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DEVELOPING A FULL RISK PICTURE FOR GAS PIPELINE CONSEQUENCES

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ABSTRACT

Properly characterizing the consequences of pipeline incidents is a critical component of assessing pipeline risk. Previous research has shown that these consequences follow a Pareto type distribution for gas distribution, gas transmission and hazardous liquid pipelines where low probability – high consequence (LPHC) events dominate the risk picture. This behavior is driven by a combination of deterministic (e.g. pipe diameter, pressure, location factors, etc.) and random factors (e.g. receptor density at specific time of release, variable environmental factors at time of release, etc.). This paper examines how the Pareto type behavior of the consequences of pipeline incidents arises and demonstrates how this behavior can be modeled through the use of a quantitative pipeline risk model. The result is a more complete picture of pipeline risk, including insight into LPHC events. Use of the modelling approach for integrity management is discussed.

INTRODUCTION

To manage pipeline risk, just like managing anything, a clear picture, specifically a genuine measure, of risk is needed. At the highest level this involves having:

- A clear picture of current risk via a measure of risk
- A clear picture of how risk will evolve over time via a projection of changes in the measure of risk
- The ability to assess the impact of Integrity Management (IM) activities on risk
- Quantitative risk measures with enough granularity to assess the risk-cost benefit of IM activities to enable true optimization of these activities

As low probability – high consequences events (LPHC) form a significant component of pipeline risk. (e.g. The top 1% of PHMSA (Pipeline Hazardous Materials Safety Administration) reported incidents accounts for 20% of reported property damage), to manage risk, it is necessary to include LPHC events in the overall risk analysis.

This paper demonstrates that, with the correct model structure and modelling approach along with (relatively) basic model inputs, a clear operator-specific quantitative view of pipeline risk can be developed that captures LPHC events. The paper also discusses how, with more detailed quantitative modeling approaches, a very granular view of risk can be obtained along with clear insight on how integrity management activities impact risk. Overall this provides operators with a clear view of the risk picture overall as well as on an asset by asset (or pipe segment by pipe segment) basis along with the ability to quantitively assess the impact of IM activities on risk.

A simplified set of risk models is used to develop an overall picture of pipeline risk for a distribution system (the same approach has been applied to transmission pipelines but not included herein). The model outputs are compared to historical PHMSA incident data, showing how even in simplified form, the approach can accurately capture the risk picture and potential consequences, including LPHC events. Using a similar approach, with Monte Carlo simulation, to develop a projected risk picture for a given pipeline operator is discussed.

NOMENCLATURE

C_n	consequence of the *n*th scenario
LoC	loss of containment
P_E	probability of explosion
P_{Gm}	probability of a grade *m* leak
P_I	probability of ignition
P_n	probability of the *n*th scenario
P_{NI}	probability of no explosion
P_{TL}	total probability of a leak for a given threat
R_n	risk of the *n*th scenario

OVERVIEW OF PIPELINE CONSEQUENCES

As shown previously [1] pipeline consequences for distribution system incidents follow Power Law or Pareto – type distributions, as shown in Figure 1. The same behavior is observed for gas transmission and hazardous liquid pipelines. Figure 1 plots the log(frequency) versus the log($ consequences) for PHMSA reported incidents from 2004-2016 based on reported property damage, injuries and fatalities with injuries and fatalities monetized at $2.5 million and $10 million, respectively. The Power Law curve, therefore, defines the relationship between frequency and incident size.

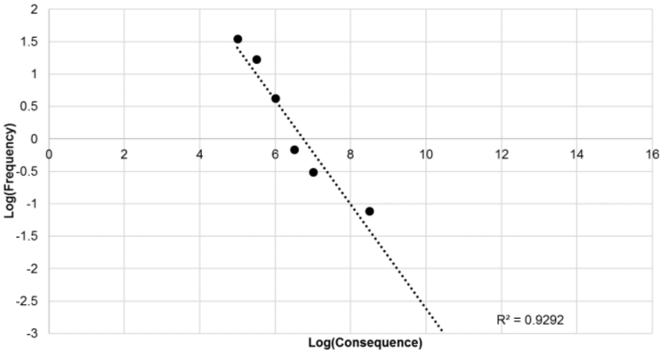

FIGURE 1: POWER LAW CURVE FOR PHMSA DISTRIBUTION SYSTEM INCIDENTS

With an understanding of the relationship between frequency and incident size, projections of risk can be made, such as – what is the probability of an incident of $10 Million in consequence occurring. While this is useful for gaining overall insight into the pipeline risk picture, to fully manage risk in their systems, pipeline operators need insight into the risk picture for their specific systems. They also need the ability to see how this risk picture will evolve into the future and how IM activities will impact this risk picture. To demonstrate how pipeline operators can obtain this level of insight in to the risk in their systems, a simplified set of risk models is used to develop a Power Law curve for gas distribution systems. Using a full set of risk models specific to a given operator and Monte Carlo simulation to develop operator specific Power Law curves is discussed.

MODELING APPROACH

A simplified version of distribution risk models was used to develop projected risk for distribution pipelines. The base model structure and model Parameters are discussed in the sections that follow.

Base Model Structure

An overall set of quantitative risk models that provide over time absolute ($ based or in terms of Risk Units) risk protections has been developed. The base model structure for these models is shown in Figure 2. Separate models are used for each asset type (e.g. Steel mains, polyethylene services etc.) and each threat (e.g. external corrosion, 3rd party damage, etc.). In this paper a single base model was used with average values to demonstrate how, with the proper modeling approach and structure, the Power Law nature of pipeline consequences can be captured.

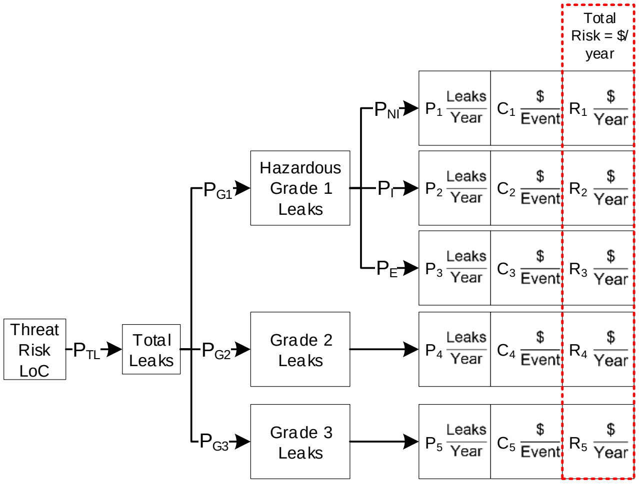

FIGURE 2: BASE RISK MODEL STRUCTURE

The Probability of a leak is assessed for each asset for each threat type using Weibull Proportional Hazard Models configured to the operator's specific data. The total leaks are further classified into Grade 1 (hazardous) Grade 2 and Grade 3 leaks as detailed in the Leak Breakdown Section below. For Grade 1 Hazardous leaks the scenarios of no ignition, ignition and explosion are assessed. Over all this results in five different potential scenarios (or consequence outcomes) for a given leak:

- Grade 1 – No Ignition
- Grade 1 – Ignition
- Grade 1 – Explosion
- Grade 2 - No Ignition
- Grade 3 – No Ignition

Each potential scenario will have a different potential set of consequences based on leak specific factors and location as detailed in the Model Factors section below. To obtain risk for a given threat, the probabilities (or likelihoods) for each potential scenario are multiplied by the consequences for that potential scenario to develop the five potential scenario risk outcomes. These five risk outcomes are then summed to obtain the total threat risk.

Model Factors

A simplified set of model parameters was used to calculate the distribution of risk outcomes as detailed in Table 1. Each of the parameters and the basis for the model inputs are discussed below.

TABLE 1: SIMPLIFIED MODEL PARAMETERS

(1) Location Class	(2) Location Breakdown	(3) Leak Class	(4) Leak Breakdown	(5) Incident	(6) Incident Breakdown	(7) Consequences
Public Building	1.00%	Hazardous (G1) Leaks	60%	Explosion	0.01%	$ 25,630,400
				Ignition	0.01%	$ 6,129,950
				No-Ignition	99.98%	$ 11,325
		Non-Hazardous (G2) Leaks	20%	Repair	100.00%	$ 11,325
		Non-Hazardous (G3) Leaks	20%	Monitor	100.00%	$ 425
Metro Core	1.00%	Hazardous (G1) Leaks	60%	Explosion	0.01%	$ 25,630,400
				Ignition	0.01%	$ 6,129,950
				No-Ignition	99.98%	$ 11,325
		Non-Hazardous (G2) Leaks	20%	Repair	100.00%	$ 11,325
		Non-Hazardous (G3) Leaks	20%	Monitor	100.00%	$ 425
Business District	14.00%	Hazardous (G1) Leaks	50%	Explosion	0.01%	$ 25,630,400
				Ignition	0.01%	$ 6,129,950
				No-Ignition	99.98%	$ 11,325
		Non-Hazardous (G2) Leaks	25%	Repair	100.00%	$ 11,325
		Non-Hazardous (G3) Leaks	25%	Monitor	100.00%	$ 425
Urban	35.00%	Hazardous (G1) Leaks	30%	Explosion	0.01%	$ 15,407,040
				Ignition	0.01%	$ 3,681,540
				No-Ignition	99.98%	$ 10,475
		Non-Hazardous (G2) Leaks	35%	Repair	100.00%	$ 10,475
		Non-Hazardous (G3) Leaks	35%	Monitor	100.00%	$ 425
Suburban	24.00%	Hazardous (G1) Leaks	25%	Explosion	0.01%	$ 12,839,200
				Ignition	0.01%	$ 3,067,950
				No-Ignition	99.98%	$ 8,775
		Non-Hazardous (G2) Leaks	38%	Repair	100.00%	$ 8,775
		Non-Hazardous (G3) Leaks	38%	Monitor	100.00%	$ 425
Outskirts	10.00%	Hazardous (G1) Leaks	10%	Explosion	0.01%	$ 12,822,400
				Ignition	0.01%	$ 3,064,975
				No-Ignition	99.98%	$ 5,800
		Non-Hazardous (G2) Leaks	45%	Repair	100.00%	$ 5,800
		Non-Hazardous (G3) Leaks	45%	Monitor	100.00%	$ 425
Rural	15.00%	Hazardous (G1) Leaks	10%	Explosion	0.01%	$ 12,815,200
				Ignition	0.01%	$ 3,063,700
				No-Ignition	99.98%	$ 4,525
		Non-Hazardous (G2) Leaks	45%	Repair	100.00%	$ 4,525
		Non-Hazardous (G3) Leaks	45%	Monitor	100.00%	$ 425

Location Class The Location Class represents regions within the distribution system that have similar characteristics in terms of density of infrastructure and building type (e.g. Suburban areas are comprised of largely single-family dwellings with similar occupancy levels) among other factors. For transmission systems, actual building structure data along the pipeline route are used (this data is not available (or relevant) for most distribution system operators). Typically, the seven categories listed in Table 1, Column 1 provide a reasonable breakdown for distribution system risk assessments (more detailed categories and sub-categories can be defined based on the specifics of the operator's system).

Class Location impacts two critical model inputs:

- Leak Breakdown
    - The percentages of Grade 1, Grade 2 and Grade 3 leaks depend on Location Class
    - For example, for a given threat (e.g. corrosion) there is a higher proportion of hazardous leaks in a Metro Core than a Rural Location Class
- Consequences
    - The potential consequences of a leak vary with Location Class

    - For example, the potential consequences of an ignition or explosion event are higher in a Metro Core than in a Rural Location Class

Location Breakdown For the simulation, the Location Breakdown (% of leaks in each Location Class) in Table 1, Column 2 was based on a typical gas distribution system.

Leak Class The Leak Class (Table 1, Column 3) represents the leak category based on PHMSA definitions for Grade 1 (hazardous), Grade 2 and Grade 3 leaks.

Leak Breakdown Analysis of PHMSA and operator data shows that the percentage of total leaks that fall into each of the three leak classes depends on the specific threat (e.g. a higher percentage of third party damage leaks are hazardous than for corrosion leaks) and the leak location (e.g. a higher percentage of total leaks are hazardous in a Metro Core versus Rural Location Class).

The Leak Breakdown percentages (Table 1, Column 4) used in the simulation are based on the typical average values across all threat types (the actual risk models use specific percentages for each threat type and by component (e.g. mains versus services)). The values in Table 1 represent the average values used in the simulation. A simplified model considering three threats (corrosion, 3rd party damage and other) was used in the simulation with separate specific leak breakdowns for each threat type (i.e. 3rd party damage leaks are more likely to be hazardous than corrosion leaks) (Table 2).

Incident The risk model considers five different possible Incident outcomes (Table 1, Column 5):

- Grade 1 Hazardous leak – no ignition (immediate repair)
- Grade 1 Hazardous leak – ignition
- Grade 1 Hazardous leak – explosion
- Grade 2 – no ignition (repair)
- Grade 3 – no ignition (monitor)

Incident Breakdown For hazardous leaks, the probabilities of ignition and explosion (Table 1, Column 6) depend on the threat type (e.g. probabilities are higher for 3rd party damage than for corrosion) and the detailed leak location factors.

For the example calculation, average values across all threats of 1 explosion event and 1 ignition event per 10,000 hazardous leaks were used [2].

Consequences The potential consequences of a distribution system leak (Table 1, Column 7) depend on a number of factors:

- Leak Class (Grade 1, Grade 2, Grade 3)
- Incident type for Grade 1 leaks (e.g. no ignition, ignition, explosion)
- Location Class (building type, occupancy level, structure value, etc.)

The potential consequences are also comprised of a number of components:

- Health & safety
    - Injuries
    - Fatalities
- Financial costs
    - Lost gas
    - Service disruption
    - Repair costs
    - Etc.
- Property damage
- Regulatory costs
- Environmental costs
- Damage to reputation
- Etc.

To enable comparison with PHMSA data (which reports property damage injuries and fatalities), only health and safety and property damage are considered in the base models for ignition and explosion incidents for the example calculation. These risks are assessed based on average structure types for each Location Class with defined structure values, occupancy rates and structure damage rates, injury rates and fatality rates. These values were determined based on a detailed analysis of historical distribution system incidents. Health and Safety risk was monitored based on \$10 million for a fatality and \$2.5 million for an injury.

For Grade 1 and Grade 2 leaks with no ignition an average leak repair cost based on location class was used (detailed cost models based on location class, asset type, size, operator practices, operator specific costs, etc. are used in the complete models). For Grade 3 leaks an average cost for monitoring the leak was used.

CALCULATION

A simple calculation was performed by taking 50,000 leaks and randomly distributing them across the various possible outcomes based on the probabilities for each outcome. The leaks were assumed to be 26% from corrosion, 15% from 3rd party damage and 59% other [2] and the parameters in Table 2 used for the leak breakdown percentages.

TABLE 2: LEAK BREAKDOWN PERCENTAGES

(1)	(2)	(3)	(4)	(5)	(6)
			Leak Breakdown		
		Threat Breakdown:	26%	15%	59%
Location Class	**Location Breakdown**	**Leak Class**	**Corrosion**	**Excavation Damage**	**Other (General)**
Public Building	1.00%	G1	60%	95%	60%
		G2	20%	2.5%	20%
		G3	20%	2.5%	20%
Metro Core	1.00%	G1	60%	95%	60%
		G2	20%	2.5%	20%
		G3	20%	2.5%	20%
Business District	14.00%	G1	50%	95%	60%
		G2	25%	2.5%	20%
		G3	25%	2.5%	20%
Urban	35.00%	G1	30%	90%	45%
		G2	35%	5%	27.5%
		G3	35%	5%	27.5%
Suburban	24.00%	G1	25%	90%	40%
		G2	38%	5%	30%
		G3	38%	5%	30%
Outskirts	10.00%	G1	10%	70%	30%
		G2	45%	15%	35%
		G3	45%	15%	35%
Rural	15.00%	G1	10%	60%	20%
		G2	45%	20%	40%
		G3	45%	20%	40%

Typically a more complex Monte Carlo simulation with distributions instead of point values and considering all threats would be run. The simulations also typically use forecast leak rates for each threat based on probabilistic models tuned to the operator's specific system. A much simpler simulation was used for this paper for ease of explaining and demonstrating the concept and to demonstrate that the observed Power Law behavior of pipeline consequences can be modelled, when the correct basis and structure are used, with relatively basic inputs.

Comparison with PHMSA incident Data

Figure 3 shows a comparison of the outputs with the Power Law curve for PHMSA incident Data. Even with a simplified model, there is close alignment between the simulation and the historical PHMSA incident Data, with the model providing slightly more conservative (i.e. higher) risk protections. This is significant for two key reasons:

1. It demonstrates that with the right modeling approach and structure it is possible to quantitively characterize risk, including risk due to LPHC events.
2. It demonstrates that even using relatively simple model inputs with the right modeling approach and structure it is possible to obtain realistic estimates of risk due to LPHC events.

It should be noted that, as it captures the relationship between frequency and consequence size, the Power Law plot is independent of the number of leaks.

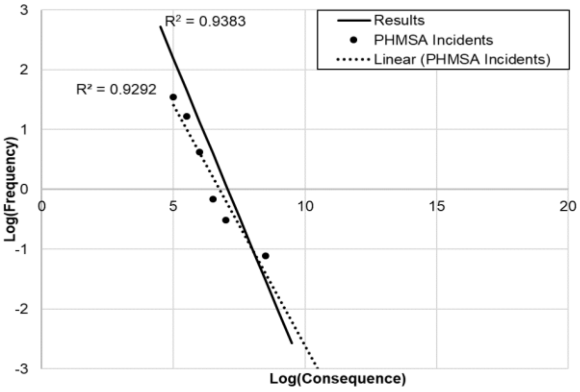

FIGURE 3: COMPARISON OF CALCULATED RESULTS WITH PHMSA INCIDENT DATA

USE FOR PIPELINE INTEGRITY MANAGEMENT

The ability to quantitively model risk, including LPHC event risk, in a realistic way provides pipeline operators with several key Integrity Management (IM) tools. While detailing the full extent of what is possible is beyond the scope of this paper, a number of key concepts are briefly reviewed.

The modeling approach demonstrates that with relatively simple model inputs that realistic estimates of high level risk can be obtained. With basic operator data (e.g. total leaks, leaks by location class, average structure type, occupancy and structure value, etc.), operator specific power law curves can be developed, giving operators a high-level view of LPHC risk in their systems.

When the general approach outlined in this paper is coupled with detailed risk models, that are configured and tuned to operator specific data, granular overtime risk estimates specific to the operator system can be developed, giving operators a clear view of current and future risk.

With models that also include the impact of IM activities on risk, operators can examine the impact of these activities on the overall risk picture. By way of example (using an extreme case to illustrate) Figure 4 shows the impact on the power law curve of reducing 3rd party leaks from 75% to 15% of total system leaks. As third-party damage leaks have a much higher likelihood of being hazardous compared to other threat types, the result is a shift of the power law curve to the left. While an extreme case, it demonstrates the concept of ‘curve shifting’ through integrity management activities. When combined with cost models, the cost – risk benefit of different IM activities can be assessed and optimized, giving operators the ability to have a clear line of sight into system risk and how best to manage it in their system.

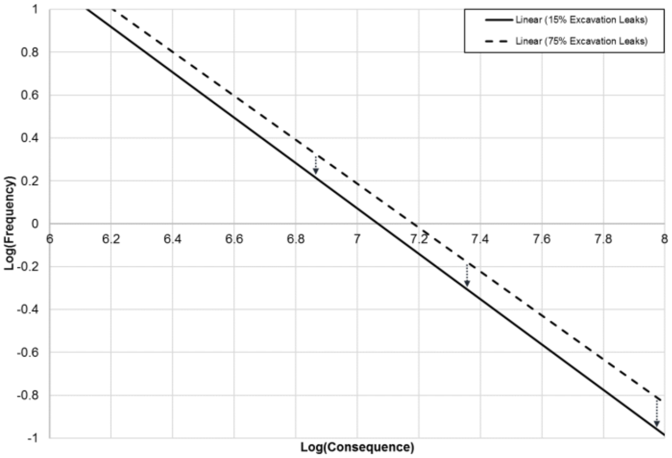

FIGURE 4: IMPACT OF INTEGRITY MANAGEMENT ACTIVITIES ON POWER LAW RISK CURVE

Conclusions

The consequences of pipeline incidents follow Power Law or Pareto-type distributions where low probability – high consequence events play a significant role in the overall risk picture. This paper has shown that, with the correct model basis and structure, even relatively simple modelling approaches can replicate the observed Power Law behavior. When this is combined with mechanistic-probabilistic risk models, operator (and asset or segment level) specific Power Law curves can be developed, giving operators a clear line of sight into risk in their system and the ability of optimize their IM activities to manage their risk.

REFERENCES

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[2] Pipeline and Hazardous Materials Safety Administration (PHMSA) Gas Distribution Incident data from 2004 to 2016 (www.phmsa.dot.gov).