Shifting Paradigms: Can We Learn from Pipeline Releases?

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ROSEN USA

Pipeline Pigging and Integrity Management Conference

February 12-16, 2024

Organized by
Clarion Technical Conferences

https://doi.org/10.52202/072781-0061

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Abstract

Achieving zero incidents has been a key safety objective across the pipeline industry. The relationship between pipeline industry and pipeline regulations has seen several iterations since the first regulations were introduced in 1968. Significant changes and rigorous regulations enacted in 2002 required pipeline operators to create a structured framework for risk and integrity management programs. However, subsequent safety performance has been static, as detailed in the preamble to more recent updates in 2019. Pipeline regulations serve as minimum requirements for achieving operational safety by reducing incidents, and there should be hope of a more substantial impact with the effects of rule changes to both gas and hazardous liquid pipeline regulations in 2019.

Failures of pipelines are often complex, involving primary, secondary and even tertiary contributory factors, while rulemaking must be discrete and realistically achievable for compliance. Thus, failures and rulemaking are not completely associative, but neither are they mutually exclusive. The preamble to the 2019 rules identified clear lineages between a subset of significant events and rulemaking i.e. measures that directly address some of the causes of significant events. Whilst this seems intuitively sensible, where do these solutions lie in the spectrum between causality and mutual exclusivity on a wider scale?

All pipeline failures are undesirable, but each provides an opportunity to learn and highlights systemic vulnerabilities by identifying areas for improvement. This paper explores reported failure data for both gas and liquid transmission pipelines in the U.S. between 2003 and 2022. The paper will identify trends and thus residual gaps in understanding of failures within the industry for proactive measures to prevent future incidents. The complexity of failure will be explored by review of supplementary NTSB investigation reports and commentary on the combination of factors at play. The primary goal of integrity management is to safely operate assets such as pipelines. Inherent is that integrity management cannot be about doing everything possible, rather maximizing everything practicable. This paper hopes to identify what practicable may look like now and in the future.

Introduction

The construction of pipelines is facing growing public opposition, leading to significant delays or the failure to obtain construction permits. The opposition extends to pipelines intended to transport emerging fuels such as hydrogen and carbon dioxide, necessary to meet net-zero emission goals. Indeed, studies have indicated that between 30,000 and 96,000 miles of additional pipelines will be required for carbon dioxide transportation alone[1].

There is general consensus that pipelines provide the safest means of transporting bulk liquid and gas products. This consensus may be at risk given the increased public opposition. In 2015, the Pipeline Safety Trust concluded that “pipelines spill more, both based on sheer volume, and on a per-ton-mile or per-barrel-mile basis”; however, that rail accidents cause more injuries[2]. The Norfolk Southern freight train derailment in East Palestine, Ohio in February 2023 provided a stark reminder of the risk involved[3]. Nonetheless, the pipeline industry must work extensively to regain public trust and secure its future. Figure 1 shows transmission pipeline incidents geospatially since 2014[4].

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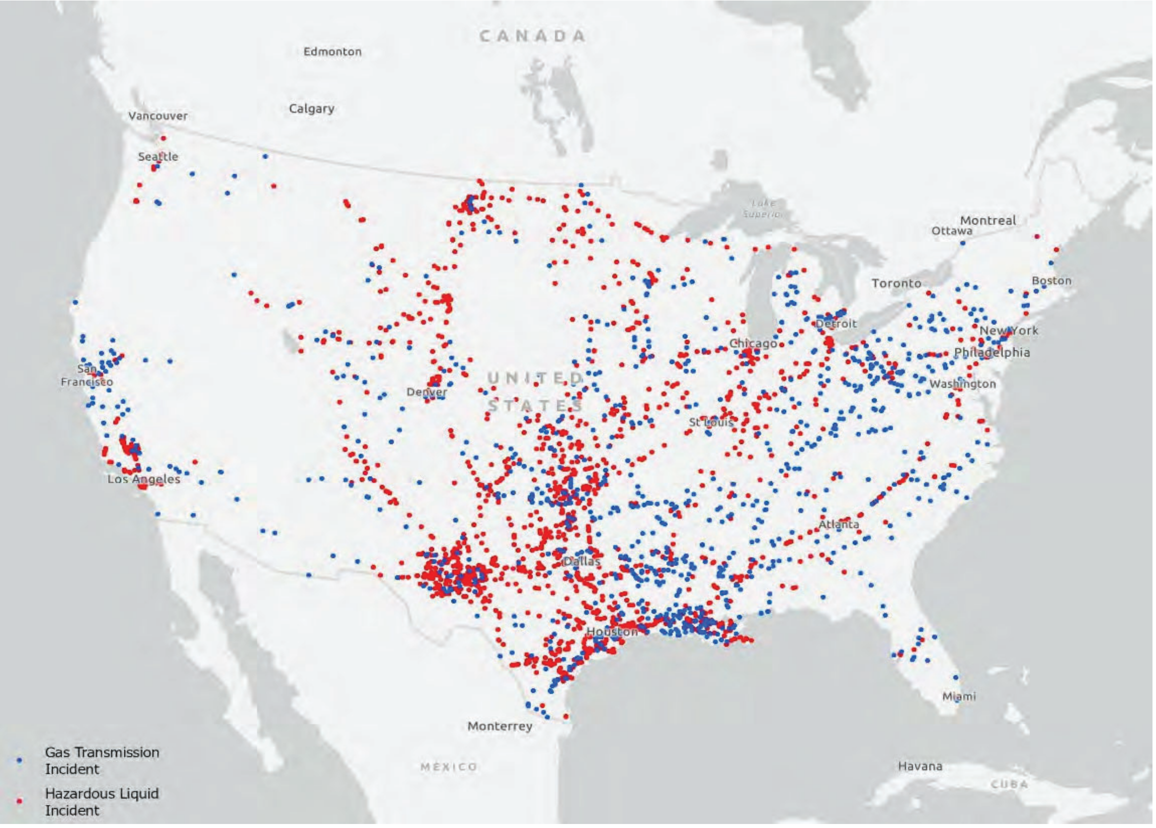

Figure 1. Transmission Pipeline Incidents in the US, 2014 to 2023

Pipeline incidents are predominant in energy-producing states, but almost all states have suffered incidents within the last decade. As will be shown in this paper, some of these incidents are disproportionately larger, and are the ones that attract the most public attention and subsequent concern.

Pipelines have been regulated by the federal government in the US since 1968 under the Natural Gas Pipeline Safety Act. Following several iterations, and in response to significant events in the1990s in Bellingham WA, Edison NJ and just outside Washington DC, and criticism from elected officials, the press and the pubic, major changes were enacted in 2002. These changes introduced integrity management requirements for transmission pipelines within high consequence areas and a series of prescriptive assessment routines. Further significant rule changes[5] were enacted in 2019; indeed, the preamble to the rule changes made direct linkages between significant events and the new rules. The preamble specifically addressed incidents in San Bruno, CA, Sissonville, WV, and Carlsbad, NM, incidents that are now synonymous with the pipeline industry, and the specific rules intended to prevent reoccurrence.

This approach undoubtedly has some merit. Whilst the issues raised and subsequent rules were characterized by the significant events, they addressed widely recognized issues. However, the key difference between a significant event and all other events is not the cause, but the consequence. Thus, there is also merit in looking more holistically at all incidents.

This study examined reported failure data for both gas and liquid transmission pipelines in the US from 2003 onwards. The objective was to identify issues beyond those evident in significant incidents only. The paper draws inspiration from the bi-annual reports issued by The European Gas Incident

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Data Group[6] (EGIG) and Conservation of Clean Air and Water in Europe[7] (CONCAWE) which respectively collate statistics on the performance of European gas and liquid pipelines respectively.

Analysis

The primary data sets analysed for this study originate from public reports submitted to the Pipeline and Hazardous Materials Safety Administration (PHMSA). The data include gas and liquid pipeline mileage inventory[8]and incident records[9].

It is important to note some key aspects of these data:

1. A reported incident means one that meets at least one of the following criteria:
    a. A death, or personal injury necessitating in-patient hospitalization;
    b. Estimated property damage of $129,300 (in 2023 dollars) or more, including loss to the operator and others, or both, but excluding the cost of gas lost;
    c. Unintentional estimated gas loss of three million cubic feet or more.
    d. The property damage threshold for a hazardous liquid pipeline accident is $50,000 (in 1984 dollars) per § 195.50.
    e. Highly volatile liquid releases of 5 barrels or more or other liquid releases of 50 barrels or more
2. Data reporting requirements and formats have changed over time; only data consistent for the period 2003 to 2022 have been considered.
3. Veracity is as reported since no data cleansing has been conducted.
4. Financial reporting is inflation adjusted to 2021.

The data for gas and liquid pipelines will be presented separately hereafter.

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Gas Transmission

In the period, 2003 to 2022, there were a reported average of 302,155 miles of gas transmission miles. Figure 2 displays the primary failure frequency for all causes.

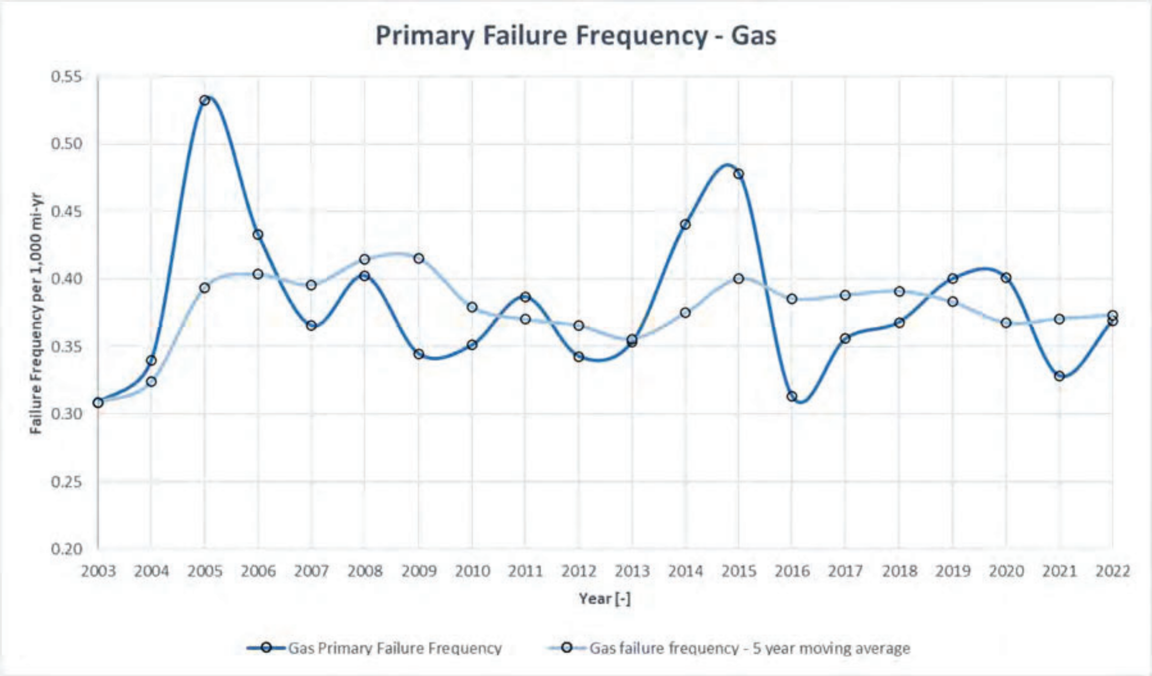

Figure 2. Primary Failure Frequency, Gas Transmission

In 2022, the failure frequency was 0.369 incidents/1000 mile-year, the average of the five preceding years was 0.373 incidents/1000 mile-year. The incident rate in the period 2003 to 2022 is largely static. Figure 3 shows the primary causes of these reported failures.

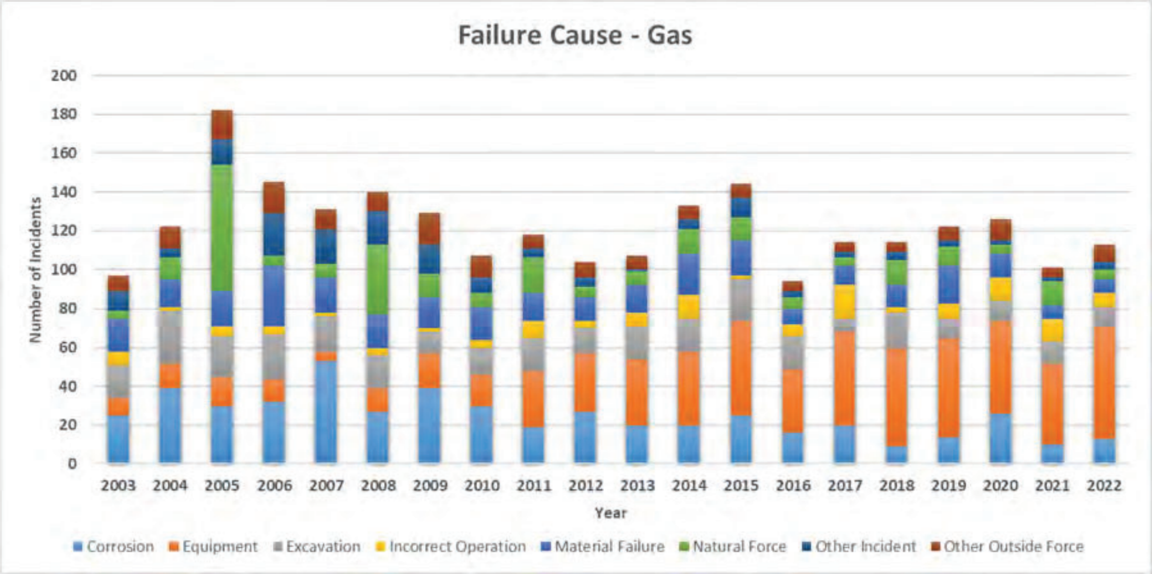

Figure 3. Failure Cause, Gas Transmission

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Evident is the rising trend in incidents where the reported cause is equipment failure. Failures due to incorrect operations also exhibit an upward trend, albeit on a smaller scale. All other causes show a static or falling trend. Of interest is corrosion, which, as a time dependent threat, would be expected to rise in the absence of any other factor. It follows that there has been significant improvement in the way corrosion is managed. The chart also displays a significant number of failures due to natural forces in 2005, coincident with Hurricane Katrina. The trends are displayed for each failure cause as annual and five-year frequencies in the following charts.

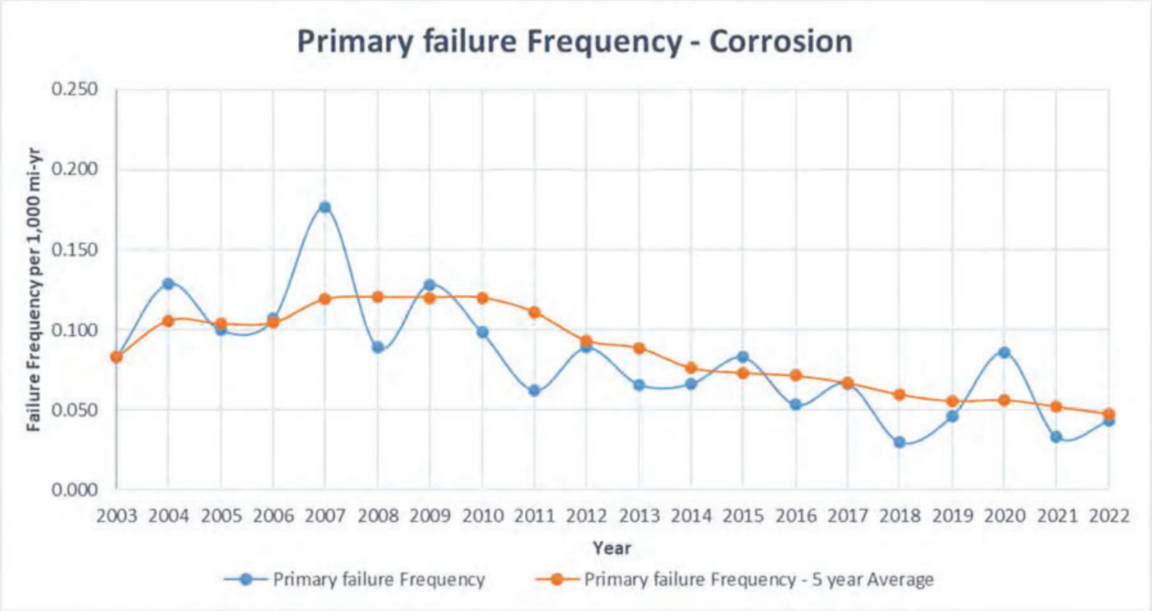

Figure 4. Failure Frequency, Corrosion, Gas Transmission

There has been an approximately 50% reduction in reported failures from corrosion in the period between 2003 and 2022.

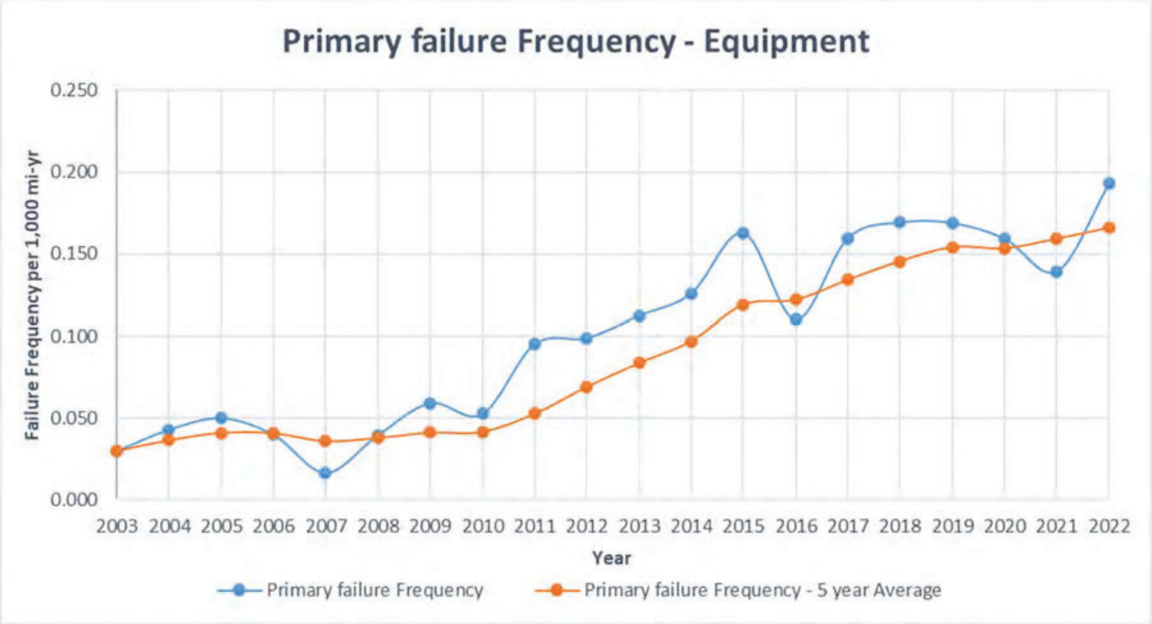

Figure 5. Failure Frequency, Equipment, Gas Transmission

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Equipment failures now represent the most common failure cause, exceeding corrosion in 2014 and continuing to rise.

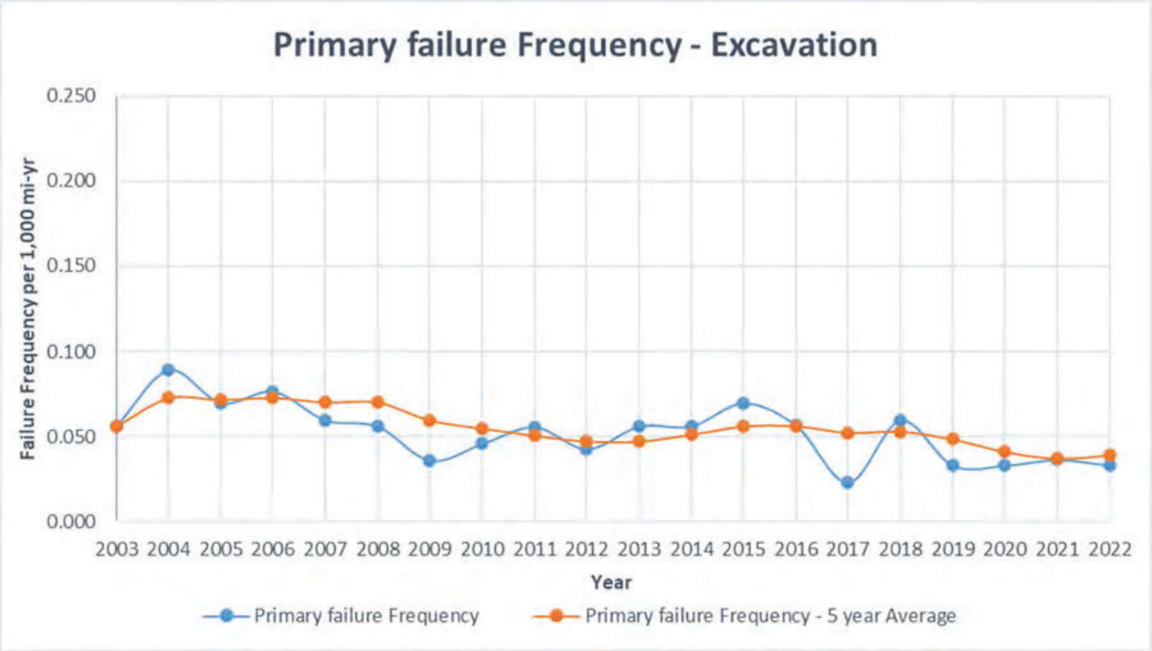

Figure 6. Failure Frequency, Excavation, Gas Transmission

Failures due to excavation also show a nearly 50% reduction in the period between 2003 and 2022.

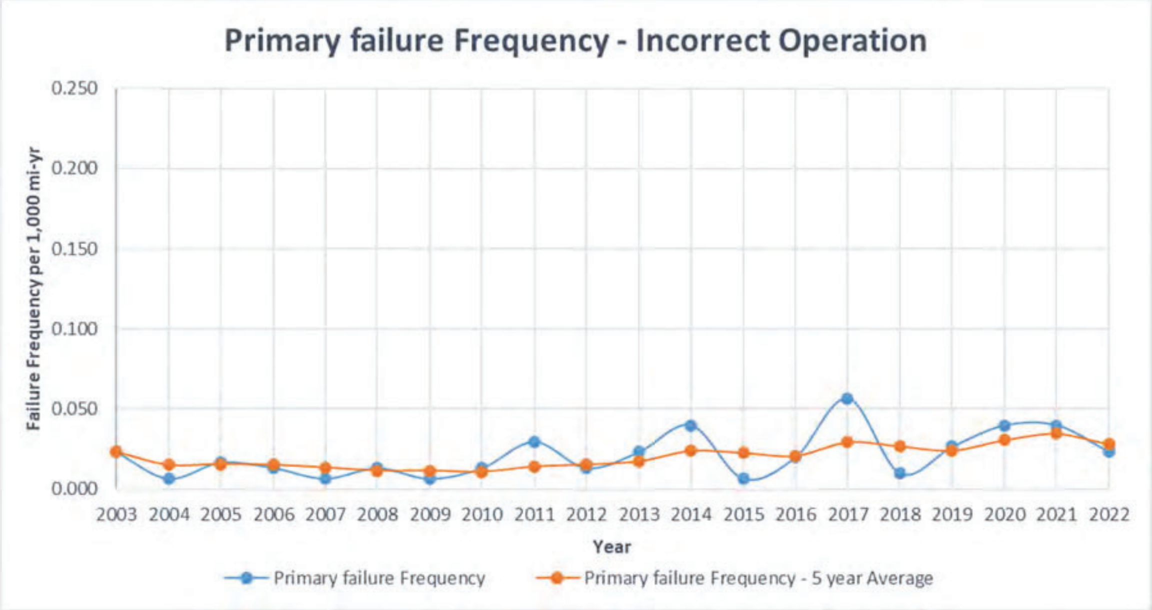

Figure 7. Failure Frequency, Incorrect Operations, Gas Transmission

Reported failures from incorrect operations show a rise of approximately 80% in the period between 2003 and 2022.

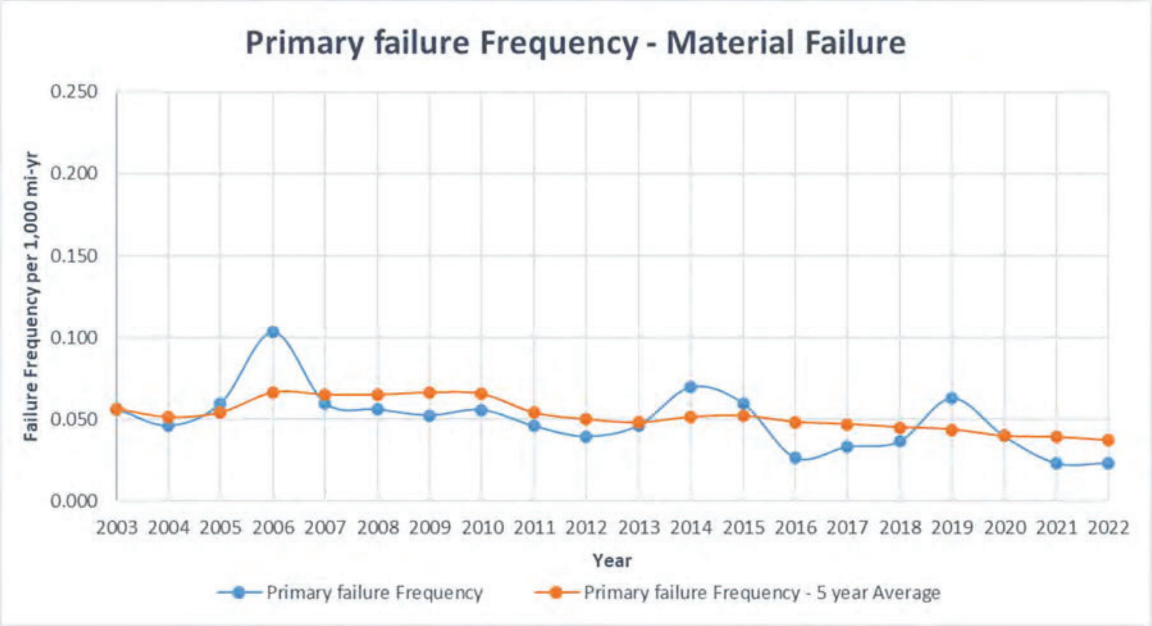

Figure 8. Failure Frequency, Material Failure, Gas Transmission

Material failures spiked in 2006, where there after they have reduced by more than 50%.

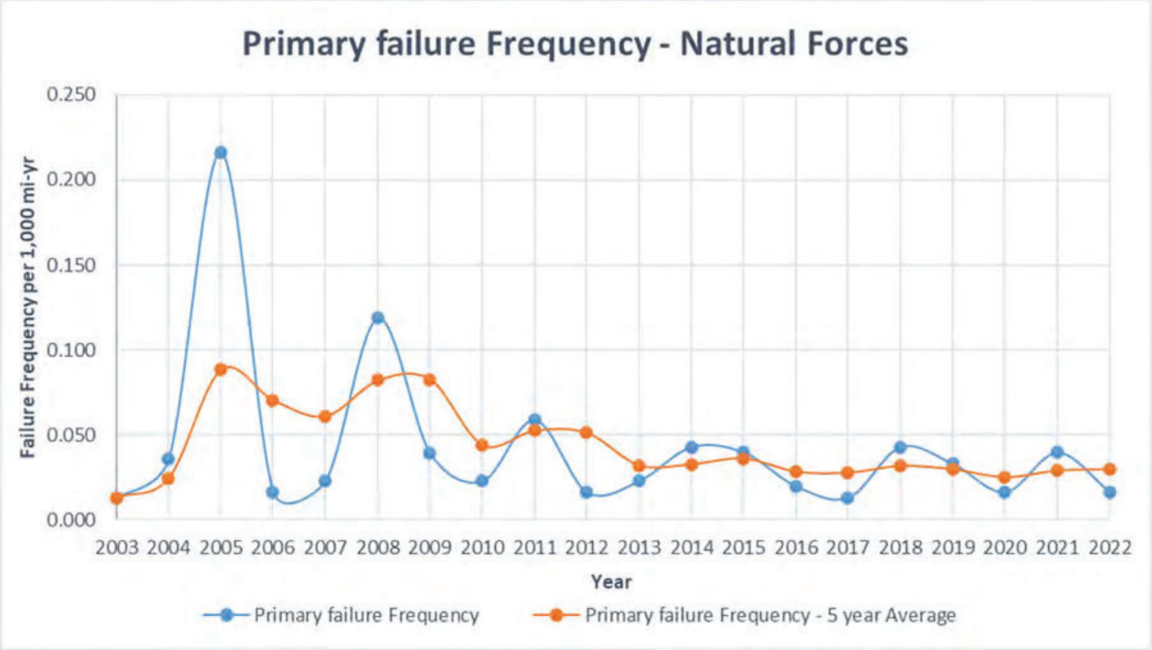

Figure 9. Failure Frequency, Natural Forces, Gas Transmission

Failures due to natural forces show an overall decline, albeit have been static for the most recent decade. There are clear spikes in the number of failures coincident with major hurricanes.

As previously stated, the significance of a failure is determined by its consequences. Certain failure causes lead to more significant failure modes; for example, corrosion tends to leak, while material failures (cracks) tend to rupture. Thus, even if a cause has relatively few failures, it becomes more significant if those failures tend to be more catastrophic. PHMSA failure reports contain a measure of the direct costs of failure, namely property damage. Indirect costs, often more significant than

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direct costs, have not been considered. Direct costs associated with each failure cause are displayed in Figure 10 as five-year averages.

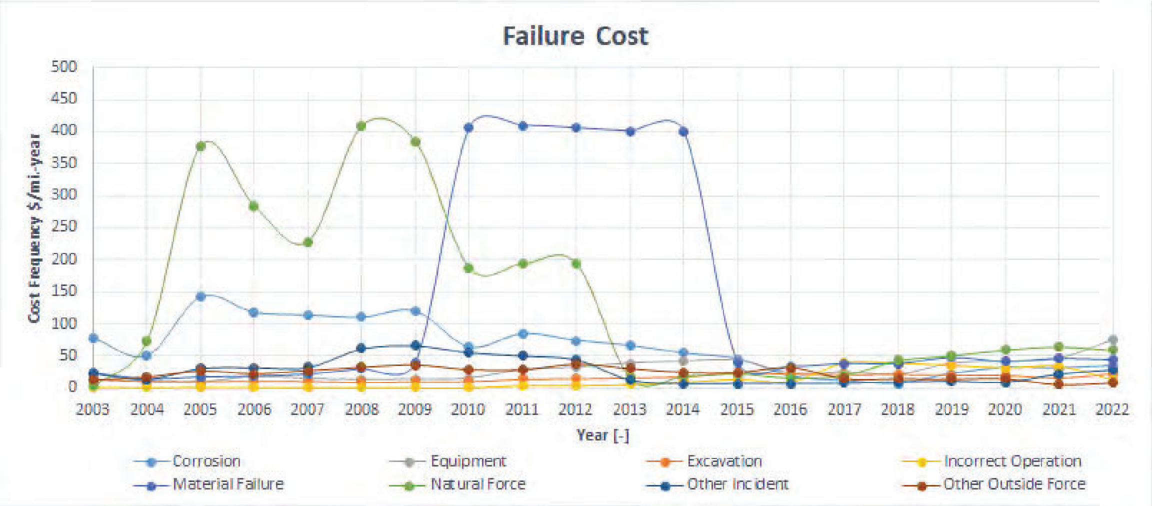

Figure 10. Cost Frequency, Gas Transmission, 5-yearly Average

The chart shows that costs are dominated by few catastrophic events. In 2005, Hurricane Katrina resulted in the failure of many pipelines along the gulf coast and the subsequent costs are evident in the natural force costs. Following that, in 2010 the material failure that resulted in the San Bruno incident became dominant. Significant events in 2005, 2008 and 2010, averaged over the five-year period and hence the delayed effect. There has not been a comparable event since 2010, and thus the costs are so disproportionate that the scale does not reveal the normal difference in the costs per failure cause. Figure 11 displays the data from 2015 to 2022.

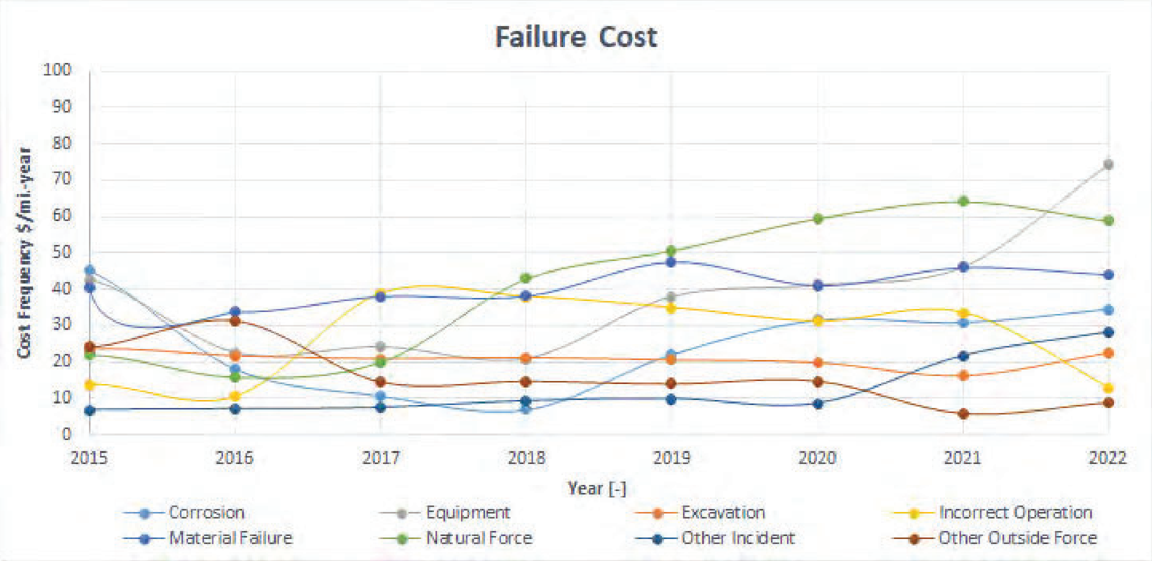

Figure 11. Cost Frequency, Gas Transmission, 5-yearly average, 2015 to 2022

In the absence of a significant incident, the predominant risks vary year to year. Incorrect operations are on a downwards trajectory, while natural forces and equipment are on an upwards trajectory and now predominate; material failures appear to be consistently high and relatively static.

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Liquid Transmission

Mileage inventory for liquid transmission pipelines was not reported prior to 2004, and incident-reporting equivalent to gas was not required prior to 2009; therefore, data are referenced from those periods. From 2004 to 2022, there were a reported average of 196,401 miles of liquid transmission miles. The total reported mileage of liquid transmission pipelines increased from 167,000 miles in 2004 to 227,000 in 2022. Figure 12 displays the primary failure frequency for all causes.

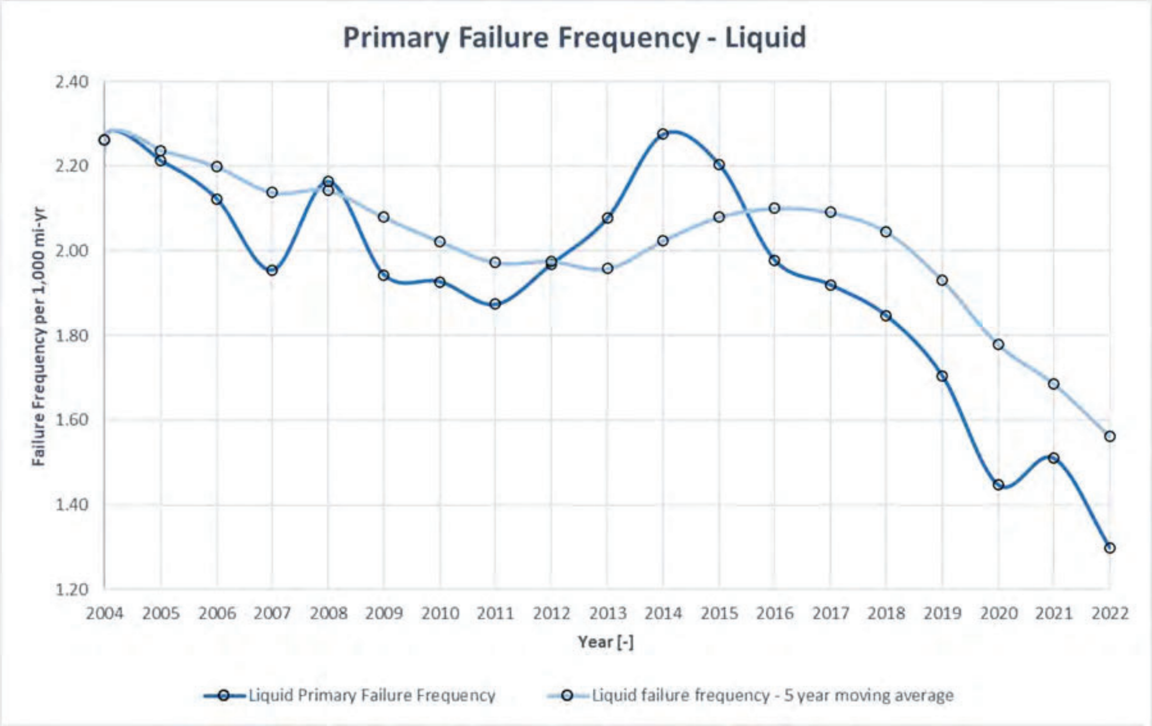

Figure 12. Primary Failure Frequency, Liquid Transmission

In 2022, the failure frequency was 1.30 incidents/1000 mile-year, with an average of 1.56 incidents/1000 mile-year over the five preceding years. The incident rate in the period 2004 to 2022 shows significant decline, albeit from a very high baseline; however, the frequency remains considerably higher than that of gas. Figure 13 displays the primary cause of these reported failures.

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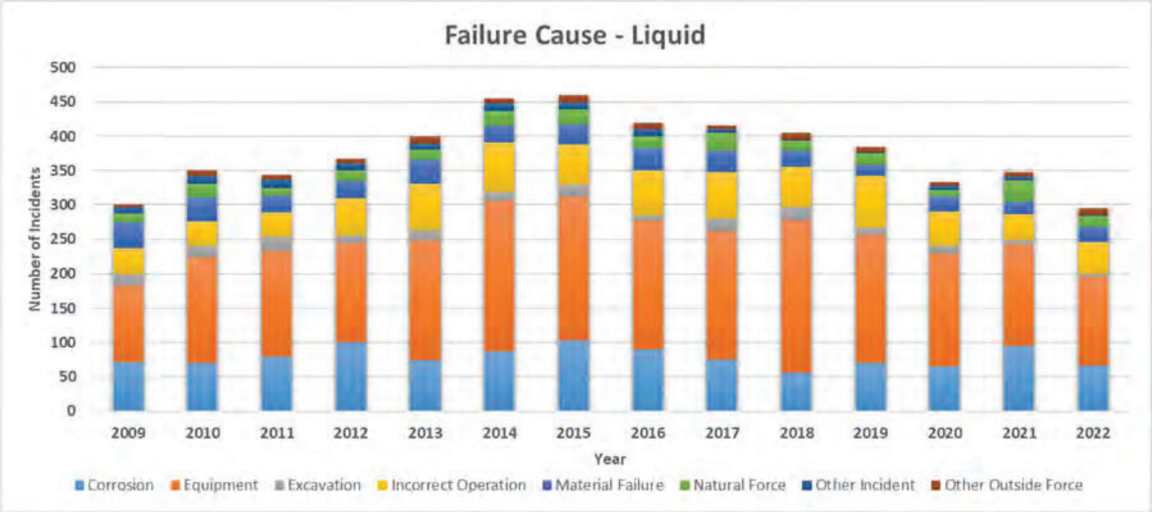

Figure 13. Failure Cause, Liquid Transmission

Evident is the peak of incidents in 2015, where equipment was the predominant failure cause. Since 2015, there has been a steady decline in equipment failures, influencing the overall trend. A similar trend is evident for incorrect operations, albeit from a much lower base. Corrosion and natural force failures appear static, while material failures show steady decline. The trends are displayed for each failure cause as annual and five-year frequencies in the following charts.

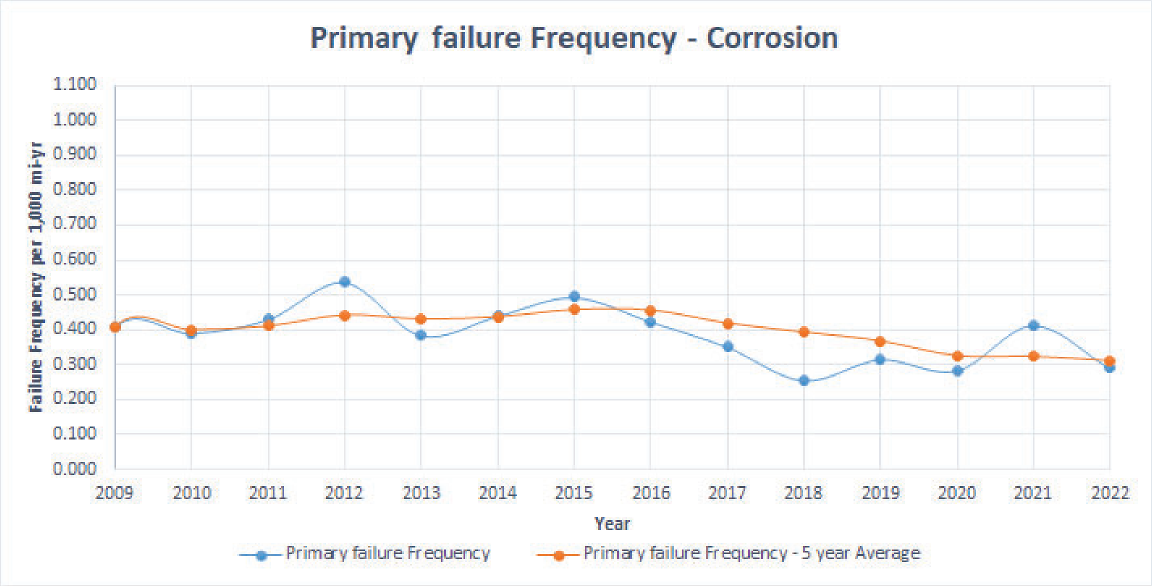

Figure 14. Failure Frequency, Corrosion, Liquid Transmission

There has been an approximate 25% reduction in reported failures from corrosion between 2009 and 2022.

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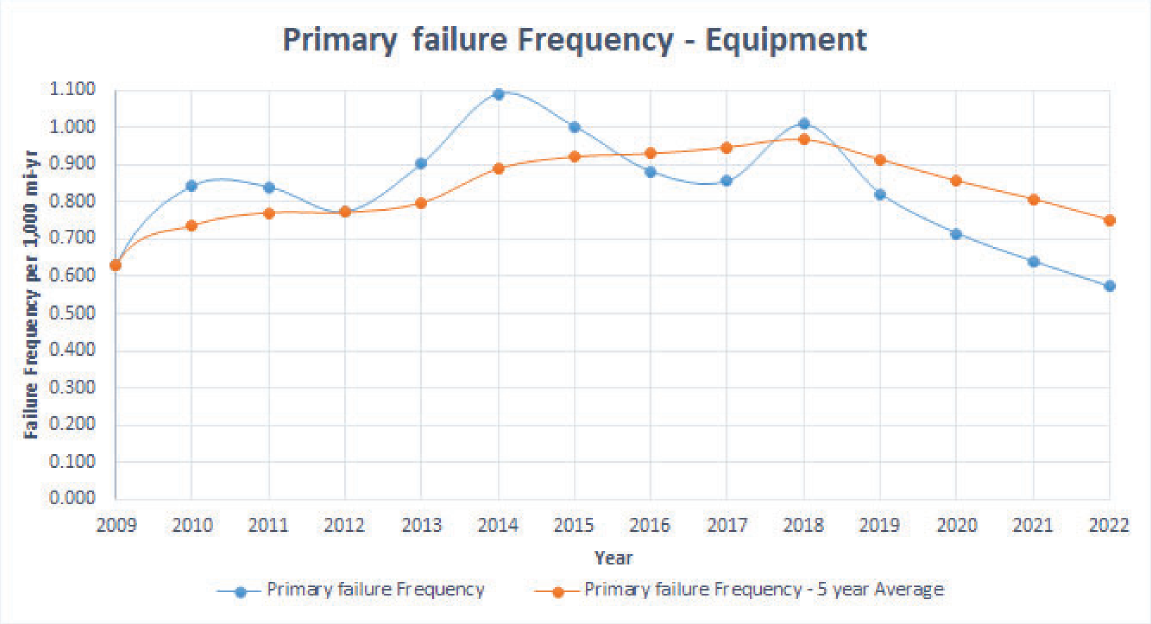

Figure 15. Failure Frequency, Equipment, Liquid Transmission

Equipment failures have seen a dynamic trend where it increased in 2009, peaked in 2014 at 1.1 incidents per 1000 mile-year, and decreased since 2018.

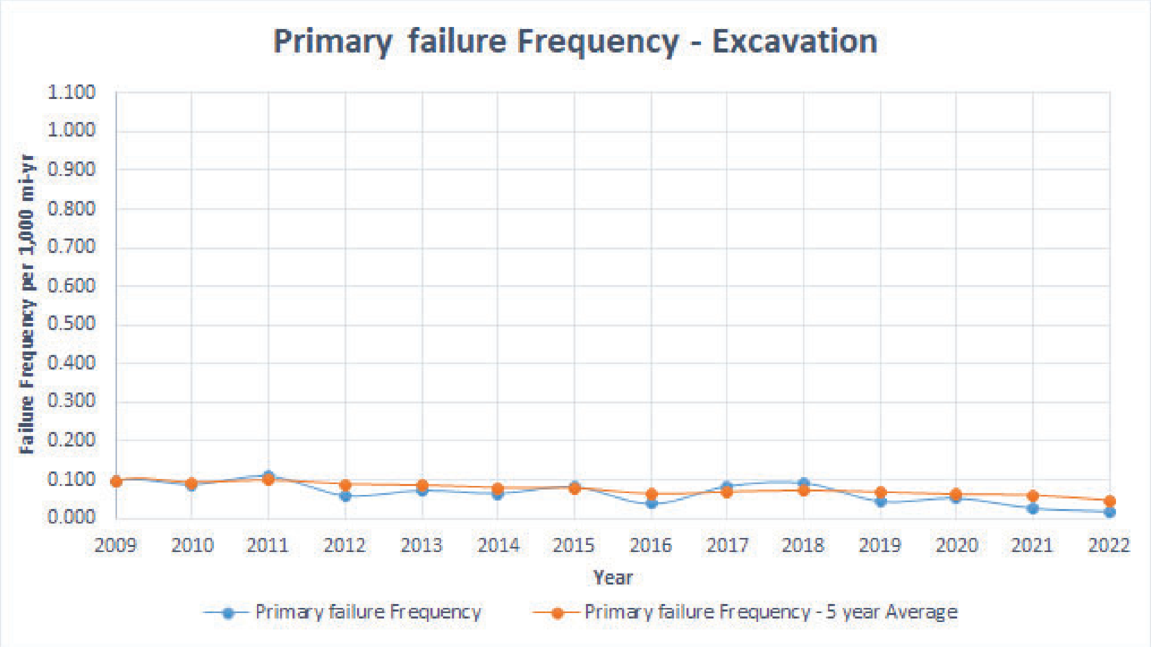

Figure 16. Failure Frequency, Excavation, Liquid Transmission

Like gas pipelines, failures due to excavation show a nearly 50% reduction in the period between 2009 and 2022.

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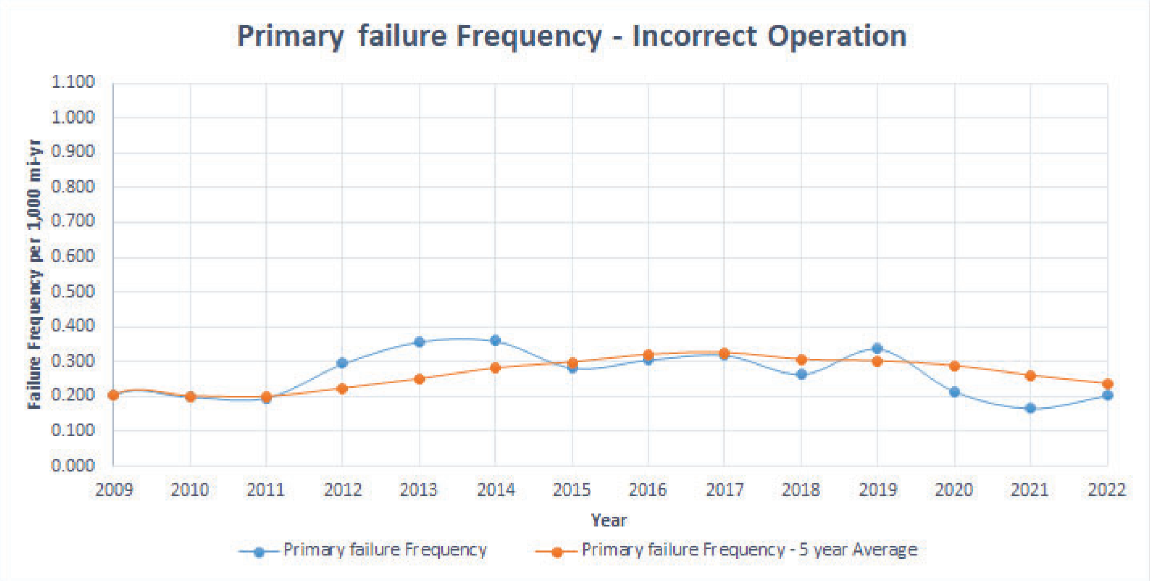

Figure 17. Failure Frequency, Incorrect Operations, Liquid Transmission

Reported failures from incorrect operations show a rising trend of approximately 20% in the period between 2009 and 2022.

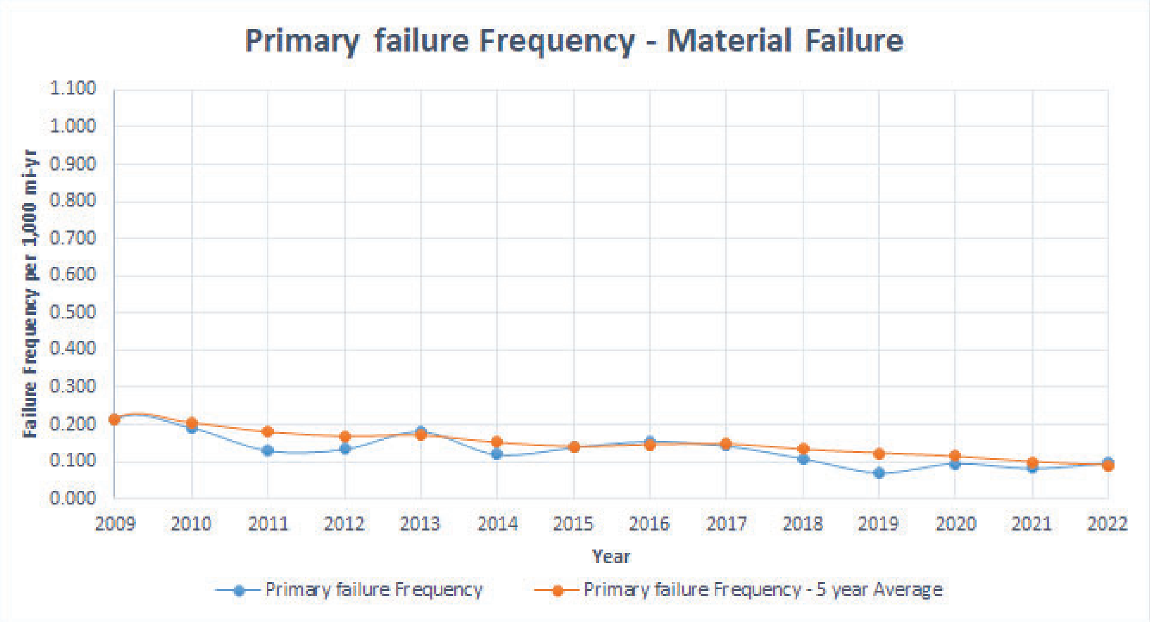

Figure 18. Failure Frequency, Material Failure, Liquid Transmission

Material failures have been on a decline from its peak of 0.2 incidents per 1000 mile-year in 2009. Since 2009, material failures have reduced by more than 50%.

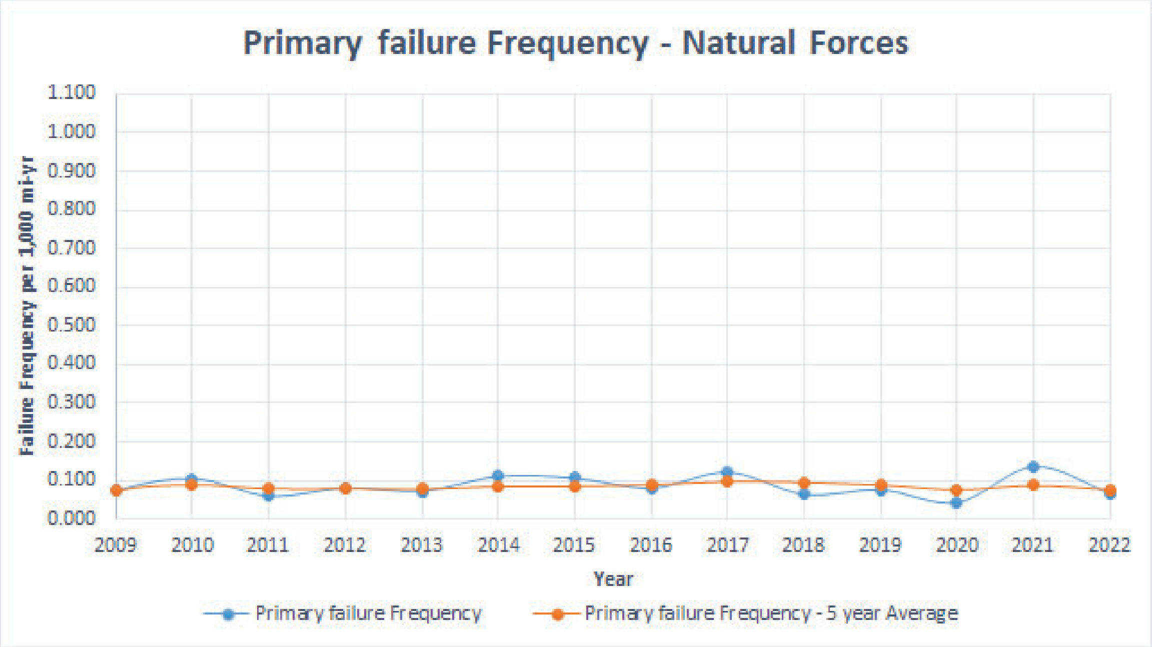

Figure 19. Failure Frequency, Natural Forces, Liquid Transmission

Failures due to natural forces show an overall static trend for the most recent decade. There are clear spikes in the number of failures coincident with major hurricanes.

Direct costs associated with each failure cause are displayed in Figure 20 as five-year averages.

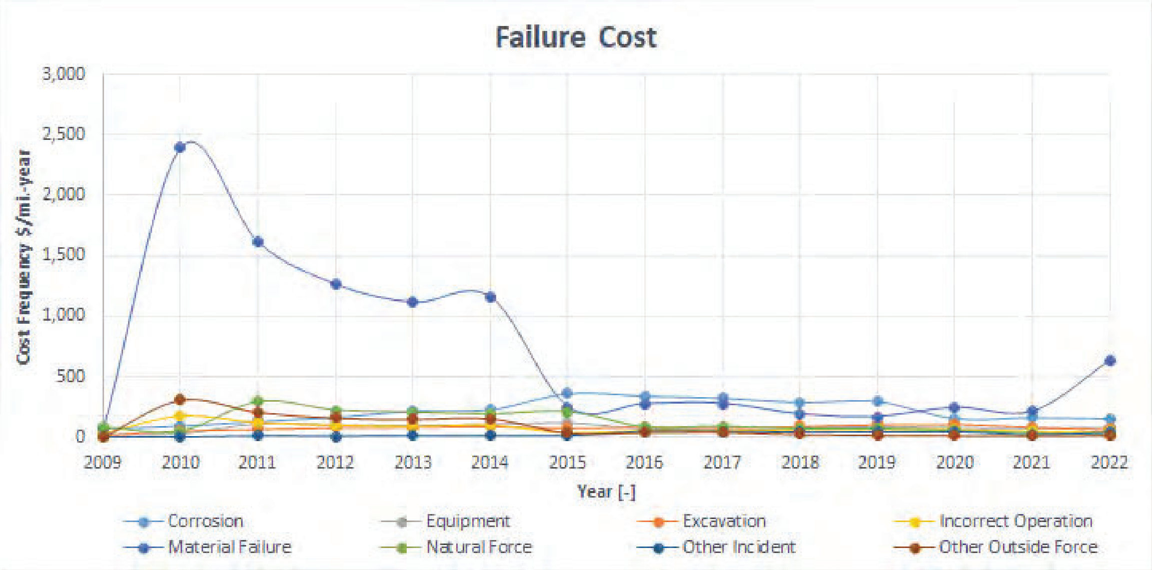

Figure 20. Cost Frequency, Liquid Transmission, 5-yearly Average

It is evident from the chart that costs associated with significant events predominate in some circumstances. The costs associated with material failure that occurred in Marshall, MI in 2010 are significantly higher than all other events. Figure 21 displays the costs from 2015 to 2022.

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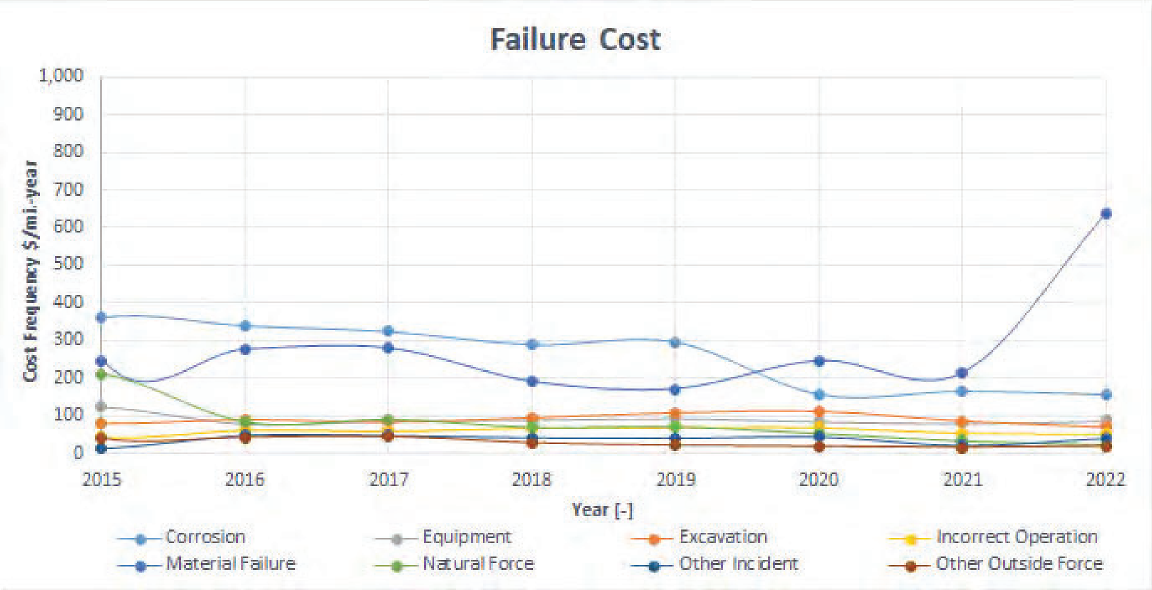

Figure 21. Cost Frequency, Gas Transmission, 5-yearly average, 2015 to 2022

A consistent pattern emerges where the highest costs are associated with failures from corrosion and materials. Corrosion costs were higher until 2020, and have been decreasing, while costs associated with materials failure remained relatively static. The significant increase in 2022 in costs associated with materials failures can be attributed to incidents in Washington County, KS, and Cushing, OK. Costs associated with all other failure causes appear much lower and relatively static.

Causes of Failure

Failure reports contain a narrative section where operators describe the incident. These reports are usually submitted within 30 days of the incident and may only contain the preliminary account of the events, and not the actual account of the root cause. These descriptions were mined to identify and count common causal words associated with the threat. The causal words were identified manually. While it is acknowledged that individual words were counted, and without context may be misleading in some cases; nonetheless, the objective was to identify potentially common themes. These data are presented as word clouds, where the larger the word, the more common its appearance in the narrative descriptions of the events. In addition, different versions of the same word were collected e.g. crack, cracking, cracks, and cracked were all assumed the same.

Corrosion

The word cloud of causal words associated with corrosion failures is presented in Figure 22.

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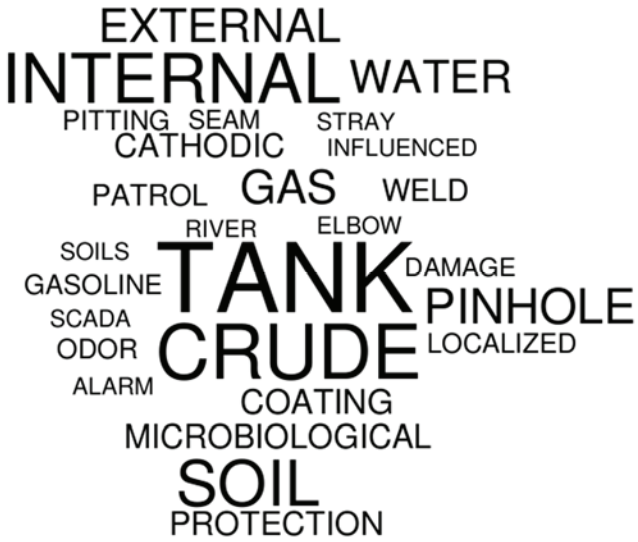

Figure 22. Corrosion Word Cloud

The word internal appeared 619 times compared to 332 times for external, indicating most failures are internal corrosion. Furthermore, the word crude appeared 695 times compared to gas 321 times and gasoline 68 times showing that the internal product influences greatly as might be expected. When describing corrosion morphology, the word pinhole appears 356 times compared to pitting 83 times indicating most failures are small leaks; this is supported by the word patrol appearing 95 times compared to SCADA 37 times and alarm 33 times. The words cathodic protection appear 138 times alongside the word coating which appears 159 times indicating that most external failures are due to localized coating failures and failure of the cathodic protections system to adequately protect the pipeline. Nonetheless, the words microbiological (129), stray (35), and seam (50) appear often enough to suggest additional factors in many cases.

Equipment

The word cloud of causal words associated with equipment failures is presented below in Figure 23.

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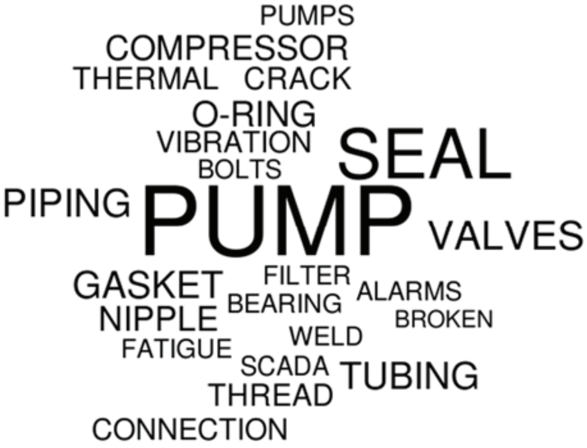

Figure 23. Equipment Word Cloud

The most common words in the cloud relate to the types of equipment that fail, these into two broad categories: rotating machinery and static equipment. The words pump (2780), compressor (470), filter (146), and bearing (125) representing rotating machinery; and, valve (690), piping (614), tubing (578), thread (344) representing fixed equipment. The words seal (1785), gasket (565), and o-ring (498) are the joints within this equipment. In terms of failure cause, the words thermal (338), vibration (279), and fatigue (121) are most common, resulting in the word crack appearing 316 times. The prevalence of issues around seals and gaskets indicates an issue with maintenance i.e. many of these issues would have or could have been identified during scheduled maintenance prior to the failure. Either maintenance inspections are not carried out, or not carried out with sufficient frequency to identify degradation prior to failure.

Excavation

The word cloud of causal words associated with excavation failures is presented below in Figure 24.

Figure 24. Excavation Word Cloud

As might be expected, the predominant word is excavation featuring 396 times. To protect pipelines from third parties, they are buried and marked, with one-call systems in place; cover is mentioned only 24 times, marked mentioned 66 times and one-call mentioned 67 times. This would suggest that in the majority of incidents where an excavator damaged a pipeline: there was no one-call ticket

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generated; that a loss cover was not a factor in incidents; and, that the pipeline was not marked at the location.

Incorrect Operations

The word cloud of causal words associated with incorrect operations failures is presented below in Figure 25.

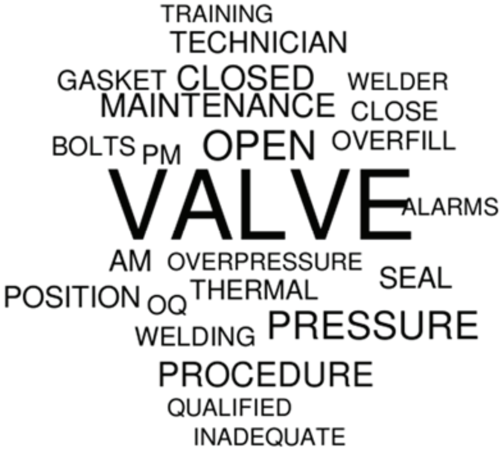

Figure 25. Incorrect Operations Word Cloud

The word valve features 2259 times and whilst it would be expected that many incorrect operations involved valves, the narrative also contains actions upon discovery of a failure and so many instances will be due to that. The words open and close appear 536 times and 448 times respectively, indicating no significant difference in the actions that led to the incident. Pressure is a significant factor appearing 451 times, though specifically over-pressure features only 43 times. Like equipment failures, the words seal and gasket have high prominence appearing 159 and 137 times respectively. Human factors are typically expected to be a significant factor in incorrect operations with words such as procedure (333), maintenance (291), technician (170), welder (123), and, Operator Qualification (OQ) (60) and qualified (40) featuring prominently. Interestingly, the word supervise appears only 66 times and the words competence or competent do not appear in the narrative records.

Materials

The word cloud of causal words associated with materials failures is presented below in Figure 26.

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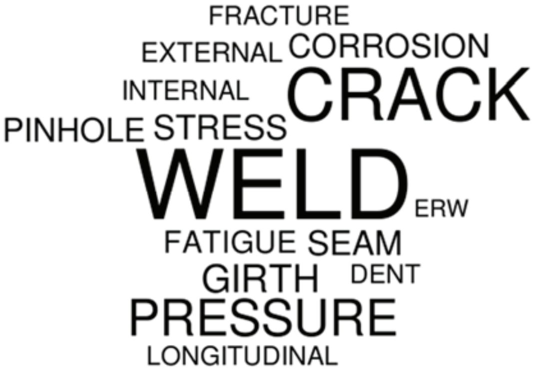

Figure 26. Materials Word Cloud

The most prominent word is weld, featuring 765 times, the longitudinal weld is mentioned 195 times and the girth weld 185 times. Pressure and stress are mentioned 299 times and 136 times respectively. Materials failures most often manifest as cracks, with cracks mentioned 505 times. Whilst fatigue, mentioned 102 times, is an issue, it seems there are often additional factors with corrosion mentioned 119 times, pinholes mentioned 114 times and dents mentioned 47 times.

Natural Forces

The word cloud of causal words associated with natural forces failures is presented below in Figure 27.

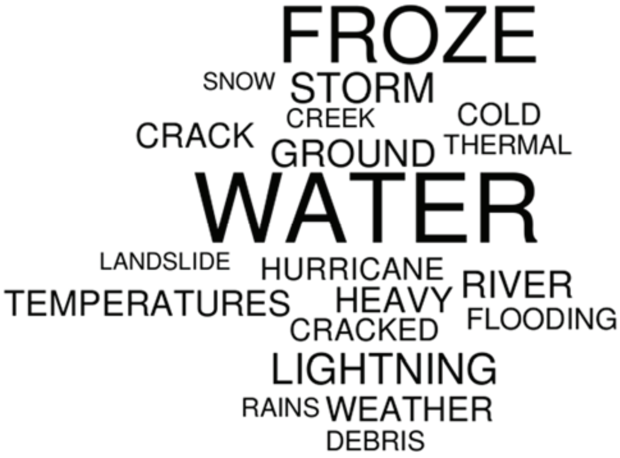

Figure 27. Natural Forces Word Cloud

The word count identify clearly the two main threats from natural forces: hydrotechnical threats and cold weather. Water is the most common word, mentioned 248 times; but, associated words such as storm (65), river (55), weather (44), hurricane (36), flooding (27), creek (21), and rains (20) all feature prominently. In terms of cold weather, there are several common words such as ice, freeze, froze which combined are mentioned 188 times. This is in addition to the words temperature and thermal that combined feature 71 times. Interestingly, the word landslide features only 14 times.

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Combined Threats

Data presented thus far has identified failures attributed to the primary cause only. In general, failures and failure mechanisms are much more complex, often representing a confluence of events. To explore this further, a sample of National Transportation Safety Board (NTSB) reports[10] pertaining to transmission pipelines was reviewed. Table 1 lists the probable primary and contributory causes listed in the reports. Several of the reports provide significant detail on the root cause, identifying physical mechanism such as coating breakdown, integrity management failings such as risk assessment, and human errors such as failure to adhere to a procedure. However, these additional factors have not been listed.

Table 1. NTSB Investigation Reports, Probable Causes

NTSB Report Number	Primary Cause	Contributory Cause(s)
PIR-23-01	Stress Corrosion Cracking	
PIR-22-01	Landslide	Materials
PIR-22-02	Hydrogen Induced Cracking	Hard Spot
PIR-22-03	Equipment	Incorrect Operations
PAB-20-01	Corrosion fatigue	Bending and Cyclic Stress
PAB-19-04	Excavation Damage	
PAB-18-01	Fatigue	Damage
PAB-17-01	Corrosion Fatigue	Dent
PAR-14-01	External Corrosion	
PAB-13-01	Stress Corrosion Cracking	
PAB-13-02	Excavation Damage	
PAB-13-03	Erosion	3rd Party Damage
PAR-12-01	Corrosion Fatigue	
PAR-11-01	Materials	Incorrect Operations
PAR-09-01	Materials	
PAB-07-02	Fatigue	Damage
PAR-04-01	Fatigue	Materials
PAR-03-01	Internal Corrosion	
PAR-02-02	Fatigue	Damage

Of the nineteen reports reviewed, more than half (11) listed a primary and specific contributory cause:

- In PIR-22-01 whilst the primary cause was an active landslide, the failure occurred at a girth weld containing lack of penetration anomalies, and thus a reduced strain capacity.
- The fatigue failures in PAB-18-01 and PAB-07-02 resulted from 3rd party damage, and thus were latent failures.
- In PAB-20-01, corrosion fatigue was intensified by both bending stress from external loading and cyclic stress from internal pressure.

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Combined loadings and coincident anomalies have long been recognized as problematic issues. The PHMSA Risk Modeling Work Group identified 98 'reasonably possible' threat interactions in their 2020 report[11]. Whilst it is inarguable that these threat interactions are reasonably possible, the residual question is whether it is reasonably practical to consider all of these possible interactions with the current mix of inspection technologies, assessment methods, and knowledge of materials and loading conditions.

Shifting Paradigms

The pipeline industry faces countless pressures from the public, from regulatory authorities, and from alternative transportation methods such as rail. To secure the future, the pipeline industry needs to reduce failures significantly. Regulatory changes to both gas and liquid pipelines were enacted in 2019, and the results of these changes are unlikely to be reflected in failure data this soon. Irrespective, there is clearly further work to be done. The following commentary summarizes the data presented in this study and suggests possible pathways for improvement.

There is a clear need to reduce failure frequency, in both gas and liquid transmission pipelines. For gas pipelines equipment failures represent the highest failure frequency, and in the absence of a catastrophic event like San Bruno, the highest expenditure on direct costs. For liquid transmission pipelines, equipment failures represented the highest failure frequency, but not the highest overall direct costs. The word cloud for equipment identified that failures are not isolated to a particular subset of equipment with pipework, valves, pumps, compressors, and threaded joints all featuring heavily. Furthermore, serviceable parts of the equipment are often involved with seals, gaskets, and bearings featuring heavily. Federal regulations, including the updated rules, have few rules governing pipeline related equipment. Application of regulations within pipeline related facilities remains somewhat unclear and a source of some debate. Integrity management of pipeline related facilities received attention via the release of API RP 1188 in 2022[12]. There is a clear need for wider adoption of this recommended practice, including a greater emphasis on inspection and maintenance schedules.

Material failures typical manifest as cracks and crack-like defects in the pipe body and welds. There is a long and storied history of low-frequency electrical resistance welded seams being susceptible to such defects. Recent changes to regulations required a confirmation of material properties, reconfirmation of the maximum allowable operating pressure, and new requirements for assessment methods, all specifically directed at these types of defects. There are a number of additional considerations and residual gaps. Whilst inline inspection tools for cracks continue to evolve and improve, there is a clear need for increased confidence and accuracy. At the time of writing, several ongoing research projects with industry organizations such as Pipeline Research Council International (PRCI) and the Interstate Natural Gas Association of America (INGAA) are focused on tool capability. Simultaneously, there are a number of other residual gaps in the assessment of cracks and crack-like anomalies: uncertainty around the effects of additional axial and flexural loadings, residual stresses, and accurate materials data, all combine to make assessment methods highly conservative, creating an aversion in some cases. A holistic understanding of all these aspects will be necessary to improve the situation.

The rates of corrosion failures were reducing in both liquid and gas pipelines, representing significant progress. Regulatory changes for gas pipelines introduced scheduled response criteria for anomalies outside of high consequence areas aimed at reducing these numbers further. Residual issues appear

https://doi.org/10.52202/072781-0061

to predominate in pipelines transporting crude oil, with water entering the pipeline systems from storage. Further separation of semi-refined fluids or the use of corrosion inhibitors should be considered to address this issue. The prevalence of small, isolated anomalies and defects such as pinholes also appeared to be a residual issue. Pinholes are challenging to reliably detect, identify and size for typical high-resolution inline inspection tools; whereas the new generation of ultra-high resolution tools are capable. The updated gas rule incorporated API STD 1163[13] by reference, as it had already been incorporated in the liquid rule. Greater adherence and consideration of tool selection, along with the requirements of NACE/AMPP SP 0102[14] for pipelines with challenging corrosion morphologies, are likely to improve outcomes.

Rates of failure associated with incorrect operations were increasing for gas pipelines and decreasing, at least in recent years, for liquid pipelines. The word cloud indicated heavy reliance upon procedures and qualifications of personnel. 29 CFR 1926.32 provides definition of the difference between qualified and competent: a qualified person can successfully resolve issue relating to the subject matter; whereas a competent person is capable of identifying existing and predictable hazards and has authorization to take prompt corrective measures. Competency models are envisaged by safety management systems, and pipeline specific safety management systems have been developed in API RP 1173[15] and EN 16348[16]. The potential benefits of safety management systems go significantly beyond incorrect operations, but do have a direct impact, not least in developing an appropriate organizational safety culture.

Whilst there has been significant reductions (approximately 50%) in the number of failures due to excavation damage during the review period, rates remain significant. In addition, the nature of the failure mode means there are often people in the immediate vicinity to the pipeline when it fails. There are specific regulations that address the risk of excavation damage, and the reduction in the review period indicates some effectiveness. The word cloud identified some inferential issues regarding one-call tickets and marker posts, but it appears that residual issue lie predominately outside the immediate control of operators. Further legislative or increased enforcement action to regulate third parties breaking ground appear to remain necessary.

Failure due to natural forces have reduced for both liquid and gas pipelines, albeit only slightly for liquid pipelines. Given the association with weather, and the increased frequency of extreme weather events this outcome was not expected. The updated gas and liquid regulations both included specific to rules to address response to extreme weather events, which given the aftermath of hurricane Katrina in 2005 appears appropriate. The review period has encompassed a period where inertial measurement units and advanced surveys such as LiDAR have found widespread use, albeit still not ubiquitous. These technologies now provide a comprehensive system to monitor most geotechnical and hydrotechnical hazards. There are also technologies that monitor weather and precipitation levels to allow appropriate responses to increased threats during extreme weather events.

All of the aforementioned suggestions have direct and indirect effects, so whilst they are intended to address specific threats, they indirectly influence others. The residual issues is interacting threats. Predictive data analytics and greater abilities to process very large datasets are likely to contribute greatly to the ability to identify and assess coincident and interacting defects, plus loading conditions. This approach needs to be coupled with the development of appropriate methods to enable routine assessments rather than specialist assessments using advanced fracture mechanics or finite element analyses.

https://doi.org/10.52202/072781-0061

Achieving a significant reduction in the number of failures requires substantial changes to the established patterns and practices of the industry — a paradigm shift.

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