A Critical Review of Pipeline Risk Modeling Approaches

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Abstract
There are many different risk modeling approaches employed in pipeline risk management. A critical review is provided of the primary approaches and their advantages and disadvantages. The key capabilities/limitations of each approach are assessed in terms of data requirements, model complexity, predictive capabilities and accuracy.

Introduction
The approach to asset management of gas distribution systems is rapidly evolving. Utilities, prompted by multiple drivers, are more and more moving towards proactive risk-aware or risk-based asset management approaches. As "Risk" is an inherently uncertain topic, and risky outcomes cannot be perfectly foreseen, effective risk modeling approaches are core components of good pipeline risk management processes.

As noted in the NTSB Safety Study on *Integrity Management of Gas Transmission Pipelines in High Consequence Areas*, there are multiple types of risk assessment permitted under the PHMSA IMP rules:
Risk is often defined as the product of (1) the likelihood of a failure occurring, and (2) the consequences of that failure. Operators are required to use one or more of the following types of risk assessment approaches:

- *Subject Matter Expert (SME): In this approach, SMEs (either pipeline employees or contractors) use their collective expertise and knowledge of a particular pipeline system to determine the likelihood and consequence of failures, leading to estimates of the risk of failure of each pipeline segment in the system.*
- *Relative Assessment Models: In this approach, algorithms (using known or estimated pipeline characteristics, SME input, historical failure experience, and failure models) assign a risk score for each threat on a pipeline segment. These threat-specific risk scores are then weighted and summed to produce an overall relative risk value for each pipeline segment.*
- *Scenario-Based Models: In this approach, various risk-producing scenarios are described (for example, using event tree or fault tree analysis), including their likelihoods and consequences.*
- *Probabilistic Models: In this approach, probabilities (in contrast to the previous approaches, which used relative likelihoods) are calculated. This approach allows an absolute risk value to be calculated for each pipeline segment (for example, deaths per mile per year). If consequences are monetized, this approach also enables monetization of risk (for example, dollars per mile per year).*

The results of the risk assessment approach(es) are threat-specific risk estimates for each pipeline segment within an HCA; these estimates can be considered on their own or with other threat risks. Using these results, operators can prioritize pipeline segments for integrity assessment, choose the appropriate assessment tool(s), and determine which P&M measures should be taken. [1]

There is growing discussion in the pipeline industry around moving more quickly toward probabilistic / quantitative risk modeling approaches that measure risk in absolute terms and moving away from the other approaches based on more subjective risk assessments such as the SME approach, index models or Relative Assessment Models. The most advanced probabilistic risk assessment (PRA) models for assets (or asset systems) effectively simulate the physical progression of failure modes in the asset, and the potential outcomes of failure, to generate a distribution of the level of risk. This paper provides a critical review of these alternative risk assessment approaches and their advantages and disadvantages.

Benefits of a Risk-Aware Asset Management Approach
There have been numerous recent developments in the area of risk-based asset management, such as the development and introduction of the ISO 55000 series[2] and PAS 55[3] asset management standards and the broad

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1 National Transportation and Safety Board, *Safety Study – Integrity Management of Gas Transmission Pipelines in High Consequence Areas.* Published January 27, 2015.

2 ISO 55001:2014 – Asset management -- Overview, principles and terminology
ISO 55002:2014 – *Asset management -- Management systems – Requirements*

movement towards quantitative or probabilistic risk assessment (PRA) methodologies. As highlighted in PAS 55, there are four critical stages in the life cycle of any asset—(1) Acquisition, (2) Operation, (3) Maintenance and (4) Disposal—and PRA methodologies are starting to be applied to all four.

The primary benefits of risk-based asset management are:
- The development of a clear overall risk picture for the asset
- The ability to make risk decisions on an informed basis
- The ability to compare risks based on the same base measure across a variety of assets with different potential for failure and consequences
- The ability to set clear desired risk targets
- The ability to reduce risk in the asset base in the most cost-effective manner

As the list above shows, risk-based asset management requires conscious and informed decisions regarding asset risk based on a clear assessment of that risk within the asset base. Critical to this is ensuring that the risk assessments upon which risk decisions are made are reflective of the true system risk. This has led to a drive towards PRAs where quantitative models are developed to create an accurate, probabilistic picture of asset risk. These probabilistic models are rapidly replacing outdated approaches such as risk indices and prescriptive maintenance and inspection practices.

Optimizing Maintenance Activities Based on Risk Benefit
A fundamental principle of modern asset management is risk-informed decision-making. In pipeline risk management, the management of all major lifecycle activities can be improved by fully considering risk:
- Acquisition
  o The level of risk introduced into the asset base by design, manufacturing, or installation should be considered and optimized with respect to minimizing the whole life economic cost of the asset.
- Operation and Maintenance
  o The risk of harm to, and the risk of damage to the asset by, operators and maintainers must be considered in any effective O&M organization.
  o Risk-Based Inspection (RBI) is a key tool in ensuring that limited inspection resources are deployed in an optimal fashion. In pipeline risk management programs many types of inspections and all can be informed by an understanding of the risk of failure of the assets:
    ▪ Maintenance (e.g. oil changes) interval selection
    ▪ Failure Mode Evaluation (e.g. in-line inspection)
    ▪ Failure Finding Tasks (e.g. leak surveying)
- Disposal
  o Risk-based replacement, replacing assets when they are at (or about to be at) a higher risk of failure rather than at an arbitrary age, or when first failure occurs.

Risk-based decision-making is gaining popularity because of the significant reductions in both system risks and the costs of the overall asset management process. These techniques stand in contrast to the commonly applied approaches of reactive repair/replacement (i.e. "fix it when it breaks"), prescriptive inspection (i.e. inspection on a predefined schedule), calendar-based replacement, etc. It has been demonstrated that getting to a higher level of differentiation of risk among assets, up to assessing risk on an individual component basis, can provide the opportunity for significant risk and cost reductions, and can also provide for significant improvements in long-range planning of maintenance activities.

Modeling the Risk of Failure of Gas Network Assets
Effective pipeline risk management programs are developed based on looking at both the probability of failure of the components in the system and the potential consequences of failure. This reflects the traditional definition of risk as the probability of failure times the consequence of failure. While there are many potential approaches to both estimating probability of failure and consequences, the state-of-the-art approach is to use probabilistic

modeling tools. In this approach, the probability of failure of each individual asset component is determined based on statistical or mechanistic modeling, typically utilizing past performance data for the asset and ideally incorporating an understanding of the specific mechanisms of failure. For example, vintage plastic pipelines manufactured from the same material installed in the same year could have significantly different probability of failures based on the end-use operating pressures, with higher failure probability for the higher pressure systems.

Similarly, consequence modeling must also be based on a probabilistic approach where the probability of consequences of different magnitudes are developed based on the specifics of the system and failures that are occurring. For example, a rupture of a high-pressure gas pipeline in a high density urban setting has the potential for significantly higher consequences then a slow leak that develops in a rural area – the specific consequences for each of these events can be measured in a probabilistic way based on consideration of factors such as distribution of potential leak size, distribution of potential gas release volumes, potential for ignition sources, and so on.

Modern Probabilistic Risk Models
Risk Definition Used in Analysis
Fundamental to any effective asset management plan is an understanding of the risk of failure of the assets covered by the plan, particularly of the probability (or likelihood) of failure and the likely consequences of failure. The combination of these two factors allows for the development a measure of the risk in an asset base:

(1)

Risk = Probability of Failure (PoF) X Consequences of Failure (CoF)

Risk management (e.g., reduction) efforts can be directed at reducing the PoF, the CoF, or both. Typically for distribution system assets, the focus is on reducing the PoF – i.e., avoiding leaks through effective design and timely replacement at the end of life of an asset. In addition, significant efforts are put in place to minimize the consequences of leaks when they do occur. These measures include regular leak survey programs to allow repairs of leaks before incidents occur and the addition of strong odorants (e.g., mercaptans) that allow people in the vicinity of a leak to evacuate the area and notify the pertinent authorities to enable a repair before an incident occurs.

Probability of Failure (PoF)
Understanding of the probability of failure may come from direct observation of the current state of the asset through physical modeling or accelerated testing, through actions such as inspection, condition monitoring or sampling and testing programs, or by analysis of the statistical patterns of the failures of similar assets in service, or by some combination of these.

PoF: Historical Analysis of Failure
As many utilities have devoted significant resources to tracking the service histories of their assets, statistical analysis of the failures of pipeline assets is possible, particularly analysis of the times to failure. Such analysis is often called reliability analysis.

An asset's reliability is the probability that it will perform its expected or desired function over a certain time, given a certain set of operating conditions. A useful mathematical description of an asset's reliability is given by its reliability function, which can incorporate knowledge about how its probability of failure changes as it ages. The reliability function, $R(t)$, provides the proportion of the population that has not failed by time t and is expressed mathematically as:

(2)

$$R(t) = \Pr(T \geq t),$$

where *T* is the typically random time to failure of an asset.

The reliability function for an asset is a representation of the distribution of times to failure of that asset. Therefore, the asset's reliability may be equivalently expressed in terms of the probability density function[4] (PDF,

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[4] The probability density function (PDF) describes the proportion of a [statistical] population that will experience an event of interest *at* time *t*.

often written as $f(t)$), the cumulative density function[5] (CDF, often written as $F(t)$), or the hazard rate[6] ($h(t)$). For assets that are repaired on failure, such as pipeline assets, the hazard rate is often equivalent to the failure intensity—the overall rate of occurrence of failures[7].

The reliability of an asset may be dependent on its age and other operating factors. Thus, to effectively model mathematically the reliability of assets in a pipeline network, information on their installation times, failure and/or repair times, operating parameters and construction parameters are required. Using these parameters, a general reliability model may be constructed and used to predict the risk of failure of the components in the installed asset base.

PoF: Physical Modeling
In physical probabilistic modeling of the probability of failure (PoF) of an asset, two useful approaches are the stress-strength model (also called the limit state or static reliability approach), and the Exposure-Mitigation-Resistance approach.

Static reliability is often expressed in terms of the stress-strength model[8], where the stochastic distribution of the variable X that measures the strength of an asset (e.g. the wall thickness) is compared to the distribution of the stress Y (e.g. hoop stress due to internal pressure), which may cause it to fail over some time period T[9]. If there is some knowledge of these distributions over an interval [0,T], then the reliability of the asset over the interval [0,T] is given as:

(3)

$$R(t) = Pr[X > Y], t \in [0,T].$$

Here, the reliability is constant, as we assume that the distributions are stationary in time. If the distributions are changing in time, as might be expected with the wall thickness of a corroding steel pipeline, then the model can be used to estimate the likelihood of failure as an asset ages.

A less math-heavy approach for physically modeling the likelihood of failure of pipelines – effectively a simplified and more direct version of the Stress-Strength model above – the Exposure-Mitigation-Resistance method is a useful approach for understanding the PoF, which can be represented as[10]:

(4)

$$PoF = exposure \times (1 – mitigation) \times (1 – resistance)$$

where:
- Exposure is an event which, in the absence of any mitigation, can result in failure if insufficient resistance exists.
- Mitigation is the effectiveness of all activities designed to stop the exposure (a number between 0 and 1 representing the probability of the mitigation stopping the exposure, 1 representing 100% effectiveness).
- Resistance is a measure or estimate of the ability of the component to absorb the exposure force without failure once the exposure reaches the component (a number between 0 and 1 representing the probability of the component to resist failure, 1 representing a design or component that is completely resistant to the exposure event of interest).

In general, these advanced probabilistic likelihood of failure models for assets (or asset systems) effectively simulate the physical progression of failure modes in the asset to generate a distribution of the level of risk in the asset.

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[5] The cumulative density function (CDF) describes the proportion of a [statistical] population that will experience an event of interest *by* time *t*.
[6] The hazard rate (h(t)) is the expected rate at which an individual asset will fail given that it is operating at time *t*.
[7] Luff, W.J.M. (2012). *Reliability Models for Linear Assets*. Master's Thesis, University of Toronto, http://hdl.handle.net/1807/32482
[8] Samuel Kotz, Yan Lumelskii, and Marianna Pensky, The Stress-Strength Model and Its Generalizations. New Jersey: World Scientific, 2003.
[9] For example, X may be the yield strength distribution of a circular pipe given an uncertain set of pipe parameters, whereas Y may be the expected distribution of pressures of the fluid carried within the pipe over a given time interval T; the chance that the pipe will fail over each time interval T is P[X>Y].
[10] K. Muhlbauer, Pipeline Risk Assessment: The Definitive Approach and Its Role in Risk Management, Clarion, 2015.

PoF: Pipe Performance Testing
Uncertainty around the current condition of piping assets is a major source of risk to pipeline operators. The uncertainty can be reduced by assessing the current state of the asset base through direct examination of the assets or physical testing of a sample of the asset base. Direct examination of the asset, as in in-line inspection, can provide highly certain and specific information about the current strength of an asset and its ability to resist the stresses applied to it. A carefully designed sampling program can do a similar thing, in that it can provide highly useful and specific information about the distribution of, for example, the strength of a population of assets, allowing for more accurate risk assessments and a lower level of asset risk.

Consequences of Failure (CoF)
Knowledge of the consequences of failure (CoF) for gas distribution assets can come from historical (statistical) analysis of previous failures, physical modeling of the system or some combination of both. Consequences of failure can range from simple service interruption and associated foregone sales income, to the cost of repairing a leak, to the significant costs associated with evacuation and disruption of use of a property, to the worst case for gas facilities – injuries or fatalities.

In physical probabilistic modeling of the consequences of failure for gas facilities, the CoF can often be represented as:

(5)
$$CoF = (Hazard\ Zone\ Size) \times (Receptor\ Density)$$

where:
- Hazard Zone Size is typically dependent on the amount of gas that has accumulated in an area, which can depend on pressure, flow rate, soil type, ground cover and proximity to enclosed spaces (e.g., buildings).
- Receptor Density is a measure of the number of people or value of property near an asset that may be injured in the event of a failure.

In this approach, the CoF is calculated for each specific threat or exposure type. A similar approach, often incorporating though one that is often more resource intensive, is the scenario model approach.

Scenario-based models for estimating consequences of failure are used in many industries as design aids to identify potential safety or other risks in a design (e.g. in a HAZOP or LOPA analysis), as they permit both quantitative and semi-quantitative evaluations of likelihood and consequence. Depending on the approach taken by the user, these scenario-based models may use subjective information (e.g. SME or relative assessment) as inputs, or may be made into probabilistic models with the likelihood and consequence of each event (branch) in the tree described with quantitative and statistically- or physically-based information.

A suite of scenario models with quantitative and validly-derived inputs, and describing all of the possible faults or adverse events and consequences that a system may experience, will provide a useful and informative probabilistic consequences of failure assessment for that system, so long as the various fault and event trees that describe the risks in the system are integrated together correctly to account for interactive threats and common cause failures.

Historical Risk Models
Several different types of risk modelling approaches have been used in the past to help manage the risk of failure of pipelines. Not all of these older methods attempt to find a reliability function (or failure rate, etc.) for each asset, as would be done in a modern probabilistic approach; several different approaches for understanding or estimating risk have been used, and mot all of them are based on the probabilistic view of risk. This section provides a discussion on historical risk modelling approaches such as expert judgement and fix-on-fail (i.e. no model), that are still in use in some situations in the modern gas industry, but which have largely been replaced by index-type models or modern probabilistic approaches.

No Formal Model

No formal "model" for the reliability of the asset – that is, an asset management or risk management process where failures simply occur and are fixed – is quite a common occurrence throughout many industries. However, one should be under no illusion that this is, implicitly, still a risk model; it is one where one only knows, perfectly, whether or not the asset is working at a particular time. This model is a completely reactive approach to managing risk – and thus is quite simple to implement and use – but it generally is not cost effective, particularly when the cost of failure is large. This type of approach can lead to a tolerance of leaks or failures. Fortunately, most utilities have moved away from such "fix-on-fail" maintenance and risk management practices.

Expert Judgement

Expert Judgement, or the Subject Matter Expert (SME) approach, is one where pipeline experts use their expertise and knowledge of pipelines to attempt to estimate the likelihood of failures and, sometimes, the consequences of such failures. Such estimates or rankings usually involve an engineer giving an opinion as to what lines are most likely to fail, usually on a relative basis (e.g. "Pipe segment A is less reliable than segment B"). The SME approach is often one of the first approaches used in risk management as it is easy to implement, engages employees or other stakeholders and can, if done carefully, produce useful and meaningful results that can support good risk management activities.

However, there are several drawbacks to using the SME approach. First is that the rankings are almost always relative, which makes managing risks on a cost-benefit basis difficult. Second, these rankings are rarely precise: for example an SME may say "I think there's about a 20% chance it'll fail this decade". In addition, SME rankings of risks are often difficult to coordinate, both among different experts – each of whom has different life experiences and may have seen potential risks that other SMEs haven't – and within a single individual SME across time. Experience changes and recency or confirmation bias may affect one's ranking. Further, SME expertise may be limited to a particular subset of assets, making one overestimate risks one is familiar with at the expense of risks that one is not familiar with, resulting in a misdirection of resources.

Simple Age Basis

Another historical risk modeling approach commonly used is the simple age basis – the model implicitly or explicitly assumes that risk is purely age based[11]. In some situations this type of approach is generally correct; however, this model is not always appropriate and may cause a misdirection of resources away from other assets that are at greater risk of failure due to some factor other than age. As seen in *Figure 1* below, there are six generally-seen failure patterns experienced by assets or components. Of these, types A and F would see a risk benefit from a simple age-based approach, and types C and E may see a benefit; however, components experiencing failure pattern B and D would see no or negative risk benefit from the approach.

Figure 1: Failure patterns observed in industrial equipment; adapted from RCM study by Nowlan and Heap

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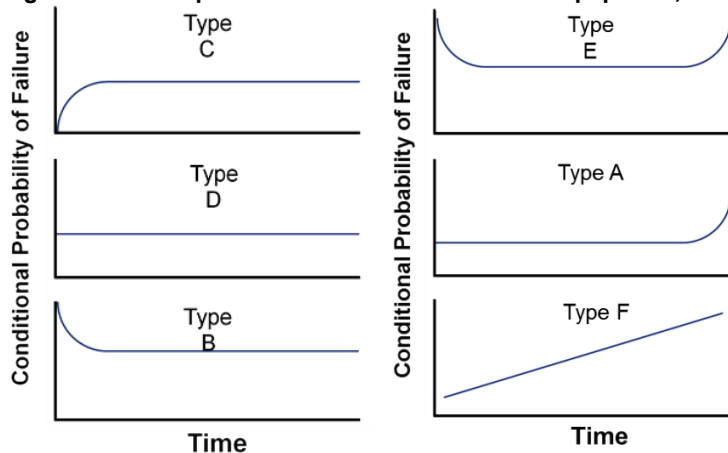
[11] It should be noted that this age-based approach is strongly aligned with the incentives in most utility regulation environments, where revenue is driven by a rate of return on the depreciated asset base, as it results in the prioritization of the replacement or maintenance of the most depreciated assets in the network. Several regulatory regimes have recognized this and are changing the rate structure to eliminate this general incentive to replace old assets, and a adopting a more performance- or risk-based approach.

Recent Risk Models

Index Models
Index models, sometimes called scoring or relative assessment models, are frequently used in the North American gas industry to model pipeline risk. These models assign a numerical model or score to important factors in asset reliability and combine them in such a way as do get a composite score that is, in some way, related to the level of risk of the pipeline. These models vary in complexity and completeness, with some being quite detailed while others are rather simplistic. One typical example might assign a total risk rating for a pipeline segment using the following two equations:

$$\text{Relative Risk Rating} = \frac{\text{Index Sum}}{\text{Leak Impact Factor}} \qquad \text{Index Sum} = \begin{cases} \text{Third Party Damage Index} \\ +\text{Corrosion Index} \\ +\text{Design Index} \\ +\text{Incorrect Operations Index} \end{cases}$$

The Index Sum in the Relative Risk Rating represents the PoF while the Leak Impact Factor represents the CoF. The Index Sum is itself a combination of several other scores reflecting the likelihood of certain issues or failure modes causing a leak.

One of the key benefits of index models is that they can be easy to implement and low cost. Analyses can be structured in such a way as to provide answers quickly and support risk management decisions in a way that can "make sense" to users. Further, complex index models often appear to be comprehensive and can include any factor the engineer feels is pertinent; they can even be implemented without significant information requirements, or in the presence of incomplete data, with suitable input from subject matter experts.

However, some of these benefits are, really, drawbacks. The appearance of comprehensiveness may mask illogical or erroneous logic and may not produce meaningful outputs. The fact that a model can include any factor the engineer feels is pertinent, whether it is physically pertinent or not, makes these types of model highly subjective and sometimes needlessly complex. Sometimes models may be based on information that has no relationship to asset reliability at all – index models can include factors that are immaterial, or may be implemented without significant information requirements or incomplete data handled in a way that does not properly reflect these items as sources of risk.

In addition, one of the most significant issues with Index models is that they often cannot be used to make projections or forecasts of future risk levels with any degree of accuracy. They are very often backward-looking models that do not fully incorporate information about the progression of failure modes.

Finally, Index models have a key challenge in communicating risk to various stakeholders, in that they provide inconsistent reporting of risk or measures of risk that are not directly connected to the world. For example, a gas distribution operator may present a rate case to its utilities board and claim that a certain action it is proposing will increase "Relative Risk Rating" of a line in a neighborhood from 56 to 88, at a cost of $4,000 per service in area, resulting in a monthly $34 increase in the bill for each customer. The change in risk rating is, in this case, almost meaningless and does not help the utility board determine whether the costs of the proposed action balance with the benefits.

Historical / Leak-based Risk Models
Several utilities have used leak or failure intensity risk assessment models – those that measure the level of risk in an asset base by the number of leaks experienced by line (generally recently). These measures are frequently used in North American distribution systems as a measure of asset health; however, there are several issues with such risk models. First is that these turn risk – a concept and measure related to uncertainty – into a measure of certain events, i.e. those that have already happened. In these approaches risk is a reactive measure of consequences experienced.

These models can, in several cases, be very useful. These situations include cases where assets are more prone to failure if they have already experienced a failure, either because the failure was caused by a damaging event that affected other parts of the line or if the failure reflects damage that has already occurred. However, such models may create a bias to only maintain assets that have been seen to fail in the past. Due to the random nature of failures, and inherent uncertainty involved in most risks, this approach can lead to different treatment of identical risks.

Transitioning to Modern Probabilistic Risk Models
Managing the transition from these models to the modern PRA models is often seen as difficult; however, this need not be the case. Transitioning from relative risk modeling to modern probabilistic (absolute) risk modeling can present many challenges for utility organizations, but the benefits are significant. Chief among the challenges in transitioning from a culture in which risk is subjective to one in which a probabilistic view of risk is taken is in how risk is viewed in the organization – if risk assessment and modeling is being done properly, changing from a relative risk approach to a probabilistic risk approach involves changing "risk" from a descriptive system feature to a business cost that should be driven down as low as possible by an efficient organization.

Key to ensuring that a cultural shift is affected among employees and other stakeholders is educating all involved in the organization on the actual measure of risk being use, and how the organization plans to manage that cost in the most effective way possible. Demonstrating that the benefits of the transition to probabilistic risk management are achievable and a plan is in place to realize them will help stakeholders see the value in the approach. Further, effective planning to handle common concerns will help ease the transition.

One of the most common concerns expressed when considering a transition to modern probabilistic risk modeling approaches is that of inadequate or uncertain data. As with any modern pipeline risk model, there are a significant number of data required for the proper functioning of a modern probabilistic risk model. As defined in ISO 31000, Risk Management is "the effect of uncertainty on objectives"[12]. In this frame the best way to conceptualize uncertainty around data in a risk model – whether due to a lack of data, poor data quality or aged data – is to treat the uncertainty in the data itself as a driver or source of risk. When seen in this light, it is clear that a plan to collect data where availability is poor or data quality is suspect is, in fact, a significant risk reduction measure for to undertake when transitioning to a more probabilistic approach to risk.

Before such a data collection plan can be implemented, however, most utilities would likely benefit from a model that can provide an estimate of the likelihood of failure of its pipeline assets even in the face of data quality issues, while providing a framework that can allow the model to evolve to handle improved data as it is gathered. There are a few approaches worth considering to accommodate these issues:
- Subject matter expert (SME) interviews
  - SME interviews can be structured in an effective way to determine the most likely value for certain parameters with a reasonable degree of accuracy; alternatively, SME interviews may be used to determine the likely distribution of values to use for model parameters, which may then be used in alternative scenarios to evaluate the probable risk of failure
- Alternative cases / scenarios
  - If data are uncertain but there is a reasonably accurate distribution of the values known, alternative cases can be considered and an average (generally weighted on the assumed likelihood of each scenario) could be considered for use as the calculated risk value
- Sampling and industry benchmarking
  - A sample of systems within an operator's network or from the broader industry's knowledge could be used to develop data distributions for the risk assessment model. Data from its own gas system will likely be most pertinent to any operator's own assets, as failure mode progression in its own operating area will be most reflective of the local environments and the maintenance and operating practices that affect its own lines
  - Broader industry data can provide a very valuable source of information for any operator's models, particularly for less-frequently-encountered failure modes, issues or interactions. Several industry

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[12] ISO 31000, *Risk Management*.

standards and guidelines have already been developed – such as those by the Institute of Gas Engineers and Managers[13] (IGEM, UK) – that assemble the current state of industry knowledge to aid in the development of risk models for natural gas pipelines. Such standards should be considered among the most useful sources of information to operators as they develops its risk models.

It must be emphasized that, if treated carefully, the risk-benefit from conducting additional data collection or verification work may be estimated using the risk model that is being implemented by the utility. A reduction in the level of uncertainty in the likelihood of failure estimate used in a system operator's risk management process may be of significant value, and this value should be weighed against the cost of additional data collection efforts.

Conclusion

The pipeline industry will experience many benefits as it moves toward more probabilistic / quantitative risk modeling approaches that measure risk in absolute terms and away from other approaches based on more subjective risk assessments such as the SME approach, index models or Relative Assessment Models. These approaches will enable risk-based decision-making that offers the potential for significant reductions in both system risks and the costs of the overall asset management process.

These modern techniques stand in contrast to the commonly applied approaches of reactive repair/replacement (i.e. "fix it when it breaks"), prescriptive inspection (i.e. inspection on a predefined schedule), calendar-based replacement, etc. It has been demonstrated repeatedly that getting to a higher level of differentiation of risk among assets, up to assessing risk on an individual component basis, can provide the opportunity for significant risk and cost reductions, and can also provide for significant improvements in long-range planning of maintenance activities. Transitions to such models from more subjective risk assessments are highly feasible, and can be achieved in a timely manner.

Many organizations, reticent to proceed due to limited data, should know that these models can be put into operation with the data that any organization currently has and offer immediate improvements to an organization's risk management. Further, these models can help point the way and identify the most valuable data that needs to be collected to reduce risk in your organization – a lack of data should no longer be considered a barrier in switching to modern PRA models.

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[13] IGEM/TD/2 Edition 2 with amendments July 2015, Communication 1779, *Assessing the risks from high pressure Natural Gas pipelines*