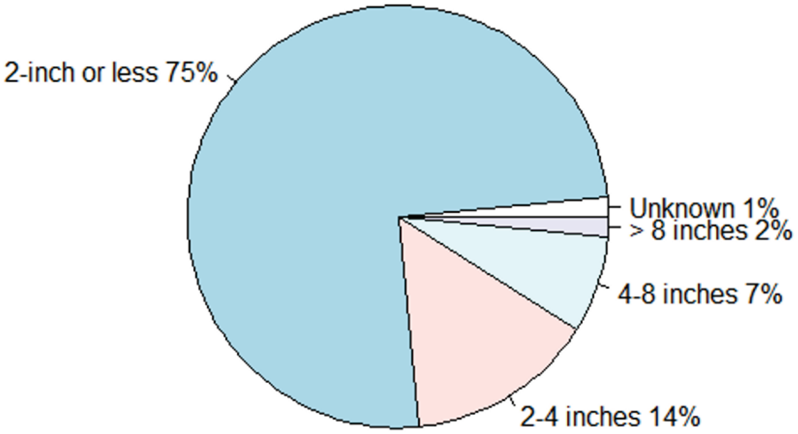


Figure 6. U.S. Gas Distribution Systems – Main and Service Lines by Diameter [2]

Table 3. Total Repairs and Repairs of Hazardous Leaks in 2018 [2]

2018	Total Repairs	Repairs of Hazardous Leaks	Repairs/Mile	Repairs of Hazardous Leaks/Mile
Excavation	81,464	38,240	3.64E-02	1.71E-02
Equipment Failure	183,916	12,856	8.22E-02	5.74E-03
Corrosion	108,439	74,925	4.84E-02	3.35E-02
Pipe, Weld, or Joint Failure	56,477	11,366	2.52E-02	5.08E-03
Other Cause	37,692	17,437	1.68E-02	7.79E-03
Natural Force	29,509	42,866	1.32E-02	1.91E-02
Other Outside Force	16,274	6,950	7.27E-03	3.10E-03
Incorrect Operation	19,641	15,124	8.77E-03	6.76E-03

Section 3.2: Threat Identification

Both the American Society of Mechanical Engineers (ASME) and PHMSA have defined gas pipeline threat categories. ASME B31.8S, *Managing System Integrity of Gas Pipelines: ASME Code for Pressure Piping, B31 Supplement to ASME B31.8*, identifies nine threat categories which are based on an analysis performed by the Pipeline Research

Committee International (PRCI). The nine threat categories are further divided into those that are time-dependent, stable, and time-independent. Time-dependent threats (internal and external corrosion and stress corrosion cracking) cause degradation over time and are addressed by using one of the integrity assessment methods (e.g., in-line inspection, direct assessment). Stable threats (manufacturing-related defects, welding/fabrication related, equipment) are addressed through specific, often one-time evaluations (e.g., pressure testing). Time-independent threats (third party/mechanical damage, incorrect operational procedure, weather-related and outside force) are typically not addressed by specific examination or evaluation but are subject to prevention measures [30]. PHMSA's reporting form has seven major causes (excluding "other incident cause") that generally align with the ASME B31.8S threat groups and categories (Table 4).

For the purposes of this evaluation, the major causes defined in the PHMSA incident reporting form (i.e., Corrosion; Natural Force Damage; Excavation Damage; Other Outside Force Damage; Pipe, Weld, or Joint Failure; Equipment Failure; Incorrect Operation; and Other Incident Cause) will be treated as the gas distribution system threats. These threats are defined by PHMSA to be mutually exclusive [31].

Table 4. Comparison of Gas Pipeline Threat Categories Used by ASME B31.8S and PHMSA [30], [31]

	ASME B31.8S	**PHMSA Major Cause**
Time-Dependent	External Corrosion	Corrosion
	Internal Corrosion	
	Stress Corrosion Cracking	Pipe, Weld, or Joint Failure [Environmental Cracking Only]
Stable	Manufacturing-related Defects	Pipe, Weld, or Joint Failure [Excluding Environmental Cracking, Excluding Previous Damage]
	Welding/Fabrication Related	
	Equipment	Equipment Failure
Time-Independent	Third Party/Mechanical Damage	Excavation Damage; Other Outside Force Damage; Pipe, Weld, or Joint Failure [Previous Damage Only]
	Incorrect Operational Procedure	Incorrect Operation
	Weather-Related and Outside Force	Natural Force Damage
Not Classified	Unknown	Other Incident Cause: Unknown

Section 3.3: Likelihood Determination

Historical data were assessed to determine the hazard rate for accidents that occurred between 2010-18 [1]. For decades that ended prior to 2010, the hazard rate was estimated based on the decade that the pipeline was installed (Table 5). For pipelines that were installed in the most recent decade (2010-19), a complete dataset did not exist for each reporting year of interest. In 2010, all pipelines that were installed in the current decade (2010-19) were 0-1 year old; in 2011, they were 0-2 years old. Therefore, the data for pipelines that were installed in the current decade were analyzed yearly based on the age of the pipe (Table 6). A script to apply this methodology to PHMSA data was developed in R [5]. The overall resulting hazard curve is shown in Figure 7. The contribution from each cause is shown in Figure 8 and Figure 9. Note that some data was grouped in Figure 7 through Figure 9 and the data points do not directly correspond to those in Table 6.

The higher hazard rate early in life was attributed to the following causes: excavation, other outside force, equipment, and incorrect operations. Three of these causes were designated to be “time-independent,” or random, in ASME B31.8S. The remaining cause was designated “stable” in ASME B31.8S. The higher hazard at the beginning of life appeared to be due to increased construction activity in the vicinity of the new pipeline for excavation, equipment, and incorrect operation failures. For failures attributed to other outside forces, increased construction activities and unexpected environmental conditions (e.g., water jet or electrical arcing from nearby utilities) explained the higher hazard early in life. Initiatives to flatten the hazard curve early in life may focus on enhancing existing processes to perform new construction safely, expanding public outreach related to new construction projects, and developing more robust processes to define and design for actual in-service conditions.

The increasing hazard rate later in life was attributed to corrosion and natural force failures. Higher hazard rates towards the end of life are typically attributed to degradation, which explains the response for corrosion failures. For natural force damage, the hazard rate may increase later in life due to less mature requirements that were in place at the time the system was installed (before 1950), or degradation that may have compromised performance during weather-related events such as cold temperatures. Initiatives to flatten the hazard curve later in life may focus on enhancing integrity assessments for pipelines that are more than 50 years old, implementing more aggressive replacement schedules for pipelines with known integrity challenges, and closely collecting, analyzing, and addressing a broad set of performance data.

In many industries, reliability improvements are implemented which change the shape of the hazard curve. This approach may lower and flatten the hazard curve at the beginning and end of life, making it indistinguishable from the useful life portion of the curve. For the remainder of this evaluation, it is assumed that reliability improvements will be pursued to improve and flatten the hazard curve. Therefore, the average hazard rates will be used. The average hazard rate is higher than it would be after improvements to flatten the hazard curves have been implemented but is appropriate for use at this point, since the improvements have not yet been made. Systems that exhibit a constant hazard curve are described by an exponential distribution. In a future probabilistic risk assessment, an exponential distribution can be used to describe the likelihood for the ages that exhibit a constant hazard rate. Fitting the data to a parametric curve in this way would allow for existing off the shelf software to be used to perform a probabilistic analysis. One program that is suitable for this purpose is the Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) developed by the Idaho National Laboratory [32].

The average hazard rates by PHMSA major causes and subcauses are shown in Table 7. The average hazard rates show that most failures which lead to a PHMSA reportable accident are attributed to excavation damage or other outside forces. When considering subcauses, insufficient excavation practices and motorized vehicle/equipment are dominant.

Table 5. Estimated U.S. Gas Distribution Hazard Rate by Decade Installed [2]

Decade Installed	Accident Year									Average No. of Accidents (#/yr)	Average Miles (mi)	Hazard Rate (#/mi/yr)
	'10	'11	'12	'13	'14	'15	'16	'17	'18			
2000-09	4	10	3	5	7	7	7	8	3	6.000	378,410	1.59E-05
1990-99	8	3	6	4	3	12	12	7	11	7.333	416,669	1.76E-05
1980-89	6	7	5	8	10	8	9	10	6	7.667	287,231	2.67E-05
1970-79	5	6	6	7	3	10	5	9	13	7.111	237,287	3.00E-05
1960-69	10	8	7	6	7	5	9	4	6	6.889	285,833	2.41E-05
1950-59	8	5	5	9	7	4	3	5	3	5.444	155,036	3.51E-05
1940-49	2	2	0	2	1	1	2	1	1	1.333	35,438	3.76E-05
Pre-1940	1	3	4	2	5	5	5	2	5	3.556	73,901	4.81E-05
Unknown	11	11	14	11	9	9	16	6	18	11.667	158,240	7.37E-05

Table 6. U.S. Gas Distribution Hazard Rate by Age (Pipelines Installed 2010-2018) [2]

Age (yr)	Incident Year									Average Accidents (#/yr)	Average Miles (mi)	Hazard Rate (#/mi/yr)
	'10	'11	'12	'13	'14	'15	'16	'17	'18			
0-1	0	1	2	3	4	2	2	2	6	2.444	30,084	8.13E-05
1-2		0	0	2	2	0	1	2	0	0.875	29,063	3.01E-05
2-3			0	0	0	1	0	2	0	0.429	28,057	1.53E-05
3-4				1	2	0	0	1	1	0.833	27,384	3.04E-05
4-5					0	1	1	1	0	0.600	26,416	2.27E-05
5-6						1	1	1	0	0.750	24,243	3.09E-05
6-7							1	0	1	0.667	22,375	2.98E-05
7-8								2	0	1.000	21,358	4.68E-05
8-9									1	1.000	21,268	4.70E-05

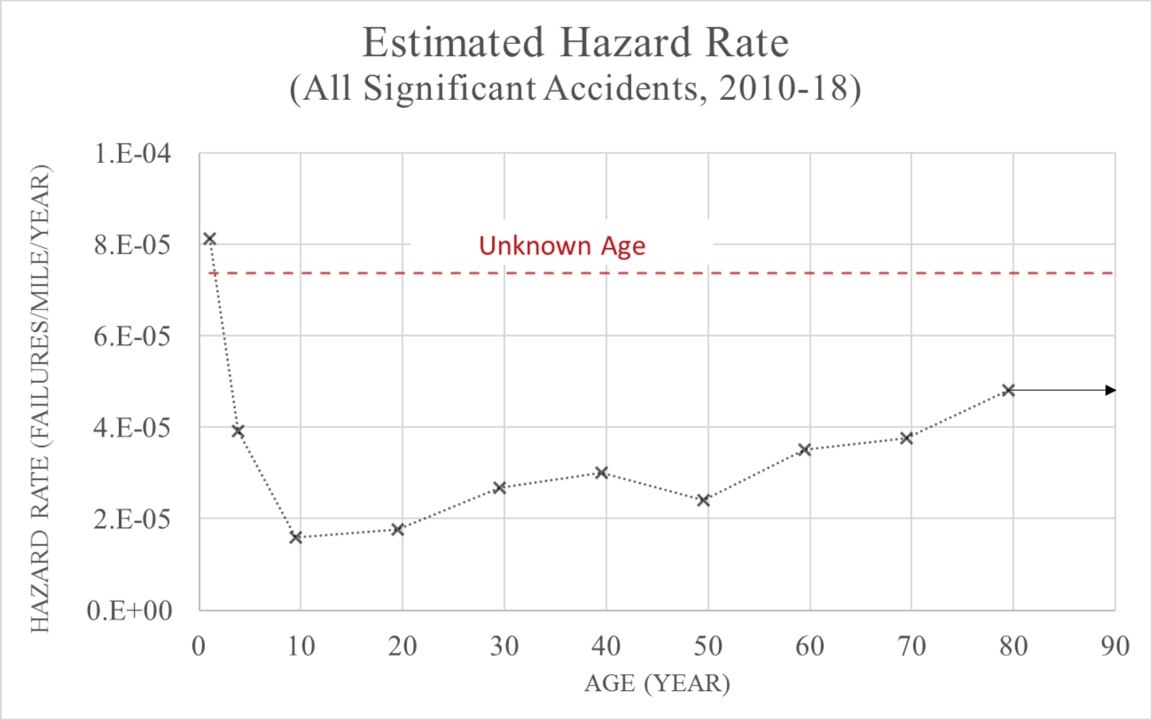
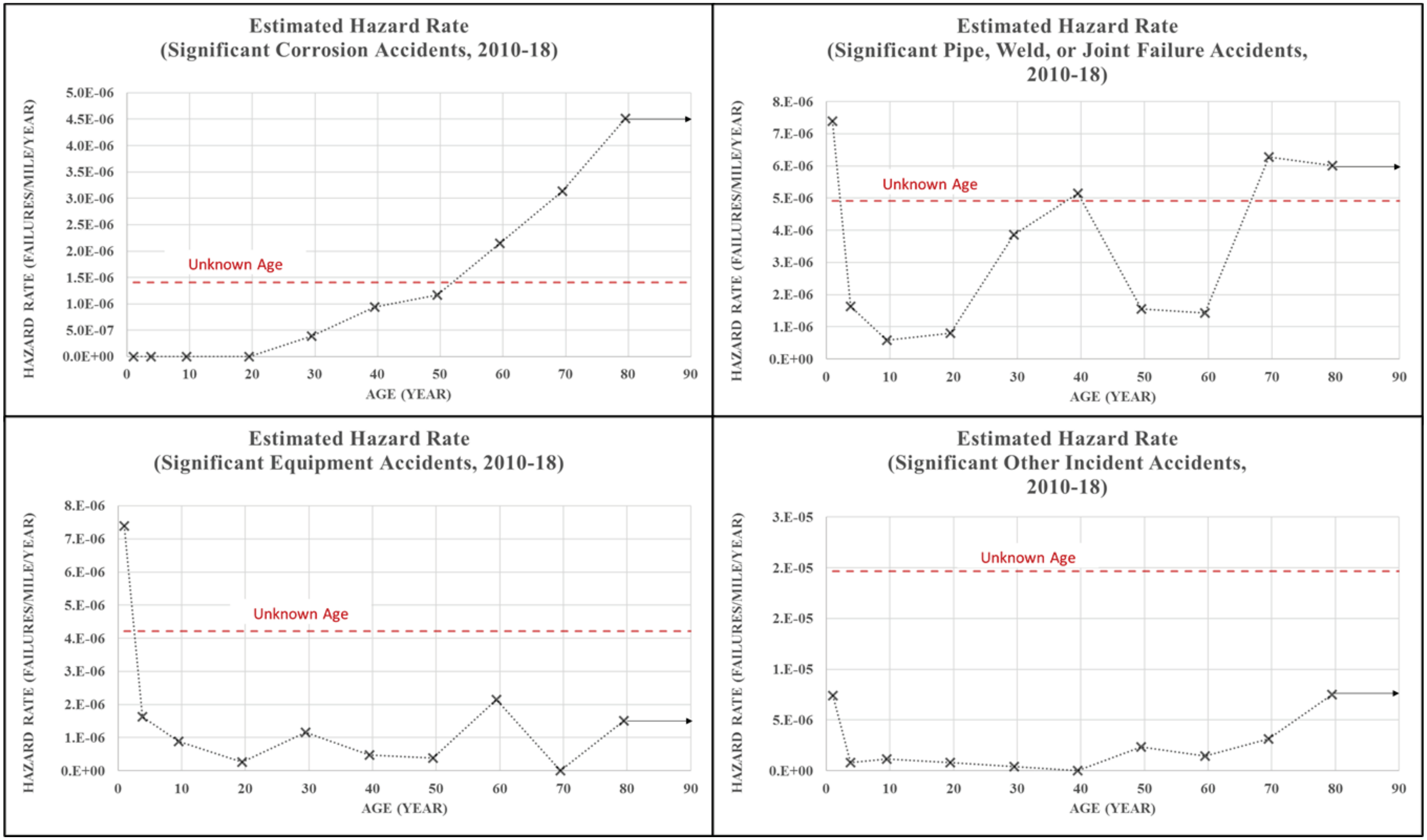


Figure 7. U.S. Gas Distribution Hazard Rate by Age



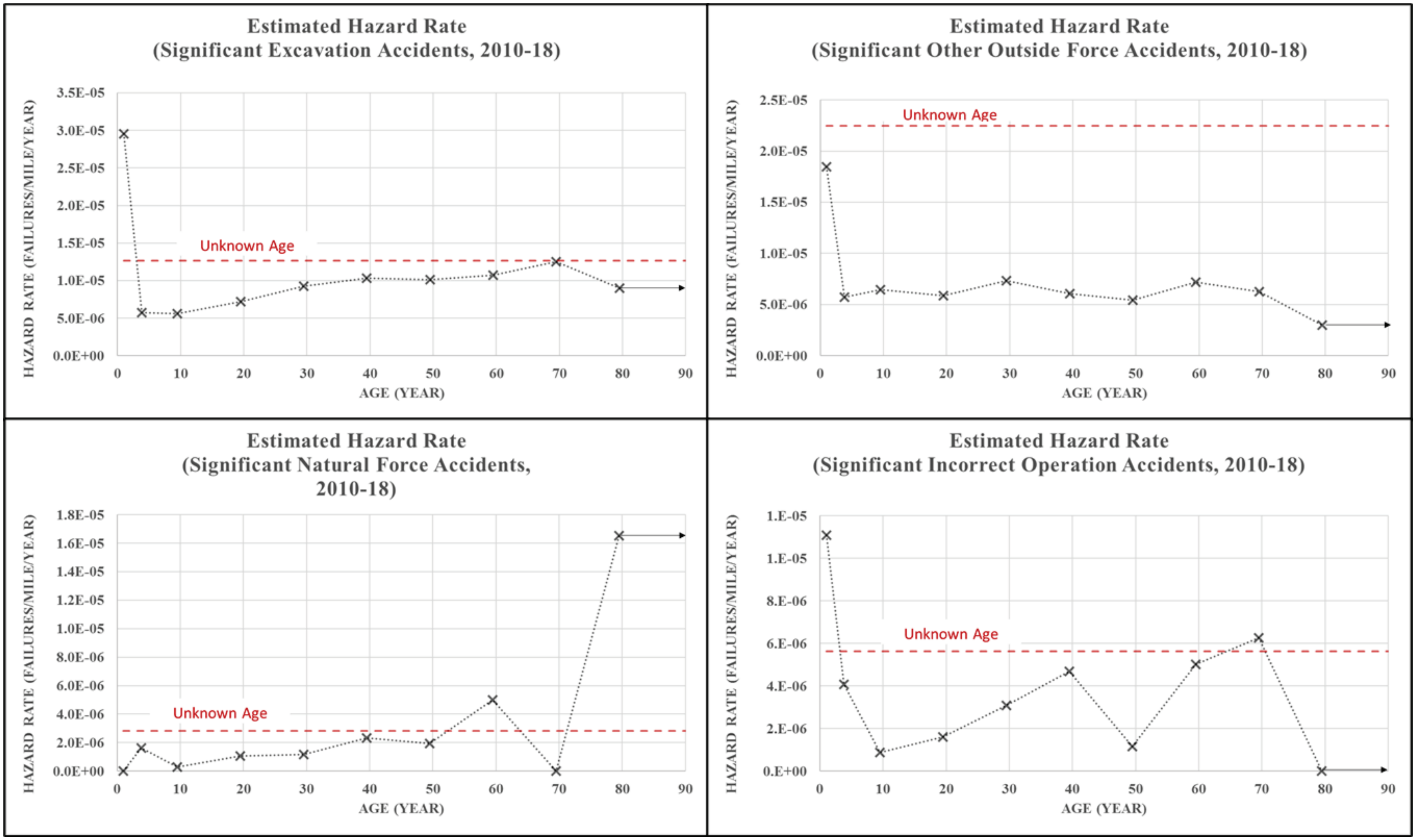
Estimated Hazard Rate
(Significant Corrosion Accidents, 2010-18)

Estimated Hazard Rate
(Significant Pipe, Weld, or Joint Failure Accidents, 2010-18)

Estimated Hazard Rate
(Significant Equipment Accidents, 2010-18)

Estimated Hazard Rate
(Significant Other Incident Accidents, 2010-18)

Figure 8. U.S. Gas Distribution Hazard Rates by Age for PHMSA Causes Identified by ASME B31.8S as Time-Dependent, Stable, or Unknown



Estimated Hazard Rate (Significant Excavation Accidents, 2010-18)

Estimated Hazard Rate (Significant Other Outside Force Accidents, 2010-18)

Estimated Hazard Rate (Significant Natural Force Accidents, 2010-18)

Estimated Hazard Rate (Significant Incorrect Operation Accidents, 2010-18)

Figure 9. U.S. Gas Distribution Hazard Rates by Age for PHMSA Causes Identified by ASME B31.8S as Time-Dependent, Stable, or Unknown

Table 7. Average U.S. Gas Distribution Hazard Rate by PHMSA Major Causes and Subcauses

Cause/*Subcause*	λ (#fail/mi/yr)	**Cause**/*Subcause*	λ (#fail/mi/yr)
Excavation	**8.74E-06**	**Other Incident Cause**	**2.63E-06**
Insufficient Excavation Practices	4.17E-06	*Miscellaneous*	1.39E-06
Insufficient One-Call Notification Practice	1.99E-06	*Unknown*	1.24E-06
Insufficient Locating Practices	1.54E-06	**Pipe, Weld, or Joint Failure**	**2.43E-06**
Other	5.96E-07	*Construction Defect*	1.09E-06
Previous Damage	3.47E-07	*Material Defect*	8.44E-07
Abandoned Facility	4.96E-08	*Other/Unknown*	1.99E-07
Data Not Collected	4.96E-08	*Design Defect*	1.49E-07
Other Outside Force	**7.35E-06**	*Previous Damage*	1.49E-07
Motorized Vehicle/Equipment	4.12E-06	**Natural Force Damage**	**2.08E-06**
Other	2.08E-06	*Lightning*	4.47E-07
Electrical Arcing	6.95E-07	*Temperature*	4.47E-07
Intentional Damage	2.48E-07	*Other*	4.47E-07
Previous Damage	1.49E-07	*Earth Movement*	3.97E-07
Adrift Maritime Equipment	4.96E-08	*Heavy Rains/Floods*	3.47E-07
Incorrect Operation	**2.73E-06**	**Equipment Failure**	**1.14E-06**
Other	1.74E-06	*Control/Relief Equipment Malfunction*	4.96E-07
Damage by Operator or Operator's Contractor	4.47E-07	*Non-Threaded Connection Failure*	2.48E-07
Valve Left or Placed in Wrong Position	1.99E-07	*Valve*	1.99E-07
Equipment Not Installed Properly	1.99E-07	*Other*	1.49E-07
Pipeline or Equipment Over-Pressurized	9.93E-08	*Threaded Connection Failure*	4.96E-08
Wrong Equipment Specified or Installed	4.96E-08	**Corrosion**	**7.45E-07**
		External Corrosion	6.45E-07
		Internal Corrosion	9.93E-08

Section 3.4: Consequence Analysis

Risk matrices were developed based on the average likelihood results presented in Section 3.3 and the actual observed consequences (number of fatalities, number of injuries, cost, and statistical value) per accident summarized by accident cause (Table 8). However, these average values suggest differences in consequences that are misleading because they do not account for the effect of the small number of catastrophic accidents.

For example, the statistical value of each significant reported gas distribution accident was calculated, resulting in a mean consequence of $5,754,368 per significant reported accident. As discussed above, this value represents the amount that the public would have been willing to pay to prevent the occurrence and the actual costs the operator incurred due to property damage, repairs, emergency response, clean-up, and lost product. This mean value is driven by a relatively low number of accidents with catastrophic consequences. The 10th percentile is $129,200; the median is $655,176; and the 90th percentile is $7,350,000.

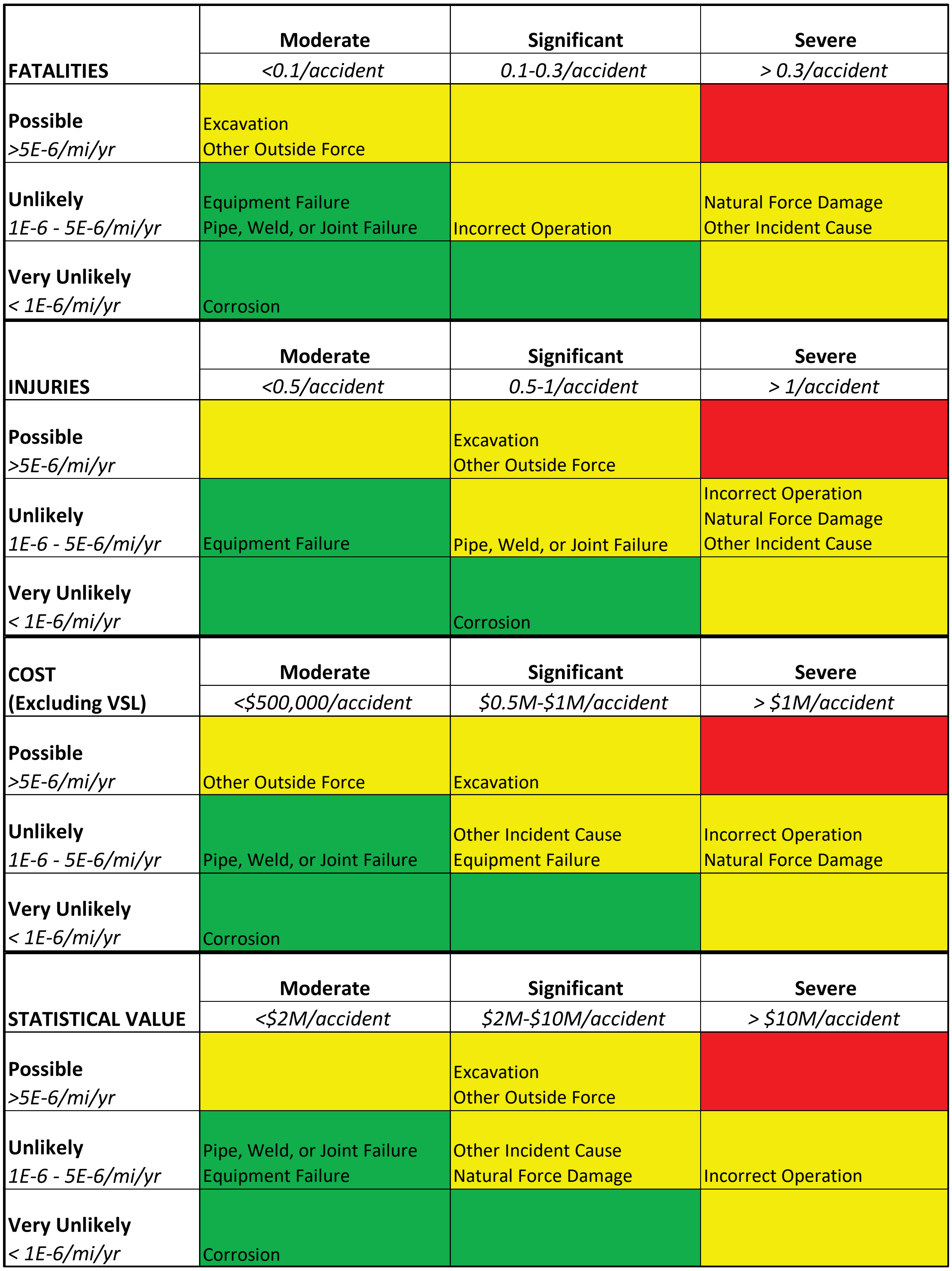
Once a reportable event occurs, the resulting consequences will be determined by the specific circumstances surrounding the event, and the response to the event itself. Many reportable events do not have the potential to result in catastrophic consequences and may not even require an evacuation. The data needed to determine which accidents would have required an evacuation is not available for each reportable accident. However, approximately 40% of the significant gas distribution accidents included in this study were considered to be serious accidents, because they resulted in at least one injury or fatality. In other words, 40% of the reportable accidents did not successfully remove people from the hazards presented by natural gas distribution operations (Figure 10). It can be difficult to evacuate people prior to a natural gas hazard in many scenarios. For example, if there is an excavation accident, there is typically an excavation crew and ignition source near the location that the pipe was breached. However, the consequence data does not show a significant difference in statistical value between any of the threats. Figure 11 shows a modified box plot that is used to highlight outliers. This whiskers on this boxplot were constructed by multiplying the interquartile range by 1.5, adding the result to the third quartile, and subtracting it from the first quartile. The whiskers were extended to include the maximum and minimum data points within this range. All data points outside of this range were indicated by circular markers. The modified box plot is used throughout this section.

Another measure that is often used as an indication of potential gas distribution system consequences is the class location. A gas pipeline's class location broadly indicates the level of potential consequences for a pipeline release based upon population density along the pipeline. According to 49 CFR 192.5(a), class locations are specified by using a "sliding mile" that extends 220 yards on both sides of the centerline of a pipeline. The number of buildings within this sliding mile at any point during the mile's movement determines the class location for the entire mile of pipeline contained within the sliding mile. Class 1 locations have 10 or fewer buildings intended for human occupancy. Class 2 locations contain more than 10 but fewer than 46 buildings intended for human occupancy. Class 3 locations contain 46 or more buildings or an outside area that is occupied by 20 or more persons on at least 5 days a week for 10 weeks in any 12-month period. Class 4 locations have a prevalence of buildings of at least four stories in height. Class locations are used to differentiate some regulatory requirements so that they are commensurate with the potential consequences. The current data shows that the statistical values of accidents are similar for each class location, but the more catastrophic accidents may be more prevalent in Class 3 and Class 4 locations (Figure 12).

Similarly, SCADA systems have the potential to significantly reduce the consequences of a gas distribution accident. However, the available data does not indicate that these benefits are being realized (Figure 12). This information was also reviewed for each cause with similar results.

Other mitigative efforts may help to reduce the consequences of gas distribution accidents. The presence of odorant, excess flow valves, automatic shutoff valves, remote-controlled isolation valves, training, and public awareness may help to mitigate consequences, but specific data on these factors as they relate to the reported accidents were not available to support this analysis.

Table 8. Risk Matrices by Accident Cause for Four Consequence Measurements (Number of Fatalities, Number of Injuries, Cost (Excluding VSL), and Statistical Value



	Moderate	**Significant**	**Severe**
FATALITIES	*<0.1/accident*	*0.1-0.3/accident*	*> 0.3/accident*
Possible *>5E-6/mi/yr*	Excavation Other Outside Force		
Unlikely *1E-6 - 5E-6/mi/yr*	Equipment Failure Pipe, Weld, or Joint Failure	Incorrect Operation	Natural Force Damage Other Incident Cause
Very Unlikely *< 1E-6/mi/yr*	Corrosion		
	Moderate	**Significant**	**Severe**
INJURIES	*<0.5/accident*	*0.5-1/accident*	*> 1/accident*
Possible *>5E-6/mi/yr*		Excavation Other Outside Force	
Unlikely *1E-6 - 5E-6/mi/yr*	Equipment Failure	Pipe, Weld, or Joint Failure	Incorrect Operation Natural Force Damage Other Incident Cause
Very Unlikely *< 1E-6/mi/yr*		Corrosion	
COST	**Moderate**	**Significant**	**Severe**
(Excluding VSL)	*<$500,000/accident*	*$0.5M-$1M/accident*	*> $1M/accident*
Possible *>5E-6/mi/yr*	Other Outside Force	Excavation	
Unlikely *1E-6 - 5E-6/mi/yr*	Pipe, Weld, or Joint Failure	Other Incident Cause Equipment Failure	Incorrect Operation Natural Force Damage
Very Unlikely *< 1E-6/mi/yr*	Corrosion		
	Moderate	**Significant**	**Severe**
STATISTICAL VALUE	*<$2M/accident*	*$2M-$10M/accident*	*> $10M/accident*
Possible *>5E-6/mi/yr*		Excavation Other Outside Force	
Unlikely *1E-6 - 5E-6/mi/yr*	Pipe, Weld, or Joint Failure Equipment Failure	Other Incident Cause Natural Force Damage	Incorrect Operation
Very Unlikely *< 1E-6/mi/yr*	Corrosion		

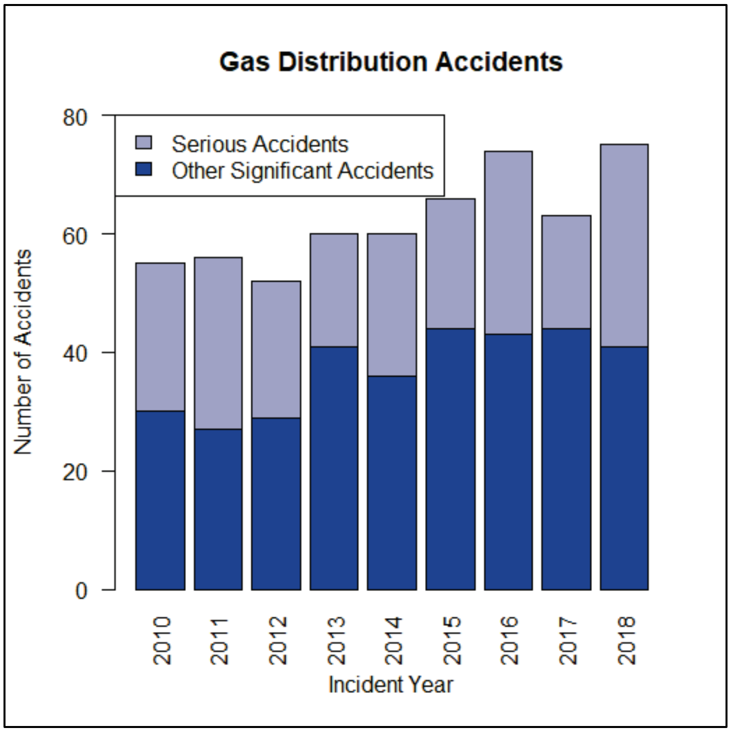


Figure 10. Serious and Significant U.S. Gas Distribution Accidents (2010-18)

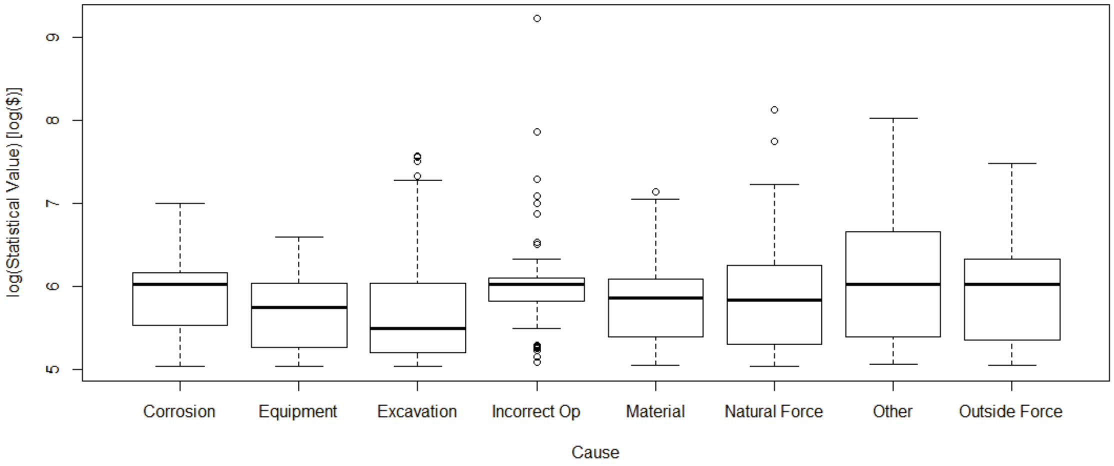


Figure 11. Statistical Value of Significant Accidents by PHMSA Major Cause (2010-18)

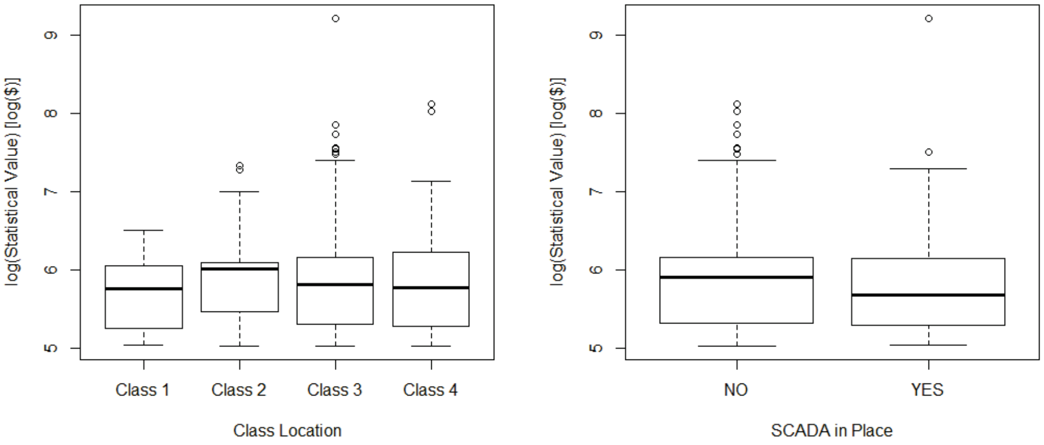


Figure 12. Statistical Value of Significant Accidents by Class Location and SCADA (2010-18)

Section 3.5: Risk Quantification

The gas distribution system risk was estimated based on the results of the likelihood determination and consequence analysis. For this evaluation, a point estimate was used to estimate the statistical value. A point estimate is an appropriate approximation for this initial framework, but a probabilistic estimate is recommended after the consequence analysis development has been completed. The mean statistical value that could be gained if all risks associated with gas distribution systems being eliminated were estimated to be $358 million per year (Table 9).

Table 9. Statistical Value of Significant Accidents

Cause/*Subcause*	**Statistical Value** ($/yr)	**Cause**/*Subcause*	**Statistical Value** ($/yr)
Excavation	**$112,529,662**	**Other Incident Cause**	**$33,886,773**
Insufficient Excavation Practices	$53,707,339	*Miscellaneous*	$17,902,446
Insufficient One-Call Notification Practice	$25,574,923	*Unknown*	$15,984,327
Insufficient Locating Practices	$19,820,565	**Pipe, Weld, or Joint Failure**	**$31,329,281**
Other	$7,672,477	*Construction Defect*	$14,066,208
Previous Damage	$4,475,612	*Material Defect*	$10,869,342
Abandoned Facility	$639,373	*Other/Unknown*	$2,557,492
Data Not Collected	$639,373	*Design Defect*	$1,918,119
Other Outside Force	**$94,627,216**	*Previous Damage*	$1,918,119
Motorized Vehicle/Equipment	$53,067,966	**Natural Force Damage**	**$26,853,669**
Other	$26,853,669	*Lightning*	$5,754,358
Electrical Arcing	$8,951,223	*Temperature*	$5,754,358
Intentional Damage	$3,196,865	*Other*	$5,754,358
Previous Damage	$1,918,119	*Earth Movement*	$5,114,985
Adrift Maritime Equipment	$639,373	*Heavy Rains/Floods*	$4,475,612
Incorrect Operation	**$35,165,519**	**Equipment Failure**	**$14,705,581**
Other	$22,378,058	*Control/Relief Equipment Malfunction*	$6,393,731
Damage by Operator or Operator's Contractor	$5,754,358	*Non-Threaded Connection Failure*	$3,196,865
Valve Left or Placed in Wrong Position	$2,557,492	*Valve*	$2,557,492
Equipment Not Installed Properly	$2,557,492	*Other*	$1,918,119
Pipeline or Equipment Over-Pressurized	$1,278,746	*Threaded Connection Failure*	$639,373
Wrong Equipment Specified or Installed	$639,373	**Corrosion**	**$9,590,596**
		External Corrosion	$8,311,850
		Internal Corrosion	$1,278,746

Section 3.6: Uncertainty Evaluation

A listing of the assumptions associated with this evaluation and justification for each is shown in Table 10.

Table 10. Assumptions with Justification

Assumption	**Justification**
Gas distribution infrastructure was generalized on a per mile basis (e.g., changes in design, configuration, and location are not considered)	Appropriate for a nationwide analysis. System-specific analyses are recommended to support proposed actions resulting from this high-level analysis.
Simplified consequence modeling	Data insufficient to support refined consequence modeling **(Recommended Future Work)**
Mean VSL used	VSL values were based on DOT guidance which recommended sensitivity study based on minimum and maximum values. A sensitivity study is included in Section 3.7.
Integration of all scenarios to estimate total risk	Each cause is treated as mutually exclusive in this dataset, although contributing causes are known to exist and may be significant. **(Recommended Future Work)**
Quality of data reported to PHMSA is sufficient to support this analysis	Data quality limitations are discussed herein **(Recommended Future Work)**
Point estimates were used to quantify risk; parameter uncertainty was not accounted for.	Point estimates are an approximation based on the maturity of the model at this point. A probabilistic model should be developed after data quality and consequence modeling has been improved. **(Recommended Future Work)**

Data Quality Limitations: Many PHMSA reportable gas distribution accidents are investigated by the operators, state regulators (sometimes with support from PHMSA), or the National Transportation Safety Board (NTSB). The use of investigation results to identify meaningful safety improvements within the gas distribution industry requires accurate data to be provided in a timely manner. Table 11 shows a comparison between the cause information reported to PHMSA and the NTSB determined probable cause for gas distribution accidents investigated by the NTSB since 2010. Note that the cause information reported to PHMSA is not consistent with the NTSB determined probable cause for the majority of these accidents (5/7) which are highlighted in the table. A similar, more comprehensive comparison could be completed with investigation results from the various State regulators and/or operators to ensure that the most accurate information is available to support analysis and consequential safety decisions. In some cases, the operator may not agree with the probable cause determined by the NTSB, PHMSA, or state regulator. However, the government-led accident investigations generally employ an independent assessment of the facts, with input from the operators; they result in the most useful cause information for this type of analysis.

Future work to capture government-led accident investigation results and combine this information with the current operator reported PHMSA data could help to make the most useful data available for future analysis. This future analysis could then support the identification of performance-based safety enhancements.

Table 11. Comparison of Cause Information Reported to PHMSA by the Pipeline Operator and the Probable Cause Determined by the NTSB (Accidents with Inconsistent Causes are Highlighted)

Accident Date	**NTSB Report Date**	**City**	**State**	**NTSB Probable Cause (Abbreviated)**	**Cause (PHMSA Reporting Form)**
9/13/18	9/24/19	Merrimack Valley	MA	Weak engineering management	INCORRECT OPERATION
8/2/17	12/2/19	Minneapolis	MN	Pipefitting crew disassembled piping upstream of a gas service meter	OTHER INCIDENT CAUSE
7/2/17	2/25/19	Millersville	PA	Improperly installed mechanical tapping tee	OTHER INCIDENT CAUSE
11/16/16	12/3/18	Canton	IL	Third-party damage from directional drilling to install underground fiber optic conduit	EXCAVATION DAMAGE
8/10/16	4/24/19	Silver Spring	MD	Failure of an indoor mercury service regulator with an unconnected vent line	OTHER INCIDENT CAUSE
3/12/14	6/9/15	New York	NY	Failure of the defective service tee fusion joint and breach in the sewer line that went unrepaired	NATURAL FORCE DAMAGE
12/17/13	3/30/16	Birmingham	AL	Large crack in 62-year-old cast iron gas main	OTHER INCIDENT CAUSE

Section 3.7: Sensitivity and Importance Analysis

Based on the uncertainty evaluation, the need for a sensitivity study to evaluate the various estimates of VSL was identified. In order to assess the sensitivity of this analysis to the range of potential acceptable VSLs, the analysis was repeated using minimum and maximum values. The minimum VSL was estimated to be $6 million and the maximum VSL was estimated to be $14 million. The results indicated that the annual statistical value has ranged from $305 million to $376 million (Table 12).

In this initial study, data (particularly consequence data) was not available to support a full probabilistic risk assessment. Therefore, the traditional importance measures were not calculated. However, the estimated risk information can be used to identify the relative importance of potential cause-based safety program improvements. For example, over 30% of the gas distribution system risk is attributed to excavation accidents. Of these, almost 50% of the risk from excavation accidents is associated with insufficient excavation practices, and over 20% is associated with insufficient One-Call notification practices. Similarly, the risk contribution of each subcause can be calculated (Table 13). This shows that insufficient excavation practices and motorized vehicle/equipment are dominant risk contributors.

Table 12. Statistical Value of Significant Accidents by Major Cause

	Statistical Value ($/yr)	
Cause	**min**	**max**
Excavation	$95,624,071	$129,435,253
Other Outside Force	$80,411,151	$94,627,216
Incorrect Operation	$29,882,522	$35,165,519
Other Incident Cause	$28,795,885	$33,886,773
Pipe, Weld, or Joint Failure	$26,622,611	$31,329,281
Natural Force Damage	$22,819,381	$26,853,669
Equipment Failure	$12,496,327	$14,705,581
Corrosion	$8,149,779	$9,590,596
TOTAL	**$304,801,726**	**$375,593,889**

Table 13. Relative Importance of Subcauses Contributing at Least 1%

Subcause (Cause)	**Statistical Value** ($/yr)	**Percent Contribution**
Insufficient Excavation Practices (Excavation)	53,707,339	15%
Motorized Vehicle/Equipment (Other Outside Force)	53,067,966	15%
Other (Other Outside Force)	26,853,669	7%
Insufficient One-Call Notification Practice (Excavation)	25,574,923	7%
Other (Incorrect Operation)	22,378,058	6%
Insufficient Locating Practices (Excavation)	19,820,565	6%
Miscellaneous (Other Incident Cause)	17,902,446	5%
Unknown (Other Incident Cause)	15,984,327	4%
Construction Defect (Pipe, Weld, or Joint Failure)	14,066,208	4%
Material Defect (Pipe, Weld, or Joint Failure)	10,869,342	3%
Electrical Arcing (Other Outside Force)	8,951,223	2%
External Corrosion (Corrosion)	8,311,850	2%
Other (Excavation)	7,672,477	2%
Control/Relief Equipment Malfunction (Equipment Failure)	6,393,731	2%
Damage by Operator or Operator's Contractor (Incorrect Operation)	5,754,358	2%
Lightning (Natural Force Damage)	5,754,358	2%
Temperature (Natural Force Damage)	5,754,358	2%
Other (Natural Force Damage)	5,754,358	2%
Earth Movement (Natural Force Damage)	5,114,985	1%
Previous Damage (Excavation)	4,475,612	1%
Heavy Rains/Floods (Natural Force Damage)	4,475,612	1%

Section 3.8: Risk Acceptance

The gas distribution industry does not have a specific safety metric that they are required to meet. However, the current Administrator of PHMSA has advocated for a goal of zero reportable pipeline accidents [11]. A significant change in our country’s gas distribution operations would be needed to realize such a significant improvement.

PHMSA’s goal is consistent with an NTSB study, which noted that traditional cost-benefit criteria are not necessarily applicable to pipeline accidents because those that are near pipelines when accidents occur are often not the same as those that benefit from them. The NTSB notes that “those who are bearing the risk deserve to be protected by expenditures far beyond the dictates of cost-benefit” [12].

Section 3.9: Risk Reduction

The U.S. gas distribution industry has undergone many safety improvements over the last two centuries. Despite many successes and improvements, the industry has not yet achieved an acceptable level of risk. Low frequency, high consequence events continue to occur, significantly increasing the overall risk across the industry.

Many industries use the concept of defense-in-depth to protect against such events. This concept originated as a military strategy where layered lines of defense would be used instead of a single strong line of defense. The use of diverse and redundant components can reduce risk by preventing system failure or mitigating its consequences. If failure of the diverse and/or redundant components is detected, timely repair of the failed components can be completed without suffering catastrophic consequences [33].

The defense-in-depth concept has been employed in nuclear safety since about 1957 [33]. In the nuclear safety arena, one acceptable method of supporting risk-informed safety decisions includes maintaining a defense-in-depth philosophy. In this context, defense-in-depth is considered to include four layers of defense which are shown in Table 14 [34]. Although it is not often referred to as “defense-in-depth,” a similar framework has been employed in the gas distribution pipeline industry, also shown in Table 14. However, many of the efforts that have been implemented in gas distribution systems to date have focused on preventing accidents, strengthening the first layers of defense.

Additional efforts to strengthen the second and third layers of defense could yield significant safety benefits. For example, the NTSB's investigation of a gas distribution accident that occurred on September 13, 2018, in Merrimack Valley, MA indicated that the NTSB had previously investigated seven accidents that involved natural gas under high pressure entering low-pressure natural gas lines. A search of PHMSA data yielded seven additional accidents that involved over-pressurization of a low-pressure distribution system (Table 15). Analysis of these fourteen accidents may have identified a cost-effective safety enhancement to protect low-pressure distribution systems from common cause failure (CCF) of their overpressure protection system (e.g., worker-monitor regulator valves). Note that inconsistencies in the cause described in the narrative section of these reports and the cause reported in the cause field are highlighted in Table 15 (see Data Quality Limitations discussion in Section 3.6).

In order to mitigate these types of accidents before they occur, the information must be available, analyzed, and safety improvements must be implemented. It is critical to have a collection of relevant, accurate data available in a useable format and representing a broad group of operators. It is beneficial for this information to be collected on a national or international basis so that individual companies are not relying on sparse and disparate data. In the nuclear industry, industry stakeholders formed the Institute of Nuclear Power Operations (INPO) after the Three Mile Island accident, in part, to serve this purpose.

Defense-in-depth concepts can be implemented through many different structures. One approach is through the implementation of Pipeline Safety Management Systems (PSMS) [35]. Whatever the mechanism, a focus on strengthening the second layer of defense can help decrease accident consequences. This focus may lead to:

- Hardware modifications which correct configurations known to have the potential for high consequences (e.g., cast iron pipe replacements, installation of excess flow valves, diverse overpressure protection for low-pressure distribution systems)
- Implementation of automatic shutoff valves and remote-control valves to mitigate the consequences of accidents if they do happen.

Table 14. Comparison of Layers of Defense Between Commercial Nuclear Safety and Gas Distribution Pipeline Safety

Layers of Defense to Protect Against Low Frequency, High Consequence Events	
Nuclear Safety	*Gas Distribution Pipeline Safety*
1. Robust design which minimizes challenges 2. Prevention of a severe accident 3. Containment of hazardous material in the event of a severe accident 4. Protecting the public from a release	1. Robust design, construction, damage prevention, and integrity management standards minimize challenges 2. Prevent serious accidents (e.g., operator leak monitoring, public awareness programs, addition of odorant) 3. Emergency response

Table 15. PHMSA Data Indicating Over-Pressurization of a Low-Pressure Distribution System (Excluding NTSB Investigations)

Date	**City**	**Cause Summarized from Narrative**	**Reported Cause**	**Fatality / Injury**	**Reported Cost**
1/24/11	Fairport Harbor, OH	CCF of overpressure protection (regulator valves) – presence of pipeline fluids and gas temperature drop	EQUIPMENT FAILURE	No	$1,293,413
10/10/05	Boonville, MO	Inadvertent over-pressurization during cast iron replacement	INCORRECT OPERATION	No	$600,000
11/3/03	Cohoes, NY	CCF of overpressure protection – Excavation damage to control line	DAMAGE BY OUTSIDE FORCES	No	$0
6/3/01	Pittsfield, MA	CCF of overpressure protection (regulator valves) – regulator pit flooding	OTHER	No	0
4/13/94	Alameda, CA	Regulator and security valve failure (may have been CCF)	OTHER	No	$3,600,000
4/01/93	South Buffalo, PA	CCF of overpressure protection (regulator valves) – lightning strike	DAMAGE BY OUTSIDE FORCES	No	$200,000
12/4/82	Springfield, IL	CCF of overpressure protection – Excavation damage of control line	DAMAGE BY OUTSIDE FORCES	No	$80,000

Chapter 4: Recommendations for Future Work

In the U.S. gas distribution industry, many safety improvements have been implemented since gas distribution first began. Some of these improvements have been codified and consistently required through regulation and others were implemented through industry initiatives and technological advancement. As the industry strives to reduce safety risks further, a set of risk acceptance criteria or safety goals should be developed, similar to the risk acceptance criteria used by the nuclear industry. To reach an acceptable level of risk, additional work to understand and manage risks is needed.

As a starting point, the analysis proposed in this thesis should be further developed. In particular, the improvements identified in the uncertainty evaluation should be completed, including:

- Develop a more complete consequence model.
- Assess the need to consider contributing causes and develop a mechanism for incorporating them.
- Improve the quality of the available data by requiring updates and incorporating information from multiple sources.
- After the data quality and consequence modeling improvements have been made, develop a probabilistic model to address parametric uncertainty and update analysis to identify and address any new model and completeness uncertainties that are introduced.

Additionally, this model should be frequently updated since it relies on historical records to predict the future. Regularly reviewing the model with the goal of continuous improvement could provide a way to accurately estimate risk given the changing infrastructure and incremental improvements in both operations and data quality.

Future improvements could be realized by moving towards a proactive, predictive approach [36]. Prognostics and health management may also be explored for this application that may enhance distribution system safety. There are examples where predictive approaches have improved safety and reliability, while also saving money [37].

Chapter 5: Conclusion

This study utilized PRA methods, nationwide gas distribution system information, and operator reported accident data to evaluate gas distribution system risks. Three phases – risk identification, risk assessment, and risk management – were completed and could be iterated in the future as knowledge is gained and system improvements are made. The risk identification phase included system characterization and threat identification. The risk assessment phase included estimating the likelihood and consequences of those threats that could lead to hazard exposure, quantifying the associated risk, evaluating uncertainties, and analyzing the sensitivity of assumptions and importance of various risk contributors. The risk management phase included evaluating risk acceptance thresholds and the need for risk reduction.

There are more than two million miles of main and service lines that distribute gas in the U.S., comprised of infrastructure that varies in design, material, configuration, and age. Operator-reported incident reports contain failure cause information, each cause was identified as a threat to the system. Historical data were assessed to determine the hazard rate for accidents that occurred between 2010-18. The overall hazard curve exhibited a higher hazard rate towards the beginning and end of life. The higher hazard rate early in life was attributed to the following failure causes: excavation, other outside force, equipment, and incorrect operations. These causes are typically thought of as being time-independent or stable in the pipeline industry. However, increased construction in the vicinity of new pipelines and unexpected environmental conditions explained the increased hazard early in life.

The increasing hazard rate later in life was attributed to corrosion and natural force failures, which is a typical response for degradation mechanisms. Less mature requirements that were in place before 1950 may have also contributed to this response for older pipelines. Initiatives to improve safety performance early in life may focus on enhancing existing processes to perform new construction safely, expanding public outreach related to new construction projects, and developing more robust processes to define and design for actual in-service conditions. Initiatives to improve safety performance later in life may focus on enhancing integrity assessments for pipeline that are more than 50 years old, implementing more aggressive replacement schedules for pipelines with known integrity challenges, and closely collecting, analyzing, and addressing a broad set of performance data.

Consequences were assessed based on the statistical value of each accident. The statistical value was estimated based on the amount the public would have been willing to pay to prevent the fatalities and injuries that occurred as a result of the accident plus the actual cost incurred. The mean consequence of $5,754,368 per significant reported accident was driven by a relatively low number of accidents with catastrophic consequences.

The overall risk was estimated based on a point estimate of likelihood and consequence due, in part, to the limited data available to support consequence analyses. The mean statistical value that could be gained if all risks associated with gas distribution systems were eliminated was estimated to be $358 million per year. Excavation and other outside force accidents were dominant contributors.

The uncertainty evaluation identified several sources of model, completeness, and parameter uncertainty which were either justified or recommended for future analysis. Data quality was found to be a significant limitation of this work. For example, the cause information reported to PHMSA and the probable cause determined by the NTSB was inconsistent in the majority of cases (5/7). Similarly, cause information summarized from the narrative provided by the operator and that reported as the official cause in the same PHMSA form was inconsistent in five of seven cases that were not investigated by the NTSB.

A sensitivity analysis was performed to address uncertainty associated with the use of the estimated VSL. The results indicated elimination of all risks to public health and safety from the U.S. gas distribution system could provide an estimated benefit of between $305 million and $376 million per year.

Commonly used importance measures were not calculated because this was not a full probabilistic risk assessment. However, the estimated risk information was used to identify the relative importance of potential cause-based safety program improvements. When assessing the information at the subcause level, insufficient excavation practices and motorized vehicle equipment were dominant contributors.

While the industry does not have a specific safety metric, the current gas distribution system risks were found to exceed acceptable levels. The current Administrator of PHMSA advocates for a goal of zero reportable pipeline accidents. A significant change would be needed to realize such a significant improvement. Low frequency, high consequence events continue to occur, significantly increasing the overall risk across the industry. One way to protect against such events would be to employ a defense-in-depth philosophy by focusing on preventing serious accidents through mitigation, rather than focusing primarily on preventing system challenges. Such an approach may lead to: hardware modifications to improve configurations known to have the potential for high consequences and installing automatic shutoff valves and remote-control valves to mitigate the consequences of accidents if they do happen.

Additional research is needed to develop this approach, to improve accident data quality, develop consequence modeling, and consider contributing causes. Once this additional research is completed, this approach can be updated to address parameter uncertainty through Monte Carlo simulation using currently available software [32].

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