An Absolute Risk Model Framework for Gas Pipelines

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Abstract

Pipelines provide a safe means of transporting hazardous materials, like natural gas, relative to alternative methods. Integrity Management (IM) has and continues to play a critical role in maintaining the safety of these pipelines. Key to these IM efforts is the ability to accurately assess the risks facing pipelines due to corrosion, third party damage, etc., so that these risks can be effectively mitigated and pipeline safety maintained. Therefore, how pipeline risk is assessed plays a critical role in maintaining pipeline safety. Currently, there is growing discussion in the pipeline industry around moving toward quantitative risk modeling approaches that measure risk in absolute terms, evolving from the so called "scoring" type risk modeling approaches based on relative or index type risk assessments that have traditionally been used. This paper explores the benefits of an Absolute Risk approach based on quantitative risk modeling, highlights the key elements that should be considered in quantitative risk models and outlines a framework for developing quantitative risk models that measure risk on an absolute basis.

Pipeline Risk Fundamentals

To set the context for the discussion that follows, an overview of the common terms associated with the pipeline risk assessment process, as generally used in the industry, is presented.

The risk assessment process involves characterizing what is commonly referred to as the "set of triplets" of risk[1]:

1. What can go wrong?
2. How likely is that to happen?
3. What are the consequences if it did happen?

In the pipeline industry this is typically referred to as (1) identifying threats, (2) determining the probability of pipeline failure due to each threat (PofF) and (3) characterizing the potential consequences of failure due to each threat (CofF). The risk for a given threat is commonly defined as the probability of failure (PofF) times the consequences of failure (CofF) for that threat.

Another important component of assessing risk is the ability to characterize the impact of current or potential mitigations or barriers in reducing the PofF or the CofF (or both) and, hence, risk. By convention, a 'mitigation' is an action that is less than 100% effective in stopping an event or the consequences of that event from happening, whereas a 'barrier' is an action that is 100% effective. In practical terms, Pipeline Risk Management is typically associated with applying mitigations that reduce risk by some level. With the proper mitigations in place, pipeline risk is reduced to an acceptable level.

Pipeline Risk Management Requirements

One of the most critical elements of IM is the ability to assess the potential risk to continued safe operation of the pipeline. When the risks to pipeline safety are well known and properly characterized, risk mitigation activities can be effectively selected and applied to ensure ongoing safety of the pipeline.

The key question Pipeline Risk Management seeks to address, therefore, is: Is the level of risk acceptable and, if not, what is required to take it to an acceptable level? Doing this requires:

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[1] B. John Garrick, "Quantifying and Controlling Catastrophic Risks", Elsevier, 2008.

- Characterization of the gap between actual risk (current and future) and acceptable risk
    - Develop and verify risk models
    - Assess risk
    - Define acceptable risk
    - Assess gap
- Understanding what actions (mitigations) can be taken to align actual risk with acceptable risk
- Developing and implementing a plan to bring actual risk to acceptable levels

The first step in characterizing the gap between actual and acceptable risk is the development of risk models. Risk models can be grouped into two primary categories – qualitative and quantitative.

Qualitative risk models assess risk on the basis of qualitative measures of probability of failure and potential consequences to establish a relative ranking of risk, typically through the use of scoring or index type models. The use of these scoring or index type qualitative risk modeling approaches is common in a wide range of industries, including the pipeline industry. These approaches typically rely on the use of some type of ordinal scale, like a 1 – 10 or 1 – 5 scale, which indicates a relative order of what is being assessed. While there are many approaches, they can be classed into two broad categories: (1) additive weighted scores and (2) multiplicative risk matrices. Weighted scores typically include several ordinal scales for factors that are meant to be indicators of risk (e.g., ranking scales for factors that could impact corrosion, third party damage, incorrect operations, etc.), which are added in some way to produce an aggregate risk score. Risk matrices generally use two ordinal scales (e.g., probability and consequence) which are then multiplied together to get an aggregate score.

Scoring methods tend to be developed by subject matter experts in isolation from scientific methods in risk analysis and decision analysis. Research in the broader risk analysis community has identified several problems with scoring methods that, in many cases, make them "borderline or worthless" [2].

The key issues that have been identified with scoring type risk models are:

- Many ordinal relative ranking schemes do not provide an overall measure of risk that can be compared to the acceptable level of risk and, therefore, do not provide decisions makers with the ability to assess the level of risk reduction that is required. They are instead typically used to prioritize resource allocation at levels determined through some other process. Whether or not these resource levels are sufficient to reduce risk to an acceptable level is not explicitly considered.
- The application of ordinal ranking schemes, with subject matter experts typically assigning ratings to the different ordinal scales, often ignores the research that, without proper training and calibration, SME's are subject to bias and overconfidence errors in assigning ratings[2].
- In addition to these broader issues, research has identified many inherent issues in scoring methods that can lead to inaccurate risk rankings, even on a relative basis. These issues are even more pronounced for low probability – high consequence events. They include[2]:
    - Range compression
    - Risk Masking
    - Presumption of regular intervals
    - Presumption of independence (i.e. issues with addressing interacting threats)

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[2] D. W. Hubbard, "The Failure of Risk Management", John Wiley & Sons, 2009.

While originally considered state-of-the-art, the growing understanding of the limitations of qualitative risk models has led to consideration of quantitative risk modeling approaches. Quantitative risk models quantify the PofF and CofF using statistical and mechanistic approaches. The result is an absolute quantification of risk or expected loss on a specific basis, typically dollars, that is intended to represent a direct and 'true' measure of the risk present. Similar to qualitative risk models, quantitative risk modeling approaches seek to identify the primary drivers of risk so that appropriate risk mitigation measures can be selected and prioritized. The key distinctions are that quantitative risk models do this on an absolute, as opposed to relative, basis in terms of measuring risk and that they are built based on the fundamental mechanisms that drive failure.

Once risk models are established, the risk assessment process involves incorporating the pipeline data into the models to assess risk. Typically a dynamic segmentation process is used, where the pipeline network is broken into segments anytime there is a change in any core pipeline attribute that impacts the risk model. The risk for each threat is then calculated for each pipeline segment. For large pipeline networks this is a significant task and automated programs are typically employed. A critical component of this process is data availability and data uncertainty. Significant data collection, processing and cleansing efforts are typically required. Data uncertainty always exists and can be captured by including it in the risk modeling process so that managing the data uncertainty becomes part of the overall risk management process.

Once risk has been assessed, the current risk level needs to be compared to the acceptable level of risk for safe operation of the pipeline. This requires definition of what is the acceptable risk level. For qualitative risk modeling approaches this is, by necessity, a qualitative definition. For quantitative risk modeling approaches, a more absolute measure of acceptable risk can be defined. With both the actual risk and acceptable risk defined, then, the gap between the two can be determined. Mitigation measures can be assessed to determine the most effective and cost efficient means of closing the gap and ensuring the pipeline is operating at a risk level that provides for ongoing safe operation.

The Evolution to Quantitative Risk Modeling Approaches

There are significant advantages to evolving from qualitative to quantitative assessments of risk that derive from the ability to assess risk in absolute as opposed to relative terms. While modeling capabilities exist to achieve this evolution, the process is not a simple one. If quantitative risk models are not properly developed and implemented, they can provide inaccurate estimates of risk and hence negate their benefits. The advantages of quantitative risk modeling and a framework for the development of such risk models are presented below.

Advantages of Quantitative Risk Models

Given the process of Pipeline Risk Management outlined above, the key benefit of moving to a quantitative risk modeling approach is that quantitative models provide an absolute measure of risk in dollar terms. This enables:

- The ability to roll up all risk elements on an absolute dollar basis for communication to stakeholders
- A direct comparison with absolute measures of acceptable risk to determine the required resources to take risk to acceptable levels
- Quantification of risk reduction related to risk mitigation activities
- Ability to apply various cost-benefit analysis (CBA) approaches to optimize the application of mitigations applied to bring risk to an acceptable level in the most cost effective way
- Establishing the magnitude of risk difference between two pipeline segments on an absolute as opposed to relative basis
- Comparison of risk across asset families (e.g. linear and non-linear assets) on an absolute basis

As they utilize probabilistic evidence based on the mechanistic drivers for threats, quantitative risk analyses can also provide greater accuracy, transparency and ease of incorporation of interacting threats than can qualitative modeling approaches.

Framework for Absolute Risk Models

While absolute or quantitative risk modeling approaches have many advantages, determining absolute risk accurately is difficult. There are several key elements that need to be addressed to ensure that the models developed provide accurate estimates of true pipeline risk. These key elements are:

- All threats to the pipeline are addressed
- Both PofF and CofF are addressed
- The risk models are mechanistic (that is they capture the true mechanism of failure and the key drivers) and probabilistic
- The models are data based and uncertainty is explicitly captured
- Risk Distributions along with Point Estimates of risk are calculated
- The models are verified

An overall framework for quantitative risk models is presented below that captures each of these elements.

Addressing Pipeline Threats

Key to any risk modeling approach is ensuring that all pipeline threats are identified and captured by the risk model. While many common pipeline threats are readily identified, capturing low probability – high consequences events can be particularly challenging, as they most likely will not have been observed for a given utility. For gas pipelines, however, while there may be differences in specific components and practices, the general similarity of the systems means that pooling of historical integrity data can be used to develop a database of integrity threats, such as the high level threat categories in ASME B31.8S for transmission pipelines[3]. JANA has developed a foundational Threats Database based on industry reported data coupled with a fault tree type hazard assessment for Gas Transmission and Gas Distribution pipelines. This database is continually updated as new potential pipeline threats are identified. This type of foundational threat database can be used as a starting point framework for threat assessment, which utility SMEs (subject matter experts) can review versus the utility's specific components and operating practices to develop a comprehensive list of pipeline threats that need to be addressed in the risk model.

PofF and CofF Models

Risk models need to address both the PofF and CofF for each threat. While there is value in comparing risk as the product of PofF times CofF at an overall level, it is also important in the risk assessment process to consider the individual contributors of PofF and CofF separately so that the distinction between high probability-low consequence events and low probability-high consequence events is not lost. The risk model should, therefore, be structured to provide separate PofF and CofF estimates along the pipeline as well as overall risk.

Mechanistic-Probabilistic Models

To characterize pipeline risk, it is necessary to develop estimates of risk through risk modeling and forecasting. Both the probability of an event occurring and its potential consequences are probabilistic and depend on many factors known with varying levels of certainty. Pipeline risk, therefore, is not something that we can measure directly, like temperature; it is something that needs to be inferred, for example, by estimation through modeling. As IM is interested in both the current state of risk and risk

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[3] ASME B31.8S-2012, "Managing System Integrity of Gas Pipelines", ASME, 2013.

into the future, risk models need to be able to model the current state of risk in a pipeline and also forecast the change of that risk into the future.

Multiple studies in the broader field of risk modeling and forecasting have shown that models based on a fundamental understanding of the mechanisms driving risk provide the most accurate forecasts[2,4,5]. With an understanding of the mechanisms driving risk, the key factors driving those mechanisms can be identified and incorporated into the risk model so that the risk model models reality as closely as possible. As risk is probabilistic in nature, these models also need to be probabilistic. The result is what has been termed a mechanistic-probabilistic model approach.

An example of a mechanistic-probabilistic modeling approach for PoF is the JANA Vintage Plastic Piping Risk Model[6]. The primary material failure mode for vintage plastic piping materials (such as Aldyl piping) is slow crack growth, (SCG). The key drivers for this are the specific material (i.e. specific material resistance to SCG), external loading (e.g. rock impingement, bending stresses, etc.), operating conditions (e.g. pressure, operating temperature) and operating history (e.g. squeeze-off, time in service, etc.). A mechanistic-probabilistic model was developed based on these key drivers, base SCG performance data for the different types and generations of vintage plastic and historical filed data.

For each vintage plastic material type and vintage (e.g. Aldyl LDIW, Aldyl 5043, TR418, etc.), hazard functions based on the Weibull Model:

(1)

$$h(t)=\frac{\beta}{\eta}\left(\frac{t-t_0}{\eta}\right)^{\beta-1},$$

were developed and tuned to historical field performance data for straight pipe specimens, those affected by rock impingement, and those affected by bending moments or squeeze-offs. A similar method was used for fittings, where models of their failure rates were generated and tuned appropriately. An aggregation model approach was used and resulted in a failure intensity model of:

(2)

$$h_{Line}(t) = n_{straight} \cdot h_{straight}(t) + n_{rock} \cdot h_{rock}(t) + n_{bending} \cdot h_{bending}(t) + n_{squeeze-off} \cdot h_{squeeze-off}(t),$$

where the n_{type} were determined by multiplying empirically determined fractions (found from the historical data and varying between main and service lines) multiplied by the number of standard length segments in the length of the pipe being investigated. A similar method was used for fittings, with a typical number of fittings per unit length of mains or services being used to determine the various n_{type}; as fittings are also affected by rock impingement, bending moments, etc., all four types of failure were included in the model.

Figure 1 provides a comparison of the actual versus projected vintage plastic leaks rates for a field trial of the model over an 18 month period. The solid blue line provides the estimated mean leak rate for all pipe segments installed in a given year based on the specific material and operating conditions for the segment, the dashed blue lines provide the 95% confidence interval estimates of the model and the red squares the observed leak rate. The mechanistic-probabilistic modeling approach is seen to provide accurate PoF estimates, demonstrating the power of mechanistic-probabilistic modeling approaches.

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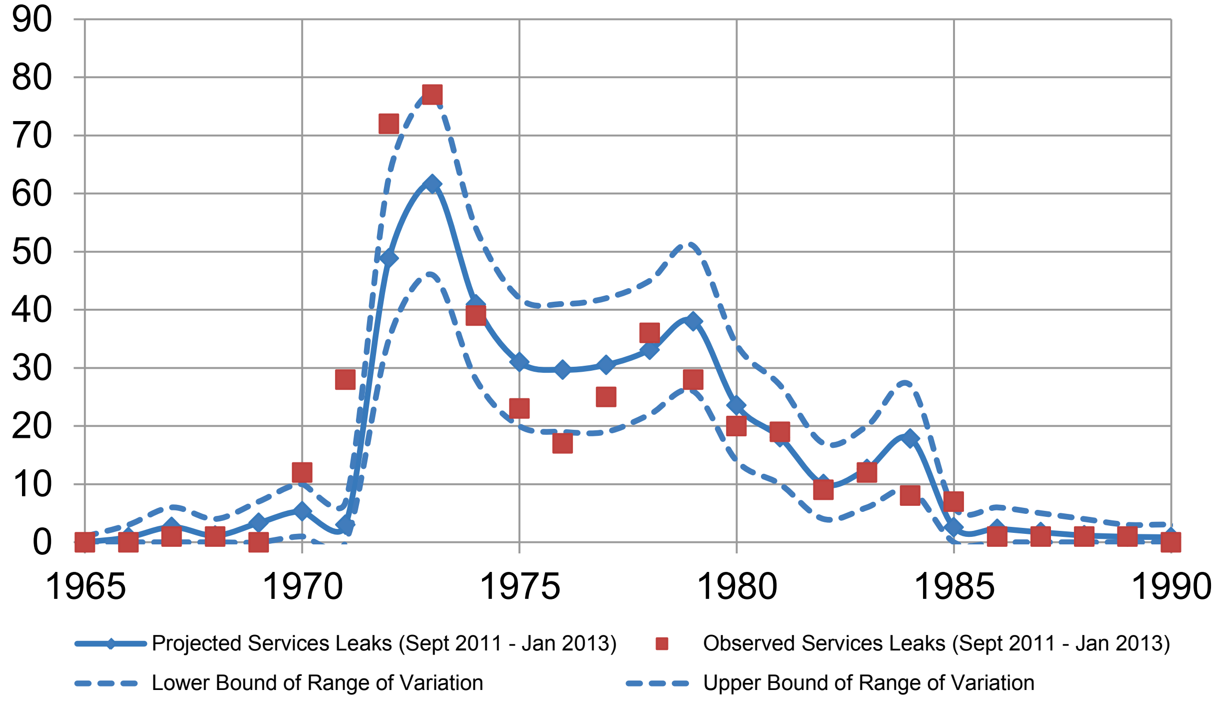
[4] N. Silver, "The Signal and the Noise", Penguin Press, 2012.

[5] P.E. Tetlock and D. Gardner, "Superforcasting – The Art and Science of Prediction", Penguin Random House, 2015.

[6] K. Oliphant et al., "A Risk Based Approach to Prioritizing Aldyl Piping Replacement in Gas Distribution Systems", PPXVII Conference, 2014.

Figure 1: Comparison of Actual versus Projected Vintage Plastic Leak Rates (PoF)



Similar mechanistic-probabilistic modeling approaches can be applied to all threat types in gas pipeline systems. The specific form of the models depends on the specific mechanism and key drivers for the threat type (e.g. corrosion, third party damage, etc.). The key is that the models are developed based on a fundamental understanding of the mechanism of potential failure and the key factors that drive this mechanism.

In addition to the PofF, the CofF also needs to be modelled. Here, two separate calculations are useful for informing Integrity Management decisions - the potential consequences and the expected consequences. The potential consequences estimate captures the possible worst case consequences. The expected consequences estimate captures the probabilities in the overall consequence string (e.g. accumulation, ignition, explosion, etc.) to arrive at an estimate of the likely consequences. The distinction is useful, through assessing the potential consequences, in explicitly identifying potential low probability-high consequence risk areas in the pipeline (this is similar to the approach used to identify HCAs (high consequence areas) in TIMP). The expected consequences estimate is used in developing the overall absolute risk estimate. Key to CofF estimates is capturing the distribution of potential consequences, which for gas pipelines follow a power law type relationship. This is discussed in a companion paper[7].

Data Driven Models with Explicit Capture of Uncertainty

Good data is key to the development of accurate estimates of risk. However, even in the absence of good data risk still needs to be assessed and managed. The recommended approach is to:

- Use all currently available data in the risk models
- Explicitly capture uncertainty in the risk models
- Use the risk assessment to direct data collection efforts

Each of these is discussed in turn below.

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[7] K. Oliphant et al., "Modeling the Consequences of Pipeline Risk", AGA Operations Conference, 2016.

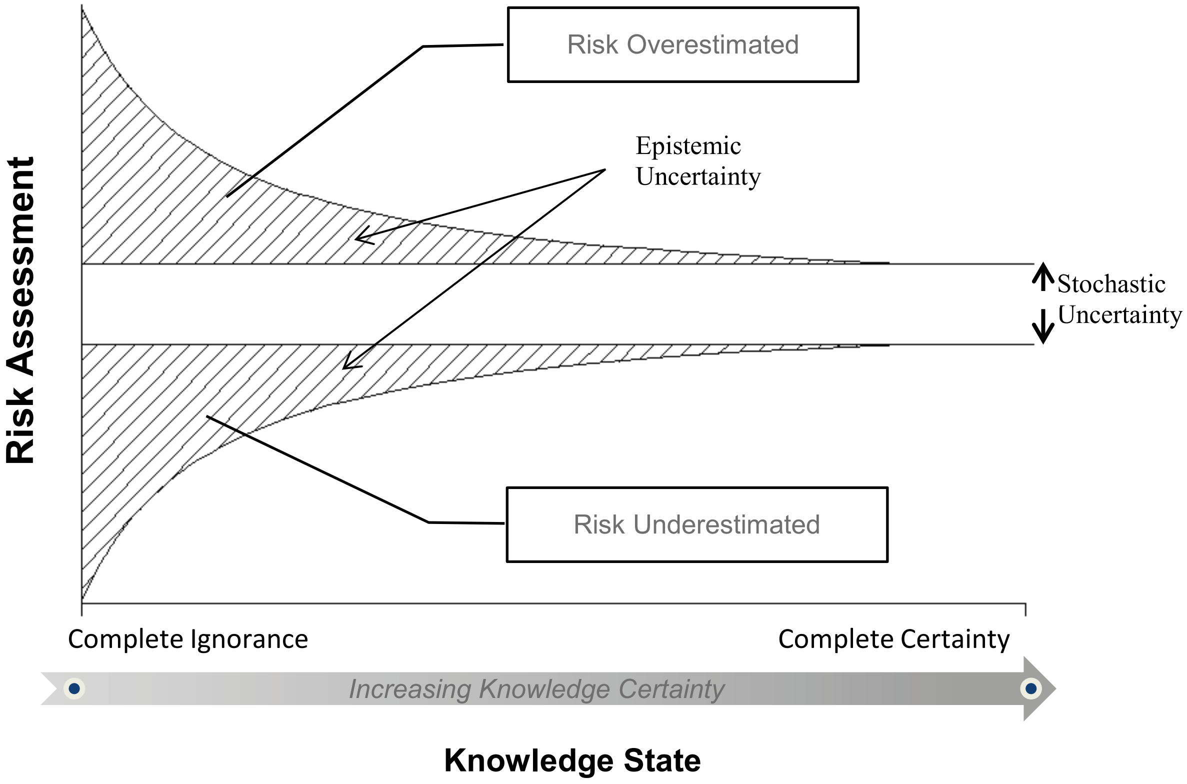
Use All Currently Available Data in the Risk Models

In risk modeling there is never enough data. The challenge is to still develop reasonable estimates of risk based on available data as, despite what data is available, risk still needs to be assessed and managed. Risk models should be structured based on the potential mechanisms of failure and the key factors driving these mechanisms. All currently available data that impacts these key factors should be included in the risk model. For currently unavailable data, industry sources (such as the PHMSA database) and SME input can be used to obtain initial estimates (see uncertainty section below for how this can be addressed in the risk model).

Explicitly Capture Uncertainty

Uncertainty is unavoidable in making risk estimates due to both imperfect information and the inherently probabilistic nature of risk. Uncertainty, therefore, needs to be explicitly captured in the risk modeling process so that it can be managed and integrated into the decision making process. These uncertainties are of two types, the underlying stochastic uncertainty ("irreducible uncertainty") and epistemic ("knowledge-based") uncertainty (**Figure 2**).

Figure 2: Impact of Uncertainty on Risk Assessments

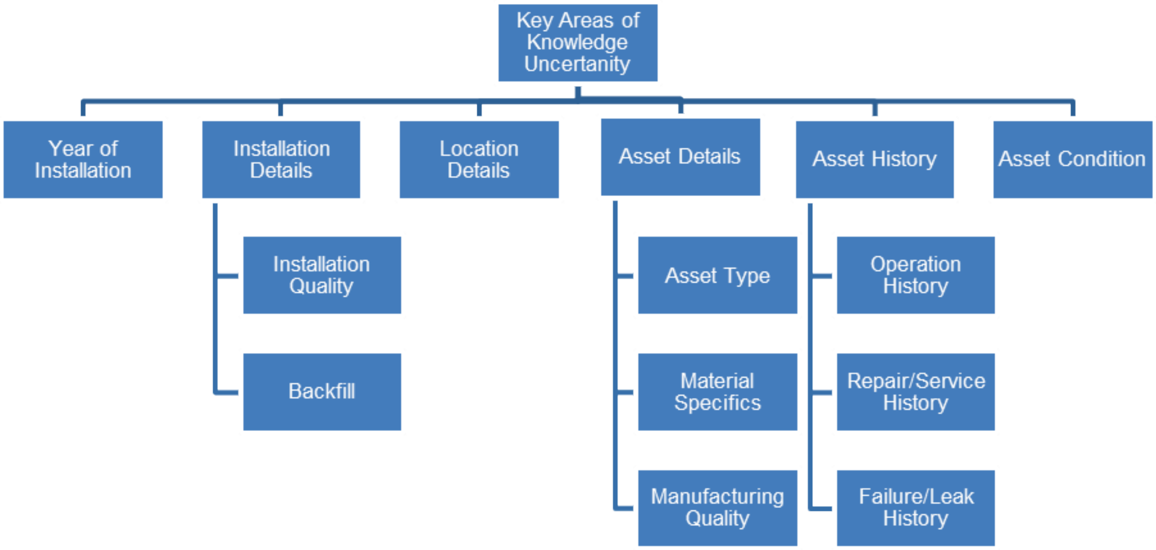


The stochastic uncertainty is due to the inherently probabilistic nature of risk in asset populations – for example, a good estimate of the probability that Aldyl pipe of a certain vintage under a given set of operating conditions will fail within a given time period can be obtained, but the precise segment of pipe that will fail at a given time cannot be determined. This irreducible uncertainty represents the best that can be achieved in terms of assessing risk when there is complete knowledge certainty.

The uncertainty arising from incomplete or imperfect knowledge (epistemic uncertainty) increases the uncertainty associated with Risk Assessments beyond the underlying stochastic uncertainty (hash marked areas in **Figure 2**). If not accounted for, this can lead to both over and underestimations of risk and the consequent cost-performance-safety implications. For example, consider a Risk Assessment for Aldyl piping installed during the period that LDIW (Low Ductile Inner Wall) Aldyl pipe was produced. It is estimated that 30 to 40% of the pipe produced during this period was LDIW pipe that has a much greater risk of failure than the non-LDIW pipe produced during the same period. A common knowledge uncertainty is not knowing specifically which pipe segments are LDIW and which are non-LDIW. If it is assumed in the Risk Assessment that all the pipe is LDIW and the leak rate projections are based on pooling all the LDIW and non-LDIW pipe together, the risk associated with the non-LDIW pipe is overestimated (as it includes the higher failure rates of the LDIW pipe) and the risk associated with the LDIW pipe is underestimated (as it includes the lower failure rates of the non-LDIW pipe). In this case, as the nature of the knowledge uncertainty is reasonably well defined, its potential impact on the RA and resulting asset management decisions can be characterized using standard statistical approaches (such as Monte Carlo simulation, see below). The costs associated with this data uncertainty and the value of addressing this uncertainty (for replacement programs, for example) can also be analyzed.

This represents a straightforward example of knowledge uncertainty; but, more often the uncertainties in the knowledge are not well defined or even known. For gas distribution pipeline assets, for example, there are six overall areas where knowledge uncertainties typically exist (a partial listing is provided in **Figure 3**). The knowledge uncertainties in these areas can arise for a number of reasons, such as incomplete historical data, transcription errors, improper reporting, etc. The different types of knowledge uncertainties and the level of uncertainty associated with them impact the Risk Assessment in different ways and, hence, impact how those uncertainties are best addressed in the Risk Assessment process. Based on the specific type of asset and the risks associated with it, different areas of knowledge uncertainty can also be more critical to the Risk Assessment than others.

Figure 3: Key Areas of Knowledge Uncertainty for Gas Pipelines



In the context of these knowledge uncertainties, the risk assessor and decision maker needs to understand:

- The degree of confidence that should be placed on the analysis
- The potential cost of the uncertainty
- The value of reducing the uncertainty in the analysis to increase the degree of confidence
- The most cost effective way of reducing the uncertainty, when warranted

To ensure consistent treatment and an equal comparison across the asset base, a holistic approach to addressing uncertainty is needed. This can be achieved by embedding uncertainty in the risk model using two key approaches: first, where data or information is not known, the worst case is assumed and flagged in the risk model as an assumption and second, estimates of uncertainty are added to the risk model and carried through the risk calculations separately. The first approach ensures that risk is not underestimated due to missing data or knowledge. For example, if the specific type of vintage plastic pipe is not known (for example if data records just show 'plastic' as the asset type installed), the model should select and calculate risk based on the poorest performing vintage plastic that could have been installed during that timeframe. The risk calculation is also run assuming the best performing vintage plastic that could have been installed during that timeframe. The difference between the two is the risk due to knowledge uncertainty. The combined information provides a more complete risk picture and enables decision makers to assess the potential risk and the value of data collection efforts to reduce the risk due to knowledge uncertainty.

Risk Model Verification

Risk models need to be verified to ensure that they are providing accurate estimates of risk. The verification process should be part of the on-going overall risk modeling process and be conducted when the risk models are first implemented and periodically afterwards.

Two primary verification approaches are recommended. For risks that are more common within the specific pipeline system (such as vintage plastic or corrosion leaks), the risk model can be verified (particularly PofF estimates) versus historical performance data for the utility. For less frequent risk (e.g. low probability-high consequence events) the risk models should be verified versus broader industry data.

Point Estimates and Probability Distribution Estimates

Many risk modeling approaches develop point estimates of risk, that is single PofF and CofF estimates that are based on, for example, the mean probabilities. As risk is probabilistic in nature, these point estimates do not describe the complete risk picture, and can mask low probability-high consequence events. In addition to point estimates, risk models should, therefore, develop probability distributions so that the more complete risk picture is captured. This can be achieved by incorporating Monte Carlo simulation into the risk modeling process. The results are typically expressed in the form of F-N or Exceedance Probability Curves.

Conclusions

There are clear benefits in evolving from qualitative or 'scoring' type risk models to quantitative risk models that express risk in absolute terms. While challenging, the development of accurate quantitative risk models that provide accurate estimates of risk can be achieved. To ensure proper development of these models, the six key elements addressed above need to be considered. The result is verified quantitative risk models that provide good estimates of absolute risk and provide an important tool in overall integrity management by providing decision makers with a more complete picture of pipeline risk.