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COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

October 5, 2018

RE: Flowline Risk Review – Final Report

To: Mark Schlagenhauf and Stuart Ellsworth

Please find attached the Final Report, incorporating the Executive Summary, Background, General Project Overview, Research Methodology, Findings, Summary of Risk Factors, Conclusions, References and other resources.

Best Regards,

Dr. William Fleckenstein

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Commissioned by the Colorado Oil and Gas Conservation Commission

Flowline Risk Review

October 2018

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Colorado School of Mines

Final Report

EXECUTIVE SUMMARY

The Colorado School of Mines searched for and evaluated published documents, articles and existing risk ranking methods at the request of the Colorado Oil and Gas Conservation Commission (COGCC). The COGCC currently uses a qualitative model using a geographic information system (GIS) that calculates the total risk factor (RF) score for every well, including associated facilities. Our finding is that a risk model *currently does not exist* which is suitable that improves the existing COGCC model to define a method to prioritize the regulatory requirements to perform instrument-based monitoring of upstream oil and gas off-location flowlines, crude oil transfer lines and produced water transfer lines. It is also our finding that the standard risk model used by most state regulatory agencies and operators is based on a similar qualitative approach. We have considered government-based survey responses and academic models from an extensive literature search. Four Colorado operators participated in interviews specific to flowline models to understand industry models. Operators do implement regulatory requirements with API and other industry standards applicable to flowline design.

Although many regulatory agencies in the US and abroad require some form of risk assessment to be performed for new and existing hazardous facilities and/or operations to assure public safety, there appears to be no comprehensive risk assessment model for flowlines. This was confirmed by the Colorado Petroleum Council -- A Division of the API who communicated that "I am not aware of risk models that have been developed for flowlines." A similar investigation (Rose and Flamberg, 2016) for pipelines was carried out by Kiefner and Associates in 2016 and shared with us through the API had similar conclusions.

There are three pipeline risk assessment models in use: (a) qualitative, (b) quantitative, and (c) scenario-based. Due to their flexibility and simplicity, the use of qualitative models is widespread for flowlines. Qualitative models have the inherent weakness of being subjective in nature, based on perceived experience outcomes and not rigorous statistical analysis. Quantitative models attempt to estimate the probabilities and consequences of specific events but require a rigorous mathematical analysis of statistically significant data sets to provide an accurate model. We are not aware of a quantitative risk model in use for modeling flowline risks, due to difficulties in acquiring the data sets necessary for analysis. Failure to find an appropriate risk model for the COGCC's needs, would suggest the need for further work to provide a more robust risk model, the scope of which has to be determined based on the results of this study.

CSM has identified the following options to address the limitations of the current model:

1. Explore joining the DOE NETL effort to quantify risk in Colorado and work with the DOE to expand the scope and funding to quantify additional risk factors to improve the existing qualitative model risk factors.

2. Obtain and analyze data sets, such as for the publicized line cuts referenced in this report, to determine risk factors to guide regulatory action on setbacks from flowlines. This may be done as part of the DOE NETL effort, or as a standalone effort, focused on Colorado. At a minimum, preparing the dataset focused on Colorado will allow analytic efforts to aid the COGCC.

3. Improve the existing model using machine learning or "reverse engineering" techniques that have been successfully applied to predict pipeline failures and could be applied to flowline risk models as well. In addition, the analytic hierarchy process (AHP) is a powerful algorithm for quantifying expert opinions for making decisions, which may also improve the existing model. Moreover, the input parameters are being grouped in categories, with a subjective way of deciding the different categories. Treating the inputs as continuous variables instead of subjectively defined categories might lead to some improvement.

4. Work with the API to establish a working group of other state and industry stakeholders focused on best practices for flowline risk management. Current API recommended practices are focused on other portions of oil and gas production, such as pipelines or drilling and production operations at well sites, but do not exist for flowlines themselves between well sites and production facilities. This is increasingly critical as oil and gas development encroaches on existing developed areas, or development encroaches on existing or legacy oil and gas developments.

5. Additional feedback from members of the industry could help produce a more robust list of risk factors. Information, such as why their pipelines have failed, locations, and specific conditions to the failure in the pipeline or surrounding area, either during pressure testing or in-service failure, could be useful in generating a risk assessment model.

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BACKGROUND

The Colorado Oil and Gas Conservation Commission (COGCC), henceforth referred to as the Commission, desired to understand if a risk model can be applied toward upstream systems. The focus is placed on lines that extend off the oil and gas location, typically referred to as flowlines. The Commission has defined these lines as Off-Location Flowlines, Crude Oil Transfer Lines and Produced Water Transfer Lines. The application of a risk model approach towards upstream systems has not been typically performed, which may be in part due to the general perception that upstream lines are of low risk. With the recent growth of onshore development, there have has been a greater emphasis to transport liquid fluids by pipelines, in order to transporting the liquids efficiently and safely with reduced truck traffic. In part, this change is due to onshore development occurring in closer proximity to population.

The Commission asked Colorado School of Mines, henceforth referred to as CSM, to locate, characterize and summarize relevant published risk models for application towards upstream systems. The intent of this review is to provide a background and understanding for potential application of a risk model to prioritize integrity monitoring of aboveground and belowground gas, condensate, oil and produced water lines.

GENERAL PROJECT OVERVIEW

The Commission has asked CSM to search for and then summarize published documents, articles and existing risk ranking methods to define a method to prioritize the regulatory requirements to perform instrument-based monitoring of upstream oil and gas off-location flowlines, crude oil transfer lines and produced water transfer lines.

This project will help the Commission to understand if a risk model can be applied toward upstream pipeline systems located in the State of Colorado. The focus would be placed on lines that extend off the oil and gas location. The Commission has defined these lines as Off-Location Flowlines, Upstream Pipelines, Crude Oil Transfer Lines and Produced Water Transfer Lines. The application of a risk model approach towards upstream systems has not been typically performed, which may be in part due to the general perception that upstream lines are of low risk. With the recent growth of onshore development, there has been a greater emphasis to transport liquid fluids by pipelines for transporting the liquids efficiently and safely with reduced truck traffic.

CSM is tasked to locate, characterize and summarize relevant published risk models for application towards upstream systems. The intent of this review is to provide a background and understanding for potential application of a risk model to prioritize integrity monitoring of aboveground and belowground gas, condensate, oil and produced water lines.

CSM's research team comprised of faculty members Dr. William Fleckenstein from the Petroleum Engineering Department, Dr. Willy Hereman and Dr. Soutir Bandyopadhyay both from the Department of Applied Mathematics and Statistics. The faculty members were assisted by undergraduate students Cooper Brown, Marcus Merritt, and Anna Thomas.

RESEARCH METHODOLOGY

INTERNET SEARCHES

The research team at CSM performed thorough internet searches for source materials in academia, government agencies, and industry; both nationally and internationally.

SURVEYS

With the help of members of Commission staff, the research team also conducted a survey of the member states of the Interstate Oil and Gas Compact Commission (IOGCC) and members of the American Petroleum Institute (API).

Agency contacts

1. Gerry Baker – Associate Executive Director of the IOGCC
    a. Oil and Gas Conservation Commissions
    b. Environmental Agencies
    c. Divisions of Oil and Gas
    d. Water Control Divisions
    e. Departments of Public Health

Statement that accompanied the survey

> The Colorado School of Mines is conducting a research study of existing rules and regulations for flowlines (upstream pipelines) and related risk assessment models. This study is being done under contract with the Colorado Oil and Gas Conservation Commission (COGCC), which is establishing a stakeholder work group to examine current and developing instrument-based inspection technologies and processes for preventing and detecting leaks and spills from flowlines, in a continuing effort to eliminate risks from flowlines and upstream pipelines.
>
> We would greatly appreciate your help with the study. Please complete the brief questionnaire no later than August 1, 2018. Upon your request, the findings of the study will be shared with those who responded to the survey. Feel free to attach any documents that are relevant to the study. Thank you for your assistance.

<u>Survey questions for member states of the IOGCC</u>

<u>Questions about agencies and regulations:</u>

1. Colorado is revising risk models and regulations for flowlines. Is there any agency in your state which oversees regulations for flowlines or rules for upstream pipelines between oil and gas wells and production facilities?

    - YES
    - NO

If 'YES', please answer questions 2-4.

2. Information about your agency.
    - Name of the agency?
    - What is this agency in charge of?
        - Public safety
        - Environment
        - Others (please specify)
    - In a few lines, please describe:
        - How do the rules/regulations differentiate between emission, spill, or integrity issues?
        - What are the rules concerning produced water, gas, crude oil, and condensate lines?
        - What are the permitting requirements for them?
        - How does the state specify standards for design, construction, operation, maintenance, and abandonment of these lines?
        - How does the state regulate changes in surface usage, such as new home construction, in areas with legacy flowline?

3. Please provide the contact information for the person or team in the previously mentioned agency who monitors integrity issues for flowlines or upstream pipelines? Contact person(s) will receive the results of the survey.

4. What type of information does your state collect on existing flowlines?
    - Materials
    - Age
    - Previous failures
    - Locations of flowlines/ upstream pipelines (maps? Web-based system?)
    - Inspection and test results
    - Others (please specify)

Questions about risk assessment models

Please provide details for the following questions about possible risk assessment models.

Feel free to attach any documents that are relevant to the study.

1. Do you use a risk profile (model) to guide flowline inspections or monitor integrity?
    - What is the basis of the risk model?
    - Which agencies or operators do you know of that have already developed, or are currently developing, a risk assessment model for upstream piping?

2. What hazards and/ or consequences related to upstream piping do you consider to be most significant? Consider categories such as human safety, impact on the environment, revenue loss, etc.

Is there anything else about upstream piping and/or your organization's role that we should know?

The results of the survey of the member states of the IOGCC are summarized in the next section. A cumulative file with the responses is available on the flash drive.

The survey was slightly modified for the members of the API.

Survey questions for members of the API

Questions about organizations and regulations

1. Colorado is revising risk models and regulations for flowlines. Does your organization have regulations for flowlines or rules for upstream pipelines between oil and gas wells and production facilities?

    - YES
    - NO

    If 'YES', please answer questions 2-4.

2. Information about your organization.
    - Name of the organization?
    - What is the purpose of your organization?
    - In a few lines, please describe:
        - How do the rules/regulations differentiate between emission, spill, or integrity issues?

- What are the rules concerning produced water, gas, crude oil, and condensate lines?
- What are the permitting requirements for them?
- How does your organization specify standards for design, construction, operation, maintenance, and abandonment of these lines?
- How does your organization account for changes in surface usage, such as new home construction, in areas with legacy flowline?

3. Please provide the contact information for the person or team in the previously mentioned organization who monitors integrity issues for flowlines or upstream pipelines? Contact person(s) will receive the results of the survey.

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Is there anything else about upstream piping and/or your organization's role that we should know?

The results of the survey are summarized in the next section.

FINDINGS

Findings of literature search

After an extensive literature search CSM's research team concluded that primarily, there are three mathematical approaches for pipeline risk assessment: (a) qualitative, (b) quantitative, and (c) scenario-based. In *qualitative* models, also known as indexing models, for each pipeline segment, numerical scores are assigned to describe certain variables. The risk index is then a function of these scores, generally giving different weights to the variables. Although numerical in nature, these models are qualitative in the sense that they output an index reflecting the perception of overall risk, not actual risk values. In contrast, *quantitative* models, also termed as probabilistic models, use a tree and historical data to estimate the probability of each failure type and their consequences to estimate risk values for each pipeline segment. *Scenario-based* models, also known as matrix models, work similarly to quantitative models, except that only a single failure type is considered. For further details, see, for example, Muhlbauer (2004) or American Petroleum Institute (2001). The differences between the three approaches are summarized in Table 1.

The research team at CSM made efforts to gather specific information from companies regarding their own proprietary probabilistic models that currently exist as well as the software's functionalities. Reluctance from companies in ownership of said software has yielded no details on models aside from basic marketing materials provided from various company representatives. Therefore, most of the findings summarized below are based on the responses obtained from different government agencies and an academic literature search. The API was willing to assist us with industry responses, but we have not received that material to date.

Table 1: Summary of qualitative vs. quantitative and scenario-based models

Model type:	**Qualitative (Indexing)**	**Quantitative (Probabilistic)**	**Scenario-based**
Description:	Assign scores to different variables, take weighted sum as a risk index	For all failure scenarios, estimate their probabilities and consequences	For a failure scenario of interest, estimate its probability and consequence
Role of historical data:	Inform variable weights	Estimate probabilities	Estimate probability
Advantages:	Flexible, inexpensive to develop, simple, doesn't require historical data, easy to add new factors,	Exhaustive, less subjective	Specific

	effective in practice		
Disadvantages:	Doesn't calculate risk, doesn't consider specific events	Complicated, expensive to develop, requires sufficient historical data, difficult to add new factors	Non-comprehensive
Suitable for:	Developing an overall risk model with limited funding, limited data, and/or many risk factors	Studying or comparing specific failure types	Managing the risk of a particular failure event

Qualitative models

Due to their flexibility and simplicity, the use of qualitative models is widespread. Since relevant historical pipeline data are sparse, qualitative models are generally more feasible than quantitative models. Some researchers (Han and Weng, 2011) are of the opinion that a 'well-developed' qualitative model can perform as well as a quantitative model.

Qualitative models consider a number of variables related to the hazards and consequences of failure of pipelines. Each pipeline segment is given an index for each variable based on current data. A weighted sum of those indices is then taken as an overall risk index for that segment. Note that this index reflects the belief in a risk, not an estimation of the actual risk.

Qualitative models for pipelines vary mainly in how their variable weights are derived. Generally, a specific algorithm or a collection of algorithms that consider some combination of historical data and expert opinions are used to assign the weights. Certain algorithms may be more suitable than others depending on the availability of data and the availability of expert opinions. Some examples of qualitative models are given in Table 2.

Table 2: Summary of qualitative models

Model	***Index selection***	***Weight selection***
Han and Weng (2011)	*Chosen from historical data, organized in a fault tree*	*Reliability engineering theory, grey correlation theory*
State of Alaska Doyonemerland and ABS Consulting (2009)	*Stakeholder survey*	
Guo et al. (2016)	*Fault tree analysis*	*Analytic hierarchy process*

Dziubiński, Fratczak, and Markowski (2006)	*Event tree analysis*	*Historical data survey*
Jafari (2011)	*Unknown*	
Brito and de Almeida (2009)	*Event tree analysis*	*Expert opinion, historical data, multi-attribute utility theory*
Brito, de Almeida, and Mota (2010)	*Event tree analysis*	*ELECTRE TRI, multi-attribute utility theory*

The advantage and popularity of qualitative models lies in their simplicity. Although variable weights may be derived using sophisticated methods, the resulting models are relatively straightforward to implement and understand. This makes qualitative models significantly less expensive to develop and use compared to quantitative models. Since qualitative models do not attempt to estimate probabilities, an abundance of data is not necessary. Additionally, it is systematic to add or remove variables within most derivational frameworks mentioned in Table 2. However, at a cost of their simplicity, the utility of qualitative models depends on the judicious selection of variables and weights. Therefore, when developing a qualitative model, it is important to choose an appropriate derivational method.

Quantitative models

Due to their exhaustiveness and mathematical rigor, quantitative models have been the subject of several academic studies. For accurate analyses, quantitative models are typically based on either event trees or fault trees. Some attempts have been made to develop methods that work for relatively small datasets, often by borrowing from methods used to derive qualitative models.

Quantitative models generally attempt to estimate the probabilities and consequences of specific events. To be thorough, an event tree or a fault tree is first developed to describe the relationship between system states. Statistical methods are then used to estimate transition probabilities between states. Since there is rarely enough applicable data available for a comprehensive analysis, a Bayesian approach is typically used. Similar to the derivation of variable weights in qualitative models, a number of methods for deriving prior distributions have been proposed. Some examples of quantitative models are given in Table 3.

Table 3: Summary of quantitative models

Model	**Probability assessment**	**Consequence assessment**
Medeiros, Alencar, and de Almeida (2017)	Sensitivity analysis based on Monte Carlo simulation	Multi-attribute utility theory
Han and Weng (2010), Han and Weng (2011)	Estimated from data	Estimated from data, based on event tree analysis

TransCanada (Peterson and Fenyvesi, 2009)	Unknown	
Breton *et al.* (2010)	Bayesian, with an experimental data-based prior distribution	N/A
Shahriar, Sadiq, and Tesfamariam (2012)	Fault tree analysis, fuzzy logic	Event tree analysis
Cagno *et al.* (2000)	Bayesian, based on the analytic hierarchy process	N/A
Lu *et al.* (2015)	Fault tree analysis, fuzzy logic	Event tree analysis
Jo and Bum (2005)	N/A	Event tree analysis based on GIS data
Wang *et al.* (2017)	Fault tree analysis, transformed into a Bayesian network	N/A
Wu *et al.* (2017)	Bayesian network informed by Dempster-Shafer evidence theory	N/A
Ma, Cheng, and Li (2013)	Empirical formulas	Event tree analysis based on GIS data
Vianello and Maschio (2014)	Estimated from data	Empirical formulas

The main advantage of quantitative models is the rigor and objectivity of those models. These models are generally more sophisticated than more heuristic qualitative models in a sense that these rely on the mathematical definition of risk and statistical (Bayesian) methods for estimating probability. Therefore, a quantitative model with enough historical data is not as subjective as a qualitative model. However, in practice, quantitative models still rely on heuristic assumptions, experience, and opinion when enough data isn't available. Their complexity makes quantitative models more expensive both to develop and to implement than qualitative models. Additionally, since they rely on data, it is difficult to add new risk factors to the model.

Scenario-based models

Scenario-based risk models consider the potential events that can lead to failure. Failure risk is calculated by first assigning a risk score to each event likelihood and consequence using a fault tree or event matrices. Failure risk is then calculated as the product of the likelihood and the consequence of the failure event. Examples are given in Chovanetz (2018) and Jones, Gahagan, and Gros-potter (2014). In specific cases, machine learning techniques have been successfully applied to predict pipeline failures; see Chen *et al.* (2004) and Hou *et al.* (2014).

Summary of terminology

Brief descriptions of methods mentioned in Table 2 and Table 3 are given here. For more details, we refer to the appropriate reference(s).

Event tree analysis (ETA) is a graphical technique for modeling the possible consequences of an event in a system. An initial event is considered, and all possible events that can directly follow from it are placed under it. Probabilities from the initial event to each following event are then assigned. This process is then repeated as desired for each new event. Event trees are widely used in consequence modeling and are often the basis of qualitative models.

Similar to ETA, **fault tree analysis (FTA)** models the possible causes of a specific failure event. ETA and FTA are opposites: in FTA, a final event is considered, and all possible events that can directly cause it are placed under it. Probabilities that a final event was caused by a preceding event are then assigned. This process is then repeated as desired for each new event. Fault trees are sometimes used as the bases of qualitative and scenario-based models. In practice, concepts from **reliability engineering theory** often inform the probabilities.

A **bow-tie model** is the combination of an ETA and an FTA: one event is used to generate both a fault tree and an event tree. In context, this event is typically chosen to be a pipeline rupture. Since bow-tie models describe both causes and effects, they are often the underlying structure behind quantitative models.

The **analytic hierarchy process (AHP)** is a powerful algorithm for quantifying expert opinions for making decisions. First, judgement criteria are chosen. Their weights are calculated by exhaustive pairwise comparisons. Options are similarly compared against each other with respect to each criterion. Combining these comparisons results in a priority index for each option, and the option with the highest index is considered the best choice. AHP is sometimes used to derive prior distributions in lieu of sufficient usable data.

Agency findings

An extensive literature review of agency resources showed that many government agencies have not yet implemented any specific regulations relating to upstream piping. Of the organizations that have, Alaska and Canada seem to be the furthest along. Alaska's qualitative model, designed in 2009 by the State of Alaska Department of Environmental Conservation, see https://dec.alaska.gov/, uses risk matrices, risk histograms, and risk summaries. Details about the model can be found in Doyonemerland and ABS Consulting (2009). The matrices display number of events by risk level. Histograms are used to show the total estimated frequency for events in each category. Lastly, the summaries utilize percentages of safety and reliability based on each individual node. Though useful in the fact that this risk model considers flowlines, it is outdated and derived using subjective rankings. In contrast, TransCanada (see, Peterson and Fenyvesi, 2009) has developed a quantitative model to assess the risks for independent operators. This may be more applicable to what the Commission is searching for as the derivation uses hard data and specific equations to calculate the risk of each event. The drawback of this model is that it is very specific to the issues TransCanada has dealt with, such as Pipe Replacement/ Recoating.

Results of survey of the member states of the IOGCC

Questions about agencies and regulations:

5. Colorado is revising risk models and regulations for flowlines. Is there any agency in your state which oversees regulations for flowlines or rules for upstream pipelines between oil and gas wells and production facilities?

    - YES from the following member states:
        - Alaska
        - Alberta
        - California
        - Colorado
        - Illinois
        - North Dakota
        - New York
        - Ohio
        - Oklahoma
        - Saskatchewan
        - Virginia
        - West Virginia
    - NO from the following member states:
        - South Carolina
        - South Dakota
    - N/A from one member state:
        - Arizona

If 'YES', please answer questions 2-4.

6. Information about your agency.
    - Name of the agency?
    - What is this agency in charge of?
        - Public safety
        - Environment
        - Others (please specify)
    - In a few lines, please describe:
        - How do the rules/regulations differentiate between emission, spill, or integrity issues?

- What are the rules concerning produced water, gas, crude oil, and condensate lines?
- What are the permitting requirements for them?
- How does the state specify standards for design, construction, operation, maintenance, and abandonment of these lines?
- How does the state regulate changes in surface usage, such as new home construction, in areas with legacy flowline?

Alaska	• Name: Alaska Department of Environmental Conservation/ Division of Spill Prevention and Response (ADEC/SPAR) • In charge of: Environment and Public Safety • Emissions, spill, integrity: ADEC/SPAR rules do not contain terms associated with emission specific to flow lines • Water, gas, crude oil, condensate: Multi-phases/ produced water/condensate lines between production pads and processing facilities are regulated under 18 ACC 75.047 as flow lines; does not extend to gas pipelines • Permitting requirements: flow lines are parts of production facilities which requires an approved oil discharge prevention contingency plan before operating • Standards for design, construction, etc.: 18 AAC 75.047 has provisions, common industry standards/ practices are referenced • Surface usage: ADEC/SPAR does not have specific provisions for changes in surface usage
Alberta	• Name: Alberta Energy Regulator • In charge of: Public safety, environment, resource conservation, and orderly development • Emissions, spills, integrity: Any releases as well as contact damage or failed hydrostatic testing must be reported to the AER • Water, gas, crude oil, condensate: The Pipeline Act, Pipeline Rules, the CSA Z662, Directive 077, and Manual 005 • Permitting requirements: Pipelines must receive an approval (license) prior to the construction of the pipeline • Standards for design, construction, etc.: CSA Z662 is a standard for design, construction, operation, and abandonment for pipeline systems • Surface usage: Pipelines must have a right-of-way with a 30 m buffer where this limits all developments
California	• Name: California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (DOGGR) • In charge of: Public safety, environment, Regulation of Oil

	and Gas Production and Pollution Prevention • Emissions, spills, integrity: Any pipelines failing a periodic integrity test are removed from service, repaired, and retested before returning to service • Water, gas, crude oil, condensate: If these type pipelines are greater than one-inch in diameter, they are regulated DOGGR pipelines subject to periodic testing and annual inspection • Permitting requirements: DOGGR does not issue permits for pipelines, but does issue permits for the wells they serve • Standards for design, construction, etc.: Under DOGGR regulations new pipelines must be constructed to applicable standards in California OSHA standards which require following ASME B31.3, b31.4, and B31.8 for certain pipelines installed after 2006 • Surface usage: Following land use changes, if gas pipelines over one-inch in diameter are located within 300 feet of human occupied building, DOGGR requires more frequent testing (every two years) per 14CCR1774.1
Colorado	• Name: Colorado Oil and Gas Conservation Commission • In charge of: Public safety, environment, responsible development of oil and gas, including protection of public health, safety, and welfare, prevention of waste, protection of mineral owner's correlative rights, and prevention and mitigation of adverse environmental impacts • Emissions, spills, integrity: Liquid spills over a certain limit (usually 1-5 bbls depending on location) are considered reportable and are reported on a spill report form 19. Grade one gas leaks are reported on the Flowline Form 44. 1100 series of rules specifies applicable technical standards to be followed and Rule 1104 covers acceptable integrity management including pressure testing, AVO, smart piping, continuous pressure monitoring (SCADA) or instrument monitoring • Water, gas, crude oil, and condensate: Basically construct and maintain according to ASME and API standards and generally accepted best practices • Permitting requirements: Registration of off-location flowlines, crude oil transfer lines, and producer water transfer systems. Notification 10 days prior to start of construction of crude oil transfer systems and produced water transfer systems • Standards for design, construction, etc.: Standards cited in the rules are American Society of Mechanical Engineers,

	Pipeline Transportation Systems for Liquids and Slurries, 2016 Edition (ASME B31.4-2016), ASME Gas Transmission and Distribution Piping Systems, 2016 Edition (ASME B31.8-2016), ASME Process Piping, 2016 Edition (ASME 31.3-2016), API Specification 155, Spoolable Reinforced Plastic Line Pipe, Second Edition, March 2016, API Specification 15HR, High-pressure Fiberglass Line Pipe, Fourth Edition, February 2016, API Specifications 15LR (R2013), Low Pressure Fiberglass Line Pipe and Fittings, API Standard 1104, Welding of Pipelines and Related Facilities, Twenty First Edition, September 2013, ASME BPV Code 2017 Section IX – Welding, Brazing, and Fusing Qualification, NDT of welds according to those standards established by the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration pursuant to 49 C.F.R. 192.243 and 195.234, in existence as of the date of this regulation, SP0169-2007, Control of External Corrosion on Underground or Submerged Metallic Piping Systems, 2007 Edition, API RP 1110, Recommended Practice for the Pressure Testing of Steel Pipelines for the Transportation of Gas, Petroleum Gas, Hazardous Liquids, Highly Volatile Liquids or Carbon Dioxide, ASTM F2164-13, Standard Practice for Field Leak Testing of Polyethylene and Crosslinked Polyethylene Pressure Piping Systems Using Hydrostatic Pressure • Surface usage: COGCC only regulates oil and gas activities and has no authority over home construction. Typically, the issue of construction is regulated by local governments. Colorado does have a setback rule from buildings (typically 500') for new oil and gas activity
Illinois	• Name: Illinois Department of Natural Resources, Office of Oil and Gas Resource Management • In charge of: Public safety, environment, permitting of wells, production facilities, and oilfield waste • Emissions, spills, integrity: Rules do not necessarily differentiate between those 3 instances. Authority stems mostly from a prohibition of waste found in Section 1.1 of the Illinois Oil and Gas Act, 225 ILCS 725/1.1. Based on that prohibition, it is required that flowlines be kept in a leak free condition. Any leak, spill, or emissions caused by an integrity issue or human error would be a violation of 820(e) • Water, gas, crude oil, and condensate: Rules for all flowlines are found in 62 Ill. Adm. Code 240.820. There are not specific rules for water, gas, crude oil, and condensate lines.

	• Permitting requirements: Flowlines themselves are not permitted • Standards for design, construction, etc.: 62 Ill. Adm. Code 240.820 • Surface usage: The Department has the authority to take enforcement action to require active flowlines existing on the effective date of the rule to be replaced, buried, or constructed in accordance with subsection (b) of the Section or to require visible inactive or abandoned flowlines to be removed and the open ends sealed if the Department finds, based on field observation, that the flowlines constitute a hazard to public safety or can be reasonably expected to cause damage to the environment through leaks and spills
North Dakota	• Name: North Dakota Industrial Commission, Department of Mineral Resources, Oil and Gas Division • In charge of: Oil and gas development (exploration and production) and underground gathering pipeline safety and integrity • Emissions, spills, integrity: The Oil and Gas Division responds to pipeline failures, oversees the line repair, and witnesses the integrity test. The North Dakota Department of Health, Division of Water Quality is responsible for all offsite spills and oversees the environmental remediation. The Oil and Gas Division is responsible for onsite (i.e. within the bounds of an oil and gas facility) oil and gas related spills, ensures the repair is done properly, and witnesses the integrity test. Both the Oil and Gas Division and the Department of Health receive oil and gas spill reporting and respond appropriately based on jurisdiction • Water, gas, crude oil, and condensate: The Oil and Gas Division has a complete and comprehensive regulatory framework in place for crude oil and produced water underground gathering pipelines. The Oil and Gas Division also regulates gas gathering pipelines, but the regulations are specific to construction, GIS location, and abandonment • Permitting requirements: The Oil and Gas Division does not permit nor site flowlines or gathering pipelines. For gathering pipelines, the Oil and Gas Division's jurisdiction begins at pipeline construction • Standards for design, construction, etc.: The Oil and Gas Division has regulations for crude oil and produced water underground gathering pipeline design, construction, operation, maintenance, and abandonment. The Oil and Gas Division's regulations for gas gathering pipelines focus on

	proper construction; submission of the GIS location after the pipeline has been placed into service, and proper abandonment. The Oil and Gas Division requires crude oil and produced water underground gathering pipeline owners to have third party independent inspectors oversee pipeline construction to ensure the pipelines are installed pursuant to the Oil and Gas Division's design and construction regulations and the pipeline manufacturer's specifications. The regulations for flowline abandonment reference the requirements for underground gathering pipeline abandonment if the flowline is deeper than 3 feet below the final reclamation contour, otherwise flowlines shallower than 3 feet are required to be removed. Gathering pipelines are required to be cut off at pipelines depth, purged, cathodic protection removed, permanently capped, surface reclaimed, and the GIS location of the abandoned line is required to be submitted to the Oil and Gas Division. • Surface usage: No above ground equipment associated with underground gathering pipelines may be installed less than five hundred feet from an occupied dwelling unless agreed to in writing by the owner of the dwelling or authorized by order of the commission
New York	• Name: Department of Environmental Conservation, Division of Mineral Resources • In charge of: The Division of Mineral Resources is responsible for ensuring the environmentally sounds, economic development of New York's non-renewable energy and mineral resources for the benefit of current and future generations
Ohio	• Name: The Ohio Department of Natural Resources, Division of Oil and Gas Resources • In charge of: The Division has sole and exclusive authority to regulate the permitting, location, and spacing of oil and gas wells in Ohio and the "production operations" in the state unless federal oversight has been delegated to the Ohio Environmental Protection Agency under Ohio's Water Pollution Control Law. The Ohio Oil and Gas Laws are designed to protect public health and safety and the environment and to ensure proper construction and operation of oil and gas wells • Emissions, spills, integrity: The rules regarding pipelines are found in O.A.C. Chapter 1501:9-10. The pipeline rules establish standards for installation and performance requirements. Separate statutes and rules establish

	prohibition of releases of brine, oil, natural gas, and other fluids associated with oil and gas operations in or on the ground or in or on waters • Water, gas, crude oil, and condensate: See above • Permitting requirements: There are no specified permitting requirements for flowlines • Standards for design, construction, etc.: Standards for pipelines are established in rules • Surface usage: The state does not regulate changes in surface usage in areas with legacy flowlines. If a well is discovered during new construction, Orphan Well Program will inspect the well and properly plug and abandon the well. If there are associate flowlines, those will typically be pulled or filled with cement
Oklahoma	• Name: The Oil and Gas Division of the O.C.C. • In charge of: Public safety and the environment • The OGCD has no rules for the construction or use of flowlines. It does require that operators conduct their operations in a manner that will not cause pollution
Saskatchewan	• Name: Petroleum and Natural Gas Division (PNG), Saskatchewan Ministry of Energy and Resources • In charge of: PNG regulates the oil and natural gas industry in Saskatchewan, including intra-provincial flowlines and transmission pipelines Depending on the location and nature of the flowline or pipeline project, other approvals may be needed from other agencies including the Ministry of Environment, Ministry of Agriculture, Water Security Agency, Ministry of Highways and Transportation, Ministry of Parks, Sport and Culture, and Ministry of Government Relations. In general, PNG approves a pipeline project from the perspective of meeting engineering standards to ensure that the public and the environment are adequately protected. Other agency approvals are needed with respect to their specific mandates. • Emissions, spills, integrity: PNG requires spills or emissions from petroleum industry infrastructure to be reported including flowlines and pipelines. More serious events also require analysis of the cause of the spill/ emission and a description of the reclamation efforts undertaken to remediate any damage. Companies with licensed pipelines in the province are expected to manage the integrity of their pipelines using the Canadian Standards Association Z662, Oil and Gas Pipeline Systems standard as the basis for guiding their work. If integrity issues are identified, the operator is

	expected to respond appropriately to ensure they mitigate any potential impacts to the environment or the public. When this work involves physical alteration to the pipeline, PNG must be consulted or engaged. Certain alterations to the pipeline require reporting only while others require applications to the regulator for review and approval prior to the commencement of work • Water, gas, crude oil, and condensate: The rules on flowlines in Saskatchewan do not differ by transported substance. All pipelines and flowlines in Saskatchewan must be, at minimum, designed, constructed, tested, operated, maintained, repaired, discontinued, and abandoned in accordance with the most recent version of Canadian Standards Association Z662, Oil and Gas Pipeline Systems • Permitting requirements: Various permit application forms can be found at https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/oil-and-gas/oil-and-gas-licensing-operations-and-requirements/pipline-licensing • Standards for design, construction, etc.: All pipelines and flowlines in Saskatchewan must be, at minimum, designed, constructed, tested, operated, maintained, repaired, discontinued, and abandoned in accordance with the most recent version of Canadian Standards Association Z662, Oil and Gas Pipeline Systems • Surface usage: There are currently no specific setback requirements for new construction of homes or developments in proximity to pipelines and/ or flowlines. There are, however, specific setback requirements for wells and facilities. In addition, when land is being subdivided, the Community Planning Branch within the Ministry of Government Relations (GR) has minimum setback requirements, which may adjust PNG established setbacks based on risk
Virginia	• Name: Virginia Division of Gas and Oil (DGO) • In charge of: Public safety, environment, and worker safety • Emissions, spills, integrity: Any spills or leaks are reported electronically to DGO • Permitting requirements: The DGO is responsible for the permitting and compliance inspections of the non-dot oil and gas gathering lines and any flowlines to the point of sale. Each gathering pipeline or gathering pipeline system may be permitted separately from gas or oil wells or may be included in the permit for the well being served by the pipeline

West Virginia	• Name: The DEP, Office of Oil and Gas (OOG) • In charge of: Public safety and environment • Emissions, spills, integrity: The requirements do not address these issues specifically. OOG does address spills and emissions in the context of line repair and any needed site remediation • Water, gas, crude oil, and condensate: There is no distinction made between transported media • Permitting requirements: Pipelines under OOG authority do not require a permit separate from the well work permit that would include site construction. Pipelines under DWWM must obtain a construction storm water permit which outlines all E&S controls to be employed with pipeline installation • Standards for design, construction, etc.: OOG/ DWWM have no prescriptive requirements associated with design, construction, maintenance, and abandonment. OOG generally addresses the requirement for pipeline burial and marking through regulation and DWWM addresses construction from and E&S perspective in its permits. Additionally, OOG does have general statutory language prohibiting wasting (leaking) of gas and the requirement for removal of production equipment upon well abandonment • Surface usage: Surface usage is not regulated, however, lines greater than a certain size must be marked by the operator upon receipt of notice of potential surface disturbance

7. Please provide the contact information for the person or team in the previously mentioned agency who monitors integrity issues for flowlines or upstream pipelines? Contact person(s) will receive the results of the survey.
    a. Responses to this question have been omitted to protect our responders.

8. What type of information does your state collect on existing flowlines?
    - Materials
    - Age
    - Previous failures
    - Locations of flowlines/ upstream pipelines (maps? Web-based system?)
    - Inspection and test results
    - Others (please specify)

Alaska	Current state regulations do not explicitly require routine submittals of flow lines information. ADEC/SPAR does request specific information on selected flow lines which could include such information

Alberta	• Materials: Yes, at the time of license application pipeline material is collected • Age: At the time of application, the pipeline is considered new • Previous failures: All incidents will need to be reported immediately after the incident is identified • Locations of flowlines/ upstream pipelines: Most of the older information has the start and end points and AER is gathering all the historic information in a GIS layer system with improved accuracy • Inspection and test results: Not collected at the time of the application but AER staff would extract this information from existing data systems depending on the type of application • Other: Occasionally a pipeline that missed the licensing process is identified. The AER then undertakes the licensing process as though the pipeline is new
California	• Materials: Yes • Age: Yes • Previous failures: Yes • Locations of flowlines/ upstream pipelines: Maps are required for all pipelines and are included in the operator's spill contingency plan • Inspection and test results: DOGGR requires operators to retain this information and have it available • Other: Product description, grade of steel, design and operating pressures, and presence of leak detection systems is required eff. October 1, 2018
Colorado	• Materials: Yes, for off-location flowlines, crude oil transfer lines, and produced water transfer lines if built after May 1, 2018. No information collected for lines built previous to that date yet (operators have until October 31, 2019) • Age: Same as above • Previous failures: If associated with reportable spill • Locations of flowlines/ upstream pipelines: Endpoints of flowlines within 1000' of a building unit were collected after the incident at Firestone. Registration of off-location flowlines, crude oil transfer lines, and produced water transfer lines includes GIS data with attributes • Inspection and test results: COGCC inspections recorded on a Field Inspection form
Illinois	• Materials: No • Age: No • Previous failures: Yes

	• Location of flowlines/ upstream pipelines: No • Inspection and test results: Yes
North Dakota	• Materials: Underground gathering pipelines as part of the attribute data in the GIS submission; not for flowlines unless the data has been voluntarily submitted or the Oil and Gas Division has specifically requested the data • Age: Same as above • Previous failures: This information is collected through the Oil and Gas Division spill reporting system • Location of flowlines/ upstream pipelines: The Oil and Gas Division has been collecting the GIS location of underground gathering pipelines through a web-based submission since 2014; not for flowlines unless the data has been voluntarily submitted or the Oil and Gas Division has specifically requested the data. The Oil and Gas Division maintains a confidential geodatabase with the GIS location of underground gathering pipelines in the state • Inspection and test results: Flowline inspection and test results are collected as part of the production facility inspection or through the underground gathering pipeline program
Ohio	• The state does not collect information specific to flowlines in one database or spreadsheet. However, the state does collect information that may contain information concerning flowlines. For example, the Division has a complaint log with flowline information, reporting requirements under the Incident Reporting Rule may have information resulting from a flowline release, or the Division's Emergency Response Team may collect information in response to a call
Oklahoma	• None
Saskatchewan	• Materials: Yes • Age: Yes • Previous failures: Yes • Locations of flowlines/ upstream pipelines: This will be collected following completion of the IT system build • Inspection and test results: Yes
Virginia	• The type of material, length, size, and whether it is buried or aboveground for any permitted gathering pipeline is included in the permit application to DGO. A map showing the location of the pipeline is also submitted as part of the permitting process. Gathering pipelines shall be visually inspected annually by the permittee. The results of each annual inspection shall be maintained by the permittee for a minimum of three years and be submitted to the DGO upon

	request. Incident reports from any permitted gathering pipeline is maintained electronically by DGO
West Virginia	• DWWM collects pipeline size and location information through their construction storm water permitting

<u>Questions about risk assessment models:</u>

Please provide details for the following questions about possible risk assessment models.

Feel free to attach any documents that are relevant to the study.

3. Do you use a risk profile (model) to guide flowline inspections or monitor integrity?
    - What is the basis of the risk model?
    - Which agencies or operators do you know of that have already developed, or are currently developing, a risk assessment model for upstream piping?

Alaska	18 AAC 75.047 does not have specific requirements for risk assessment. ADEC/SPAR did use a consequence-based process during the initial phase of implementation of the flow line oversight program in 2009. ADEC/SPAR believe that major Alaska North Slope operators have already developed their own internal processes for risk assessment for their flow lines
Alberta	The AER has a risk program to focus the inspectors to particular types of pipelines as well as for particular aspects. The risk model is reviewed annually and changes focus as necessary. A change to a more "integrated decision approach" is in process where the risk assessment could trigger specific action on behalf of the AER such as inspection or audit. British Columbia Oil and Gas Commission (BCOGC) and National Energy Board (NEB) currently regulate flowlines, and the province of Saskatchewan is currently moving in that direction as well.
California	An operator's pipeline integrity testing is required every two years based upon a risk ranking triggered by proximity to the public and environmentally sensitive areas. The key ranking criteria is pipeline location (proximity to human and environmental receptors). Other factors, such as pipeline diameter, operating pressure, pressure of hydrogen sulfide leak, history, and routing (buried, submerged, or over surface water) are also to be identified.
Colorado	The COGCC uses a risk profile that is based upon population density, environmental risk, the number of reportable spills,

	years in service, operator history, and time since last inspection.
Illinois	No
North Dakota	The Oil and Gas Division uses a risk-based approach to regulation, inspection, and enforcement. The risk-based approach accounts for environmentally sensitive areas, sensitive geology, recreational areas, historic sites, and wildlife management areas. The Oil and Gas Division is currently developing a risk assessment model for focusing regulatory efforts on crude oil and produced water underground gathering pipelines that pose the greatest risk. The University of North Dakota's Energy and Environmental Research Center (EERC) is finalizing a legislative report on liquid gathering pipelines and applications of risk assessment to improve pipeline integrity. The report is due to be completed September 30th, 2018
Ohio	No
Oklahoma	No
Saskatchewan	Pipeline inspections may occur during pipeline construction and/ or during pressure testing. Saskatchewan does not, however, currently have a program for inspecting or monitoring the integrity of operating flowlines or pipelines. Programs for monitoring and inspecting transmission pipeline and flowline operations will be developed over the next one to two years.
Virginia	The DGO does not have a risk-based model guide for inspections. However, their inspection policy takes into account if there have been any issues with the pipeline
West Virginia	No

4. What hazards and/ or consequences related to upstream piping do you consider to be most significant? Consider categories such as human safety, impact on the environment, revenue loss, etc.

Alaska	Impact on the environment. • North Slope on-shore: internal corrosion, corrosion under insulation, ice/hydrates plugs, and wind-induced vibration • North Slope off-shore: internal corrosion, ice scour, and Strudel Scour • Cook Inlet area off-shore: corrosion, unsupported spans (vortex-induced vibration), and external forces (boulders and ship anchors) • Cook Inlet area on-shore: corrosion

Alberta	Human health and the environment. The AER regulates a number of sour gas pipelines which have acute human health implication. The Province of Alberta has put in significant legislative requirements for ground disturbance practices which have gone a long ways of controlling the hazard of contact damage. It is viewed that maintaining pipeline integrity and good IMP implementation is the most cost-effective way to ensure that the environment (and human health) is protected.
California	Significant hazards are adverse impacts to public safety and the environment resulting from spills or releases.
Colorado	Proximity to population, inhabited buildings, and water is significant.
Illinois	Human safety and impact on the environment are the two consequences considered most significant
North Dakota	Human safety and health, environmental damage, property damage, regulatory, financial, etc.
Ohio	Human safety and impact on the environment
Saskatchewan	In developing pipeline and flowline operational regulatory programs, PNG intends to consult with other Saskatchewan Ministries and agencies on spill and emission consequences. This will be used to evaluate and assess risk and to design regulatory programs and activities
Virginia	There is a concern of a pipeline causing environmental issues or a fire if there should be a rupture of the line

Is there anything else about upstream piping and/or your organization's role that we should know?

Alberta	Prior to 1975, the AER did not regulate flowlines…the gathering system from the wellhead to the satellite battery or storage, etc. The AER undertook a process to require pipeline operators to license existing pipelines collecting information that normally is required for new pipelines such as materials, location, age, failure history, what it connects to, service fluid, operating pressure, burial depth, pipeline crossings (including pipelines crossing a water body), etc.. The information was collected to the best of the ability of the pipeline operators recognizing some information would be available.
California	We coordinate with local agencies having co-jurisdiction, so that locals can monitor their right-of-way per operator franchise agreements.
Colorado	New rules took effect May 1, 2018 for newly constructed lines and operators have until October 31, 2019 to comply with the

	rules for lines existing before May 1, 2018.
North Dakota	North Dakota has developed a regulatory program focused on improving crude oil and produced water underground gathering pipeline integrity. In North Dakota, the term flowline refers to a pipeline transporting emulsion fluids from the wellhead to a tank battery where the fluids are separated into gas, crude oil, and produced water. The pipelines that the separated fluids enter for further transport are defined in North Dakota as underground gathering pipelines. North Dakota regulates flowlines to the extent that the flowlines are associated with the production well and regulated as part of the production facility. In addition, North Dakota has defined transfer lines used for transferring fluids within an enhanced recovery unit and saltwater disposal injection lines for instances where the saltwater disposal well is separate from the facility and the pump. The Oil and Gas Division requires an annual pressure test on all saltwater disposal injection lines, to be witnessed by a representative of the Oil and Gas Division.

Industry findings

As previously described, a series of internet search results from a variety of sources such as API Standards, technical papers from professional organizations such as the Society of Petroleum Engineers (SPE) and National Association of Corrosion Engineers (NACE) were used to characterize current industry practices for flowline risk modeling. In addition, industry personnel from four operators within the state of Colorado and representatives of the Colorado Petroleum Council – A Division of API were consulted to determine the use of risk models for flowlines. The results of these interviews, summarized in *Table 4* below, indicate an industry adoption of qualitative, index-based models for risk prioritization. In addition, regulations set forth by the Pipeline and Hazardous Materials Safety Administration (PHMSA) as well as recommended practices from the American Petroleum Institute (API) were examined. Examples of representative risk assessment/management regulations or standards as provided by PHMSA include for example: ASME B31.8s, 49 CFR 192 & 195, NACE DA RP's, CSA Z662, & ISO.

The API stated that they are not aware of risk models that have been developed for flowlines, nor has the API developed any Recommended Practices specific to Flowlines. API has developed a variety of standards for offshore flowlines and piping, but the operating environment is sufficiently different between onshore and offshore environments that the API does not advertise these standards as useful for onshore application. However, for well pad developments, with concentrated facilities, flowlines are much larger and beginning to approach the characteristics typically associated with offshore operations, which may allow instrument-based inspection techniques normally associated with offshore operations to be used on onshore flowlines. For instance, the API has published API Std 1163 (R2018) "In-line Inspection Systems Qualification

Standard, Second Edition." The description of this document is: *This standard covers the use of in-line inspection (ILI) systems for onshore and offshore gas and hazardous liquid pipelines. This includes, but is not limited to, tethered, self-propelled, or free flowing systems for detecting metal loss, cracks, mechanical damage, pipeline geometries, and pipeline location or mapping".* Upon further investigation, this standard is designed for internal inspections of pipelines, which necessitates an entry and exit point for the inspection devices, which onshore flowlines are not equipped with, and therefore this standard has not been applicable for onshore, instrument-based flowline inspection. This standard, and similar standards and recommended practices, such as NACE SP0102, "In-Line Inspection of Pipelines" may be useful for guidance for inspection protocols for use on well pad production facilities and flowlines.

Table 4: Results of Industry Representative Interviews

Company Representative	1	2	3	4
Do you use a risk profile (model) to guide pipeline (Flowline) inspections or monitor integrity?	Yes	Yes	Yes	Yes
What is the basis of the risk model?	Index (Matrix) Based, probability is a function of liklihoods and consequence of an event	Index (Matrix) Based, probability is a function of liklihoods and consequence of an event	Index (Matrix) Based, probability is a function of liklihoods and consequence of an event	Index (Matrix) Based, probability is a function of liklihoods and consequence of an event
What are some examples of hazards and/ or consequences related to upstream piping that you consider to be most significant?	Impacts to public, environment, and the business	Proximity to environmentally sensitive locations, or the community	Environmental, public, & business impacts	Potential for water contamination, proximity to the public, amount produced
What are some examples of information your company collects for consideration of upstream piping risks?	Mechanical failure, internal/external corrosion potential, operating pressures	Previous companies that owned wells or lines, pressures, materials used, integrity management, frequency of pressure tests	Pressures, materials used and corrosion potential, proximities	Heat radius calculations, pipeline size, normal operating pressures, compressibility pressures
What drives the decision regarding what goes into the formation of the model?	Information is adapted from agency regulations such as PHMSA and API practices	Federal regulations dictate how companies are to operate, the model is developed with consideration of those regulations	NA (Didn't ask)	NA (Didn't ask)

The industry consensus appears to be that the benefits of the rigorous statistical analysis afforded by quantitative models tend to be outweighed by the idea that the models require sufficient historical data and the collection of large, statistically significant data sets to determine the likelihoods and consequences of possible specific events in order to accurately quantify risk potential. However, the U.S. Department of Transportation's PHMSA released a report in May of 2018 stating, "such models are not necessarily more complex or need more data than other types of risk models." The report further elaborates that small pipeline operators will likely continue to use index models but that other pipeline operators should seek to "supplement personal judgment with as much physical data as can be reasonably be acquired over time." Although this suggests that there should be a gradual shift towards a more quantitative based probabilistic model, PHMSA is explicit in their summary conclusion that the type of risk model used should not be the point of dispute as all models use available data. Instead, PHMSA suggests that operators should focus their attention on developing the best practices of using the statistical data that is available to them to continually refine their preferred risk assessment model of choice. Though not intended for flowlines, the PHMSA recommendation of using statistical data to improve the existing qualitative model is a valid one and may be used to improve COGCC's existing risk model, if the data can be acquired and analyzed.

A case history of the use of inspection data to improve qualitative models can be found in Areeniyom (2011). Though this paper is for larger flowlines that are essentially gathering lines, it illustrates a possible method to improve COGCC's existing model by incorporating statistical data from inspections such as pressure testing, and failure history to improve weighting factors for both likelihood and consequences of failures to improve the model accuracy. Broadly speaking, the estimates for both the frequency of a failure event and the consequence of that event could be improved with verification by data analytics.

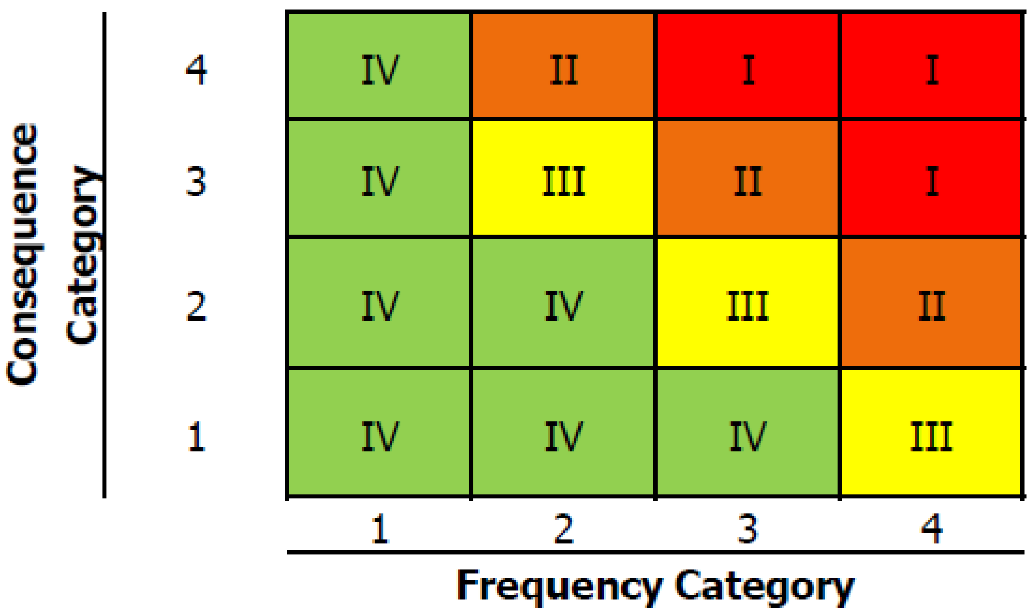

Figure 1: Risk assessment matrix (Rose and Flamberg, 2016)

This inspection and failure data may need to be gathered from multiple operators and combined into a single dataset, for the most robust model improvements. As illustrated in the case history, data improves estimates in the risk matrix pictured above. However, to use a multi-variate approach to estimate risk, incorporating all the risk factors discussed later in this report, and the data associated with the flowlines, such location characteristics, including factors such as distance to occupied buildings, county and municipality, soil type etc., may drive both the estimate of likelihood and consequence to differ significantly from the initial estimates. These data sets may come from other agencies as well. For instance, it has been estimated that as many as 1300 gas lines are cut every year by human action https://www.denverpost.com/2017/05/23/gas-lines-damaged-daily-sanctions-rare/. Though these damaged lines are not all flowlines, the analysis of this large dataset may allow a more accurate estimate of the probability and consequence of accidental line cuts, and bring into the analysis some new risk factors, such as construction permits issued for locations, or the likelihood of those permits being issued, and their proximity to flowlines.

This approach, recommended by PHMSA in the report referenced above for pipelines and gathering lines, may be particularly relevant for new petroleum developments as flowlines are starting to look more like gathering lines than the traditional flowlines when transferring produced fluids from several, multi-well pads. The most obvious data to be acquired are failure data from reported spills, and pressure test data, both failed and successful. Pressure test failure data may be particularly useful. However, as a destructive test the value of the data acquired, and the size of the spill prevented must be weighed against environmental damage of the spill leaking from the pipeline caused by the failed pressure test. The pressure used for the pressure test may be calibrated against lab and modeling data to determine failure at a certain wall loss, to fail pipe at an acceptable wall loss and preventing greater environmental damage with an undetected flowline failure.

Although it appears that operators have not developed mathematics-based risk assessment models for flowlines, there are some proprietary options that exist on the market that may be altered for flowline use. Five companies that offer risk management services were contacted during the study to gain an understanding of what products or services they actually offer and how they go about assessing risk. Although they offered probabilistic modeling software, it would not be immediately applicable for flowlines as they were developed with a focus on pipeline applications. A list of these companies can be found in Table 5.

Table 5: Proprietary industrial risk models for pipelines

Risk Management methods used in Industry	DeepWater Concession & Engineering Services Limited	DNV-GL	Genesis Oil and Gas Consultants	Integrity Plus	SGS Consulting

Notes	Out of all consulting companies considered for proprietary information, the Deepwater website has the most limited information	Safety Software, utilizes consequence analysis, can rank risk contributions, can be overlaid graphically on GIS data	Appears to focus on more integrity data management, or risk-based inspection. How does the Genesis team determine the risk for the inspection need?	Integrity plus offers data management, algorithm development, and probabilistic risk analysis, Also the capability to identify specific risk factors in pipeline data, and "What If" scenario analysis	Not specifically an Oil & Gas company, works for a variety of industries, including but not limited to: food, Food, Retail, Energy, Environment. Mentions risk-based application. How does SGS determine the risk for the inspection need?
Pipeline Risk Analysis	NA	yes	NA	yes	NA
Flowline Specific	NA	NA	NA	NA	NA
Risk Assessment Methodology	NA	Quantitative Risk Analysis	NA	Quantitative Risk Analysis	NA
Examples of Parameters	NA	Flammable, Explosive and Toxic Impact, emergency response	Corrosion	NA	NA
GIS based	NA	Potentially	yes	Potentially	NA
Contact Info	info@deepwaterconcession.com	Through Website	Through Website	Through Website	Through Website
Contacted?	yes	yes	yes	yes	yes

Response?	NA	"Safety models the risks associated with a release of materials contained in the pipeline into the atmosphere. These materials can be toxic or flammable. It includes release and dispersion models to model how far the material will disperse."	NA	NA	NA

<u>Industry contacts</u>

1. BP Pipeline Assets, Durango, CO
2. Noble Midstream Partners, Denver, CO
3. PDC Energy, Inc., Denver, CO
4. High Point Resources Corporation, Denver, CO
5. Denver Water -- Information about assessment of integrity of water lines
6. American Petroleum Institute (API) Standards and Recommended Practices
7. Pipeline and Hazardous Materials Safety Administration (PHMSA) -- Office of Pipeline Safety (OPS) and similar regulators

SUMMARY OF RISK FACTORS, POSSIBLE RISK METHODS AND MODELS

In meetings with representatives of the Commission and from the documents they provided us, we learned that the Commission is currently using a systematic, automated, and simple geographic information system (GIS) model that calculates the total risk factor (RF) score for every well, including associated facilities. In order to establish the RF for a particular well, the model starts with classifying individual data parameters on a 1-5 scale and then combines these parameter values to get RF area scores. Next, it combines the weighted area scores to calculate an overall risk score.

Although the existing model is useful and practical, it has some drawbacks. A major disadvantage of the current approach is that it is not based on any probability distribution for the input parameters. Moreover, the input parameters are being grouped in categories, with a subjective way of deciding the different categories. Treating the inputs as continuous variables might lead to some improvement. Another restriction of the current approach is that it only considers six individual risk factors in determining the overall risk score. Even if these are viewed as the most important 'broad' risk factors, it would be worthwhile to examine the significance of each of these risk factors as well as others which are currently not included in the model, yet might be important based on scientific data, and common practices in flowline risk analysis. Another shortcoming of the present model is the choice of the RF weights. The weights are currently based on a survey done among the Commission modeling experts. How each of them perceives the importance of the risk factors might lead to selection bias in the current approach. The accuracy of these RF weights could be tested by a rigorous examination of a specific control population in a limited area, if the data set could be made available.

LIST OF RISK FACTORS

Basic risk factors include but are not limited to:

- Vandalism
- Pipeline proximity to human activity
- Human error
- Pipeline age
- Operator history
- Pipeline material
- Pipeline inspection methods and frequency of inspections
- Pipeline damage due to internal corrosion or material damage, which may be accentuated by the nature of fluids carried by the pipelines
- Pipeline damage due to external corrosion
- Pipeline damage due to external stresses, such as ground movement or material creep
- Pipeline pressure
- Pipeline location uncertainty
- Soil qualities (external corrosion)
- Carrier fluid qualities (internal corrosion)
    - H_2S potential
    - CO_2 potential
- Explosive potential
- Flammable potential
- Toxic impact
- Emergency response time
- Natural disasters

Potential hazards due to pipeline failure include:

- Immediate safety – depends on type of failure and proximity to population
- Long term health impacts
- Watershed and surface water impacts
- Environmental impacts

Additional feedback from members of the industry could help produce a more robust list of risk factors. Information, such as why their pipelines have failed, could be useful in generating a risk assessment model.

We have completed an intensive literature search for models for flowline risk analysis as currently adopted by different agencies, in industry or academia. However, based on the nature of the problem, an additional search could be done to see if (a) linear discriminant analysis and /or (b) support vector machine type classification rules have already been used in this field.

CONCLUSIONS

As summarized in the previous sections, CSM's team members have conducted an extensive search to identify a useful risk model which can be adopted to prioritize the regulatory requirements to perform instrument-based monitoring of upstream oil and gas off-location flowlines, crude oil transfer lines and produced water transfer lines in Colorado. In particular, it has been noted that there are three types of models (namely qualitative, quantitative and scenario based) which are commonly used in practice and the respective pros and cons of each of the models have also been identified. CSM's team has also conducted surveys to the members of IOGCC. The research team also has interviewed both industry and agency contacts to gain further insight into standards and practices. The details of the survey and interviews have been included in the report. Commercial products used specifically for flowlines were not identified, and the utility of commercial pipeline software for use with flowlines could not be determined because companies offering commercial modeling products were reluctant to disclose their algorithms, which is problematic for evaluating the utility of those models.

CSM has not identified a risk model used in either industry or by regulatory agencies that can be adopted by the COGCC as an improvement over the current qualitative model. Further study of Alaska and/or Canada's risk assessment models may be of value in Colorado, since those models seem to have the most effort and recent work.

A common weakness of qualitative models in general and a shortcoming of the present COGCC model is the choice of the RF weights. The weights are currently based on a survey done among the Commission modeling experts. How each of them perceives the importance of the risk factors might lead to selection bias in the current approach. The accuracy of these RF weights could be tested by a rigorous examination of a specific control population in a limited area, if the data set could be constructed.

To address the identified weaknesses in the current COGCC model, CSM has identified three possible action items:

1. Explore joining the DOE NETL effort to quantify risk in Colorado and work with the DOE to expand the scope and funding to quantify additional risk factors to improve the existing qualitative model risk factors.

2. Obtain and analyze data sets, such as for the publicized line cuts referenced in this report, to determine risk factors to guide regulatory action on setbacks from flowlines. This may be done as part of the DOE NETL effort, or as a standalone effort, focused on Colorado. At a minimum, preparing the dataset focused on Colorado will allow analytic efforts to aid the COGCC.

3. Improve the existing model using machine learning or "reverse engineering" techniques that have been successfully applied to predict pipeline failures and could be applied to flowline risk models as well. In addition, the analytic hierarchy process (AHP) is a powerful algorithm for quantifying expert opinions for making decisions, which may also improve the existing model. Moreover, the input parameters are being grouped in categories, with a subjective way of deciding the different categories. Treating the inputs as continuous variables instead of subjectively defined categories might lead to some improvement.

4. Work with the API to establish a working group of other state and industry stakeholders focused on best practices for flowline risk management. Current API recommended practices are focused on other portions of oil and gas production, such as pipelines or drilling and production operations at well sites, but do not exist for flowlines themselves between well sites and production facilities. This is increasingly critical as oil and gas development encroaches on existing developed areas, or development encroaches on existing or legacy oil and gas developments.

5. Additional feedback from members of the industry could help produce a more robust list of risk factors. Information, such as why their pipelines have failed, locations, and specific conditions to the failure in the pipeline or surrounding area, either during pressure testing or in-service failure, could be useful in generating a more robust risk assessment model.

ACKNOWLEDGEMENTS

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Areeniyom, P. (2011) ‘The Use of Risk-Based Inspection for Aging Pipelines in Sirikit Oilfield’, in *International Petroleum Technology Conference*. Bangkok.

The Sirikit oilfield located in the north part of Thailand has now been in operation for 28 years and intends to continue production in excess of a further 10 years. The Sirikit oilfield manages 187 intra- field pipelines with total installed length of approximately 417 km. installed from 1983 onwards. A number of the infield pipelines have been in service for more than 20 years and with original design life of 15-20 years, they are reaching the end of or exceeding their original lives. Pipeline degradation due to corrosion leading to spills and production deferment has become critical problem. In addition, frequent and continuous inspection of pipelines to achieve sufficient and reliable inspection data with optimal inspection resource have become increasingly important. In order to keep this oilfield long operational life as well as to assurance sustained pipelines safety and integrity, Sirikit oilfield has implemented the Risk Based Inspection (RBI) to assess a number of 187 infield pipelines with respect to corrosion mechanisms, inspection effectiveness, likelihood of failure and consequence to failure. Pertaining to the results of the implementation, it was a successful implementation for Sirikit assets. The major success was identifying the risk, ensuring that the risk remains as low as reasonably practicable. Optimal inspection plan was also successfully established by extending a number of pipelines inspection intervals from 1 to 2-3 years under some certain conditions and will gradually increase to 4-5 years. The higher level of inspection and scrutiny to reduce potential threats on the pipelines based on what, where, when and how to inspect in order to control and reduce the risk to be within an acceptance level were used. This paper describes the implementation of a risk-based inspection program for the Sirikit oilfield. The paper addresses the RBI matrix, the likelihood attributes, the consequence scores, and the overall risk. Pipelines are plotted on the RBI matrix to develop inspection priorities followed by inspection planning.

Bauer, J. and Rose, K. (2018) *Assessing natural gas infrastrucure hazards and risks in Colorado using advanced data computing*. Albany, OR.

Breton, T. *et al.* (2010) ‘Identification of failure type in corroded pipelines: A Bayesian probabilistic approach’, *Journal of Hazardous Materials*. doi: 10.1016/j.jhazmat.2010.03.049.

Spillover of hazardous materials from transport pipelines can lead to catastrophic events with serious and dangerous environmental impact, potential fire events and human fatalities. The problem is more serious for large pipelines when the construction material is under environmental corrosion conditions, as in the petroleum and gas industries. In this way, predictive models can provide a suitable framework for risk evaluation, maintenance policies and substitution procedure design that should be oriented to reduce increased hazards. This work proposes a Bayesian probabilistic approach to identify and predict the type of failure (leakage or rupture) for steel pipelines under realistic corroding conditions. In the first step of the modeling process, the mechanical performance of the pipe is considered for establishing conditions under which either leakage or rupture failure can occur. In the second step, experimental burst tests are used to introduce a mean probabilistic boundary defining a region where the type of failure is uncertain. In the boundary vicinity, the failure discrimination is carried out with a probabilistic model where the events are considered as random variables. In turn, the model parameters are estimated with available experimental data and contrasted with a real catastrophic event, showing good discrimination capacity. The results are discussed in terms of policies oriented to inspection and maintenance of large-size pipelines in the oil and gas industry.

Brito, A. J. and de Almeida, A. T. (2009) 'Multi-attribute risk assessment for risk ranking of natural gas pipelines', *Reliability Engineering and System Safety*. doi: 10.1016/j.ress.2008.02.014.

The paper presents a decision model for risk assessment and for risk ranking of sections of natural gas pipelines based on multi-attribute utility theory. Pipeline hazard scenarios are surveyed and the reasons for a risk assessment model based on a multi-attribute approach are presented. Three dimensions of impact and the need to translate decision-makers' preferences into risk management decisions are highlighted. The model approaches these factors by using a multi-attribute utility function, in order to produce multi-dimensional risk measurements. By using decision analysis concepts, this model quantitatively incorporates the decision-maker's preferences and behavior regarding risk within clear and consistent risk measurements. In order to support the prioritizing of critical sections of pipeline in natural gas companies, this multi-attribute model also allows sections of pipeline to be ranked into a risk hierarchy. A numerical application based on a real case study was undertaken so that the effectiveness of the decision model could be verified.

Brito, A. J., de Almeida, A. T. and Mota, C. M. M. (2010) 'A multicriteria model for risk sorting of natural gas pipelines based on ELECTRE TRI integrating Utility Theory', *European Journal of Operational Research*. doi: 10.1016/j.ejor.2009.01.016.

This paper proposes a multicriteria model for assessing risk in natural gas pipelines, and for classifying sections of pipeline into risk categories. The model integrates Utility Theory and the ELECTRE TRI method. It aims to help transmission and distribution companies, when engaged in risk management and decision-making, to consider the multiple dimensions of risk that may arise from pipeline accidents. Pipeline hazard scenarios are presented, and it is argued that the assessment of risk in natural gas pipelines should not be based solely on probabilities of human fatalities, but should involve a wider perspective that simultaneously takes into consideration the human, environmental and financial dimensions of impacts of pipeline accidents. Finally, in order to verify the effectiveness of the model set out, a numerical application based on a real case study is presented.

Cagno, E. *et al.* (2000) 'Using AHP in determining the prior distributions on gas pipeline failures in a robust Bayesian approach', *Reliability Engineering and System Safety*. doi: 10.1016/S0951-8320(99)00070-8.

The paper proposes a robust Bayesian approach to support the replacement policy of low-pressure cast-iron pipelines used in metropolitan gas distribution networks by the assessment of their probability of failure. In this respect, after the identification of the factors leading to failure, the main problem is the historical data on failures, which is generally limited and incomplete, and often collected for other purposes. Consequently, effective evaluation of the probability of failure must be based on the integration of historical data and knowledge of company experts. The Analytic Hierarchy Process has been used as elicitation method of expert opinion to determine the a priori distribution of gas pipeline failures. A real world case study is presented in which the company expertise has been elicited by an ad hoc questionnaire and combined with the historical data by means of Bayesian inference. The robustness of the proposed methodology has also been tested.

Chen, H. *et al.* (2004) 'Application of support vector machine learning to leak detection and location in pipelines', *Proceedings of the 21st IEEE Instrumentation and Measurement Technology Conference (IEEE Cat. No.04CH37510)*. doi: 10.1109/IMTC.2004.1351546.

Leak detection in oil pipelines is important for safe operation of pipelines. Negative Pressure Wave (NPW) in pressure curve can be an indication of leakage of a pipeline. In this paper, we propose to use the support vector machine (SVM) learning to detect NPW in pressure curves. In the approach, NPW's detection is formulated as a supervised-learning problem and the method of SVM is employed to develop the detection algorithm. The proposed method is evaluated using a database of 1500 pressure curves containing 500 NPWs. Experimental results demonstrate that, when compared to the Wavelet based methods, the proposed SVM framework offers the better performance.

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Dziubiński, M., Fratczak, M. and Markowski, A. S. (2006) 'Aspects of risk analysis associated with major failures of fuel pipelines', *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2005.10.007.

This paper presents a methodology of risk assessment for hazards associated with transportation of dangerous substances in long pipelines. The proposed methodology comprises a sequence of analyses and calculations used to determine basic reasons of pipeline failures and their probable consequences, taking individual and societal risk into account. A specific feature of this methodology is a combination of qualitative (historical data analysis, conformance test and scoring system of hazard assessment) and quantitative techniques of pipeline safety assessment. This enables a detailed analysis of risk associated with selected hazard sources by means of quantitative techniques. On the ground of this methodology typical problems that usually pose serious threat and constitute part of risk analysis for long fuel pipelines are also presented. To verify above methodology, complete risk analysis was performed for the long distance fuel pipeline in Poland.

Guo, Y. *et al.* (2016) 'A novel method of risk assessment based on cloud inference for natural gas pipelines', *Journal of Natural Gas Science and Engineering*. doi: 10.1016/j.jngse.2016.02.051.

The safety of natural gas pipelines not only is very important to the economy but also significantly affects social security, considering the flammable property of natural gas. This study proposes a risk assessment method based on cloud inference, with multiple factors such as third-party damage, corrosion damage, misuse of factors, design flaws, biological erosion, aging factors, and so on. First, an assessment index system is established, considering the risk factors that may lead to an accident by using a fault tree analysis (FTA). Second, the index weights and index scores are established via the analytic hierarchy process (AHP) and expert scoring method, respectively. Third, the marking results of experts are transformed into the numerical characteristics of a cloud model by using the backward cloud generator. Finally, the whole assessment cloud droplet distribution of a natural gas pipeline is acquired by using the normal cloud generator and virtual cloud. The risk assessment result of natural gas pipelines using the cloud inference method indicates that the whole risk evaluation level can be clearly shown. Moreover, the cloud inference method can solve the fuzziness and randomness of the quantitative description and qualitative concept transformation in the risk assessment process for natural gas pipelines.

Han, Z. Y. and Weng, W. G. (2010) 'An integrated quantitative risk analysis method for natural gas pipeline network', *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2010.02.003.

Natural gas industry is developing rapidly, and its accidents are threatening the urban safety. Risk management through quantitative assessment has become an important way to improve the safety performance of the natural gas supply system. In this paper, an integrated quantitative risk analysis method for natural gas pipeline network is proposed. This method is composed of the probability assessment of accidents, the analysis of consequences and the evaluation of risk. It is noteworthy that the consequences analyzed here include those of the outside and inside gas pipelines. The analysis of consequences of the outside pipelines focuses on the individual risk and societal risk caused by different accidents, while those of the inside pipelines concerns about the risk of the economic loss because of the pressure re-distribution. Risk of a sample urban gas pipeline network is analyzed to demonstrate the presented method. The results show that this presented integrated quantitative risk analysis method for natural gas pipeline network can be used in practical application.

Han, Z. Y. and Weng, W. G. (2011) 'Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network', *Journal of Hazardous Materials*. doi: 10.1016/j.jhazmat.2011.02.067.

In this paper, a qualitative and a quantitative risk assessment methods for urban natural gas pipeline network are proposed. The qualitative method is comprised of an index system, which includes a causation index, an inherent risk index, a consequence index and their corresponding weights. The quantitative method consists of a probability assessment, a consequences analysis and a risk evaluation. The outcome of the qualitative method is a qualitative risk value, and for quantitative method the outcomes are individual risk and social risk. In comparison with previous research, the qualitative method proposed in this paper is particularly suitable for urban natural gas pipeline network, and the quantitative method takes different consequences of accidents into consideration, such as toxic gas diffusion, jet flame, fire ball combustion and UVCE. Two sample urban natural gas pipeline networks are used to demonstrate these two methods. It is indicated that both of the two methods can be applied to practical application, and the choice of the methods depends on the actual basic data of the gas pipelines and the precision requirements of risk assessment.

Hou, Q. *et al.* (2014) 'Experimental study of leakage detection of natural gas pipeline using FBG based strain sensor and least square support vector machine', *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2014.08.003.

Leakage is the most common cause of natural gas pipeline accidents. This work was devoted to natural gas pipeline leakage detection, which is based on detecting negative pressure wave signals caused by leakage. The FBG strain sensor, which is based on monitoring the hoop strain of a pipeline to detect negative pressure wave signals, is fabricated and experimentally tested. Compared to conventional pressure sensors, FBG strain sensors were shown to be less influenced by noise, and they have the advantage of being a nondestructive sensing method. This makes them ideal for sensing pressure transients, which could be analyzed to detect natural gas pipeline leakage. Toward this objective, a least square support vector machine (LS-SVM) classifier was developed as an automatic leakage detection technique. This technique proved to be effective at detecting leakage.

Jafari, H. R. (2011) 'Applying Indexing Method to Gas Pipeline Risk Assessment by Using GIS: A Case Study in Savadkooh, North of Iran', *Journal of Environmental Protection*, 02(07), pp. 947–955. doi: 10.4236/jep.2011.27108.

Gas pipelines are environmentally sensitive because they cross varied fields, rivers, forests, populated areas, desert, hills and offshore and also different parameters in gas transmission progresses are effective. Underground gas trans-mission pipelines have been grown as one of the low risk methods with low cost in the world specially in middle east and Europe. Physical and chemical properties of liquid gas, pipeline properties and also its environmental condition are the main factors of increasing the technical and environmental risk. In this article the quantitative risk assessment has been done by using GIS and overlaying the information layers. For this purpose, all effective risk factors were identified and projected. In order to achieve the same and comparable results, the entire pipeline route was divided into 500 meter intervals and the risk was calculated in each interval, finally the scores of these intervals such as each criterion risk was calculated. The case study of the article is Savadkooh to PoleSefid pipeline in Mazandaran.

Jo, Y. D. and Bum, J. A. (2005) 'A method of quantitative risk assessment for transmission pipeline carrying natural gas', *Journal of Hazardous Materials*. doi: 10.1016/j.jhazmat.2005.01.034.

Regulatory authorities in many countries are moving away from prescriptive approaches for keeping natural gas pipelines safe. As an alternative, risk management based on a quantitative assessment is being considered to improve the level of safety. This paper focuses on the development of a simplified method for the quantitative risk assessment for natural gas pipelines and introduces parameters of fatal length and cumulative fatal length. The fatal length is defined as the integrated fatality along the pipeline associated with hypothetical accidents. The cumulative fatal length is defined as the section of pipeline in which an accident leads to N or more fatalities. These parameters can be estimated easily by using the information of pipeline geometry and population density of a Geographic Information Systems (GIS). To demonstrate the proposed method, individual and societal risks for a sample pipeline have been estimated from the historical data of European Gas Pipeline Incident Data Group and BG Transco. With currently acceptable criteria taken into account for individual risk, the minimum proximity of the pipeline to occupied buildings is approximately proportional to the square root of the operating pressure of the pipeline. The proposed method of quantitative risk assessment may be useful for risk management during the planning and building stages of a new pipeline, and modification of a buried pipeline.

Jones, J., Gahagan, B. and Gros-potter, N. (2014) 'Preliminary Mustang IDP Pipeline Risk Evaluation', pp. 8–25.

Lu, L. *et al.* (2015) 'A comprehensive risk evaluation method for natural gas pipelines by combining a risk matrix with a bow-tie model', *Journal of Natural Gas Science and Engineering*. doi: 10.1016/j.jngse.2015.04.029.

Leakage from natural gas pipelines causes severe economic loss and significantly affects social security considering the gas' combustibility and the difficulties in detecting leakage. This study proposes a comprehensive risk evaluation method by combining a risk matrix with a bow-tie model. First, a bow-tie model is built, considering the risk factors that may lead to an accident using a fault tree; the consequences of unwanted events are then described in an event tree. Second, a fuzzy method is used to calculate the failure probabilities. Third, the severity of an accident is evaluated through an index system that includes personal casualties, economic losses and environmental disruptions. Finally, a risk matrix consisting of a probability ranking criterion and a consequence ranking criterion is proposed to reach an integrated quantitative conclusion of a bow-tie model. A case study of an underwater pipeline carrying natural gas has been investigated to validate the utility of the proposed method.

Ma, L., Cheng, L. and Li, M. (2013) 'Quantitative risk analysis of urban natural gas pipeline networks using geographical information systems', *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2013.05.001.

This paper presents a novel quantitative risk analysis process for urban natural gas pipeline networks using geographical information systems (GIS). The process incorporates an assessment of failure rates of integrated pipeline networks, a quantitative analysis model of accident consequences, and assessments of individual and societal risks. Firstly, the failure rates of the pipeline network are calculated using empirical formulas influenced by parameters such as external interference, corrosion, construction defects, and ground movements. Secondly, the impacts of accidents due to gas leakage, diffusion, fires, and explosions are analyzed by calculating the area influenced by poisoning, burns, and deaths. Lastly, based on the previous analyses, individual risks and social risks are calculated. The application of GIS technology helps strengthen the quantitative risk analysis (QRA) model and allows construction of a QRA system for urban gas pipeline networks that can aid pipeline management staff in demarcating high risk areas requiring more frequent inspections. © 2013 Elsevier Ltd.

Medeiros, C. P., Alencar, M. H. and de Almeida, A. T. (2017) 'Multidimensional risk evaluation of natural gas pipelines based on a multicriteria decision model using visualization tools and statistical tests for global sensitivity analysis', *Reliability Engineering and System Safety*. doi: 10.1016/j.ress.2017.04.002.

Multidimensional risk analysis in pipelines has been addressed in the literature in recent years which has led to a greater understanding of risk in the decision context. A risk assessment model based on different perspectives becomes attractive to decision-makers (DMs) who are responsible for the maintenance of pipelines, and can help to prioritize maintenance efforts, and therefore optimize the use of human financial and other resources. As to the transportation of gas by pipeline, efforts at risk analysis must consider the physical and operational characteristics of the product, failure modes and their consequences, based on each accidental scenario considered. Different parameters are collected and/or estimated in order to produce a recommendation for the DM. Therefore, this paper enhances previous suggestions for a multi-criteria decision model that evaluates multidimensional risk by using visualization tools and statistical tests as part of global sensitivity analysis. Simulations are made considering patterns which provide the DM with information about the uncertainty of different groups of parameters for the model. Furthermore, the output of the disturbance can be checked based on Kendall's correlation coefficient. Finally an evaluation can be made graphically of the different rankings of sections, thereby making a more assertive recommendation to the DM.

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Shahriar, A., Sadiq, R. and Tesfamariam, S. (2012) ‘Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis’, *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2011.12.007.

Vast amounts of oil & gas (O&G) are consumed around the world every day that are mainly transported and distributed through pipelines. Only in Canada, the total length of O&G pipelines is approximately 100,000 km, which is the third largest in the world. Integrity of these pipelines is of primary interest to O&G companies, consultants, governmental agencies, consumers and other stakeholder due to adverse consequences and heavy financial losses in case of system failure. Fault tree analysis (FTA) and event tree analysis (ETA) are two graphical techniques used to perform risk analysis, where FTA represents causes (likelihood) and ETA represents consequences of a failure event. 'Bow-tie' is an approach that integrates a fault tree (on the left side) and an event tree (on the right side) to represent causes, threat (hazards) and consequences in a common platform. Traditional 'bow-tie' approach is not able to characterize model uncertainty that arises due to assumption of independence among different risk events. In this paper, in order to deal with vagueness of the data, the fuzzy logic is employed to derive fuzzy probabilities (likelihood) of basic events in fault tree and to estimate fuzzy probabilities (likelihood) of output event consequences. The study also explores how interdependencies among various factors might influence analysis results and introduces fuzzy utility value (FUV) to perform risk assessment for natural gas pipelines using triple bottom line (TBL) sustainability criteria, namely, social, environmental and economical consequences. The present study aims to help owners of transmission and distribution pipeline companies in risk management and decision-making to consider multi-dimensional consequences that may arise from pipeline failures. The research results can help professionals to decide whether and where to take preventive or corrective actions and help informed decision-making in the risk management process. A simple example is used to demonstrate the proposed approach.

Vianello, C. and Maschio, G. (2014) 'Quantitative risk assessment of the Italian gas distribution network', *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2014.07.004.

European Critical Infrastructures include physical resources, services, information technology facilities, networks and infrastructure assets, which, if disrupted or destroyed would have a serious impact on the health, safety, security, economic or social well-being of the Member States. The gas distribution network is a critical infrastructure and its failure can cause damage to structures and injury to people. The aim of this paper is to analyze and then assess the risk of the Italian high pressure natural gas distribution network. The paper describes an application of a methodology for quantitative risk assessment. Failure frequencies considered in risk calculation were found in the European Gas pipeline Incident data Group (EGIG) database, whereas consequences were computed as a function of pipe diameter and operating pressure for each section of the network. The results of this quantitative risk assessment is the determination of local and social risks for the Italian North East Area. © 2014.

Wang, W. *et al.* (2017) 'Failure probability analysis of the urban buried gas pipelines using Bayesian networks', *Process Safety and Environmental Protection*. doi: 10.1016/j.psep.2017.08.040.

Failures of urban buried gas pipelines have caused significant fire and explosion accidents with tremendous losses. This work presents an advanced two-step approach to analyze failure probabilities of the urban buried gas pipeline. First, a logical failure model is developed with the operational, material and environmental parameters contributing to the failure (Fault Tree Analysis). Second, the logical model is transformed into a network model (Bayesian Network). This novel approach can better reveal the relationships among failure causal factors and can also update the failure probabilities as operational and environmental conditions evolve. The Bayesian network failure model is subsequently applied to a case study. The results indicate that this approach is feasible and reasonable which can assist in identifying safety critical factors. Improving reliability of these safety critical factors can be of great help in enhancing the safety of urban buried gas pipelines.

Wu, J. *et al.* (2017) 'Probabilistic analysis of natural gas pipeline network accident based on Bayesian network', *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2017.01.025.

Natural gas pipeline network (NGPN) accident is a kind of catastrophic disaster as the hazard of natural gas may present a large-scale extension in NGPN that can easily result in cascading accidents. In this paper, the Bayesian network (BN) was employed to probabilistically analyze natural gas pipeline network accidents. On the basis of case-

studies of typical NGPN accidents, eleven BN nodes were proposed to represent the evolution process of natural gas pipeline network accidents from failure causes to consequences. The conditional probabilities of every BN node were determined by expert knowledge with weighted treatments by the Dempster-Shafer evidence theory. Through giving evidences of some BN nodes with certain state values, the probabilities of evolution stages and consequences of the natural gas pipeline network accident can be estimated. The results indicate that the combination of Bayesian network and Dempster-Shafer evidence theory is an alternative method for evaluating NGPN accident, and the proposed framework can provide a more realistic consequence analysis since it could consider the conditional dependency in the evolution process of the NGPN accident. This study could be helpful for emergency response decision-making and loss prevention.

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