Critical Review of Candidate Pipeline Risk Models

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Overview

1. Project objectives & scope
2. Industry survey
3. Literature review – pipeline industry and other industries
4. Quantitative Risk Guidelines
5. Summary & Recommendations

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Definitions

Quantitative Risk Analysis (QRA)

- An approach that quantifies risk using probabilities to quantify likelihood and measurable parameters to quantify consequences

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Project Objectives

1. Conduct a critical review of QRA approaches used in the pipeline industry

2. Review QRA approaches used in the nuclear, offshore, aviation and power transmission industries

3. Comment on the use of QRA for facilities and LNG plants

4. Create guidelines for developing and assessing probabilistic QRA models based on the following:
   - Survey responses from industry participants and regulators on the attributes of a quantitative pipeline risk assessment
   - The critical review of pipeline QRAs

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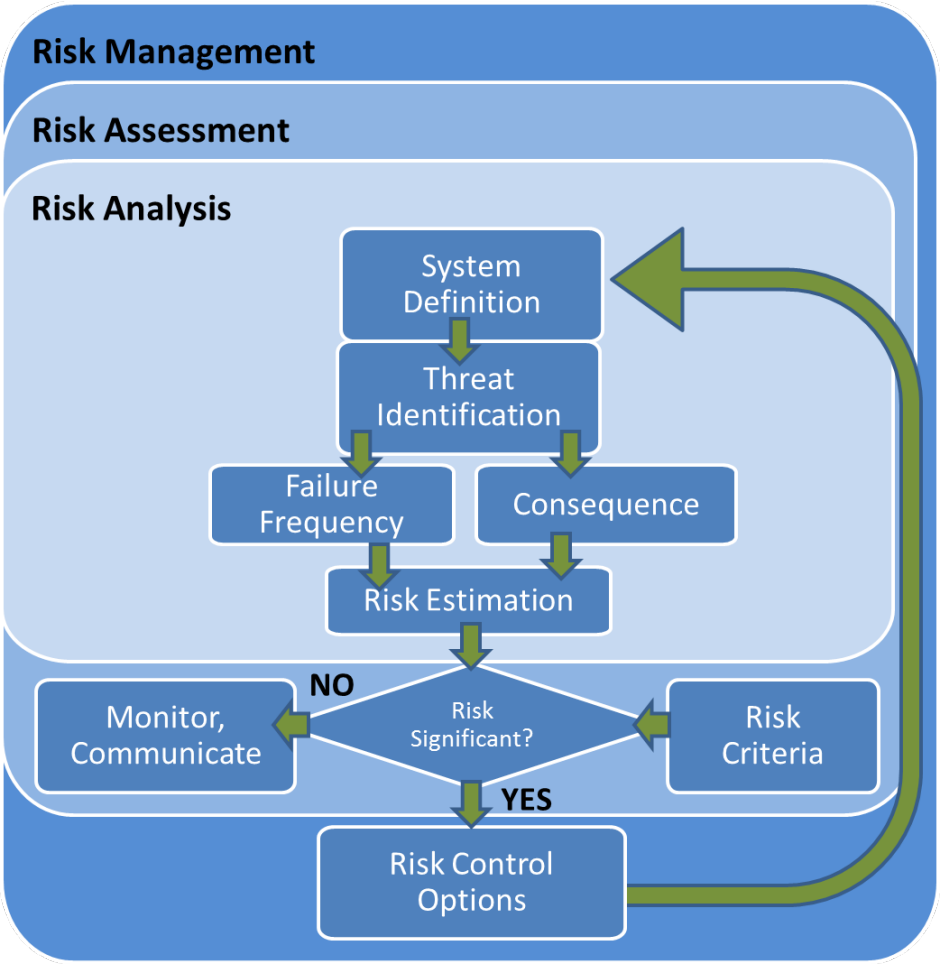
Scope

- Critical review
  - Failure frequency
  - Consequence in measurable units
- Identify ideal model attributes
- Identify modelling levels



Industry Survey

Purpose

- Learn about quantitative risk models not in open literature
- Determine the risk model attributes that industry considers important
- Evaluate readiness of industry to adopt quantitative risk models

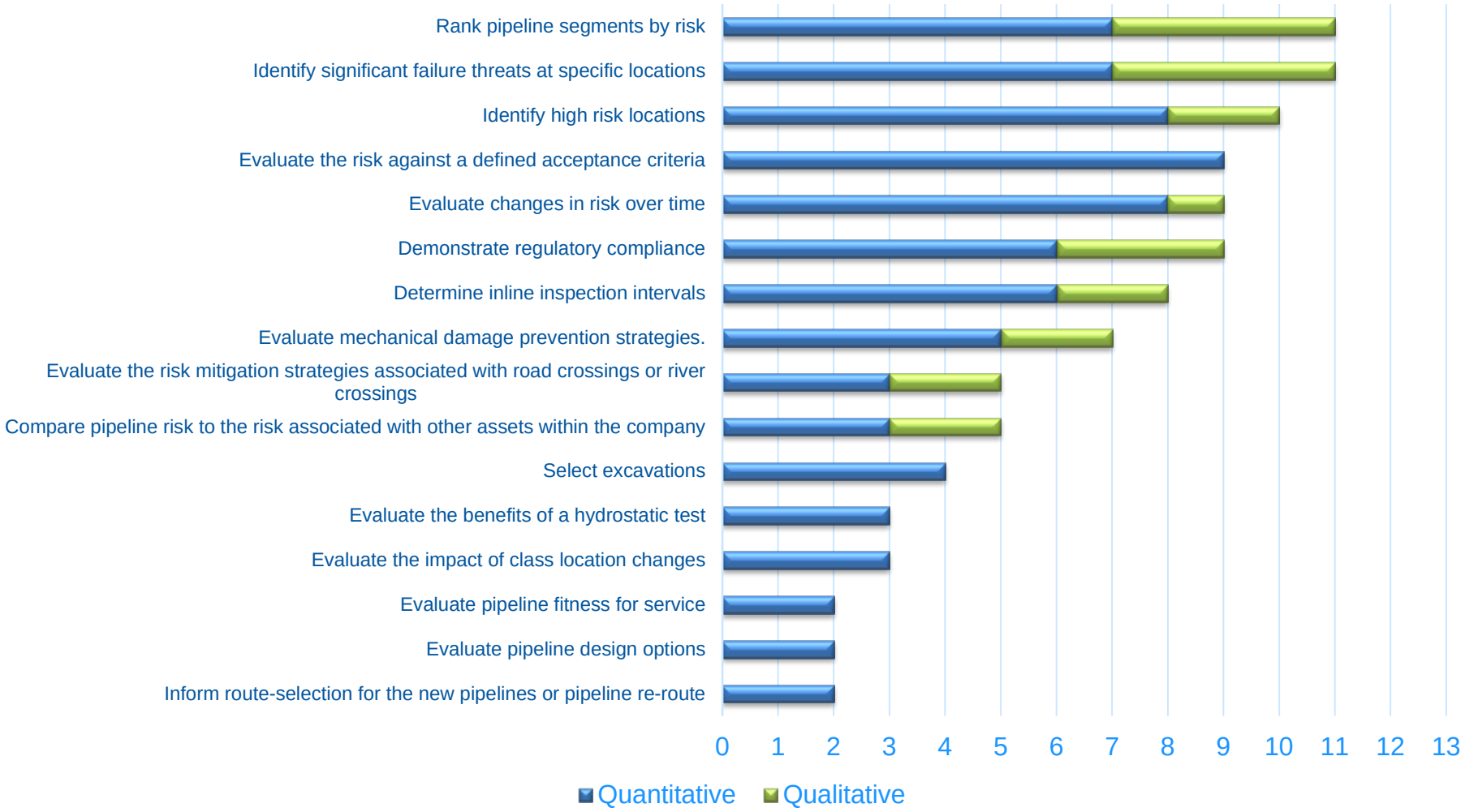
Survey topics

- QRA model description
- Model applications
- Desirable attributes of an ideal quantitative model
  - Ease of use, analytical rigor, model outcomes
- Perceived obstacles to the adoption of QRA models
- Importance of risk model standardization

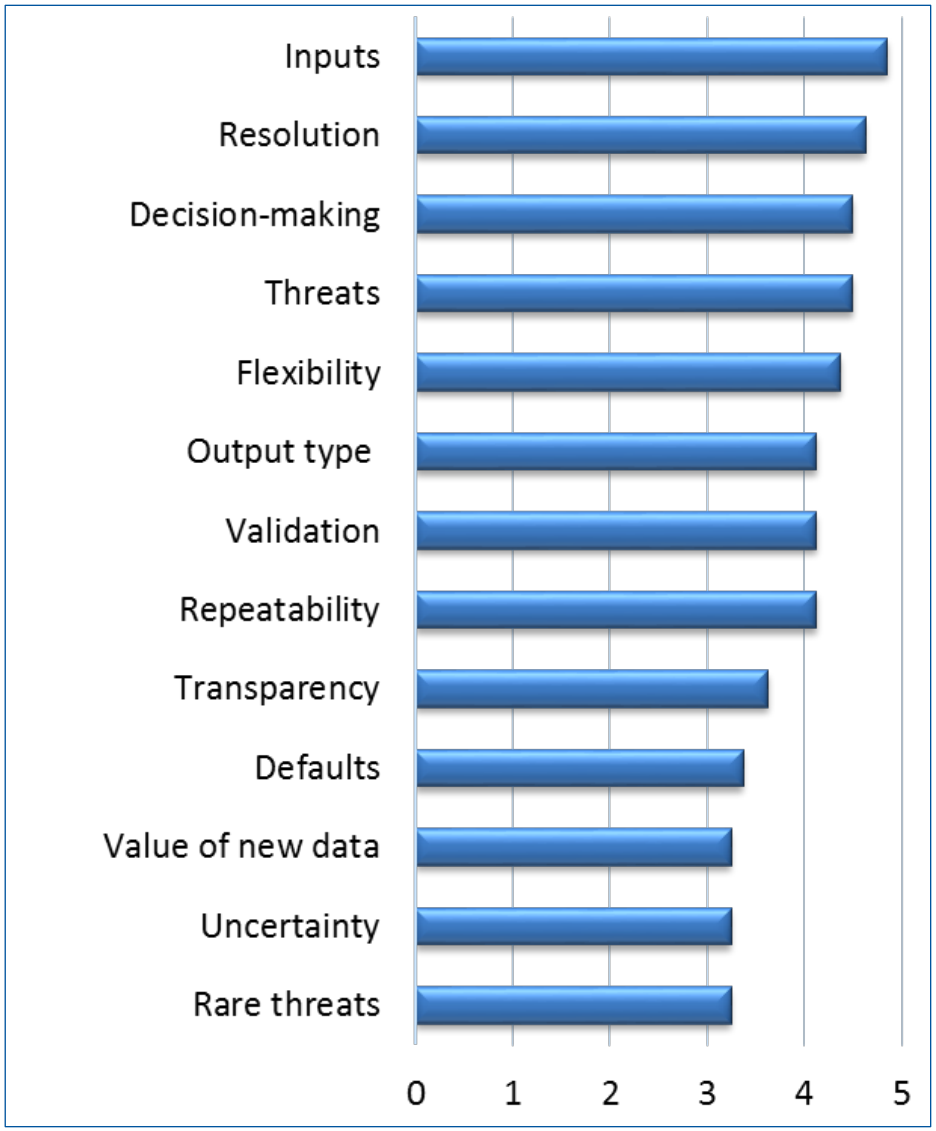
Industry Survey

- Overview:
  - 17 requests for survey participation to operators and consultants
  - 8 responses
  - 13 risk models described

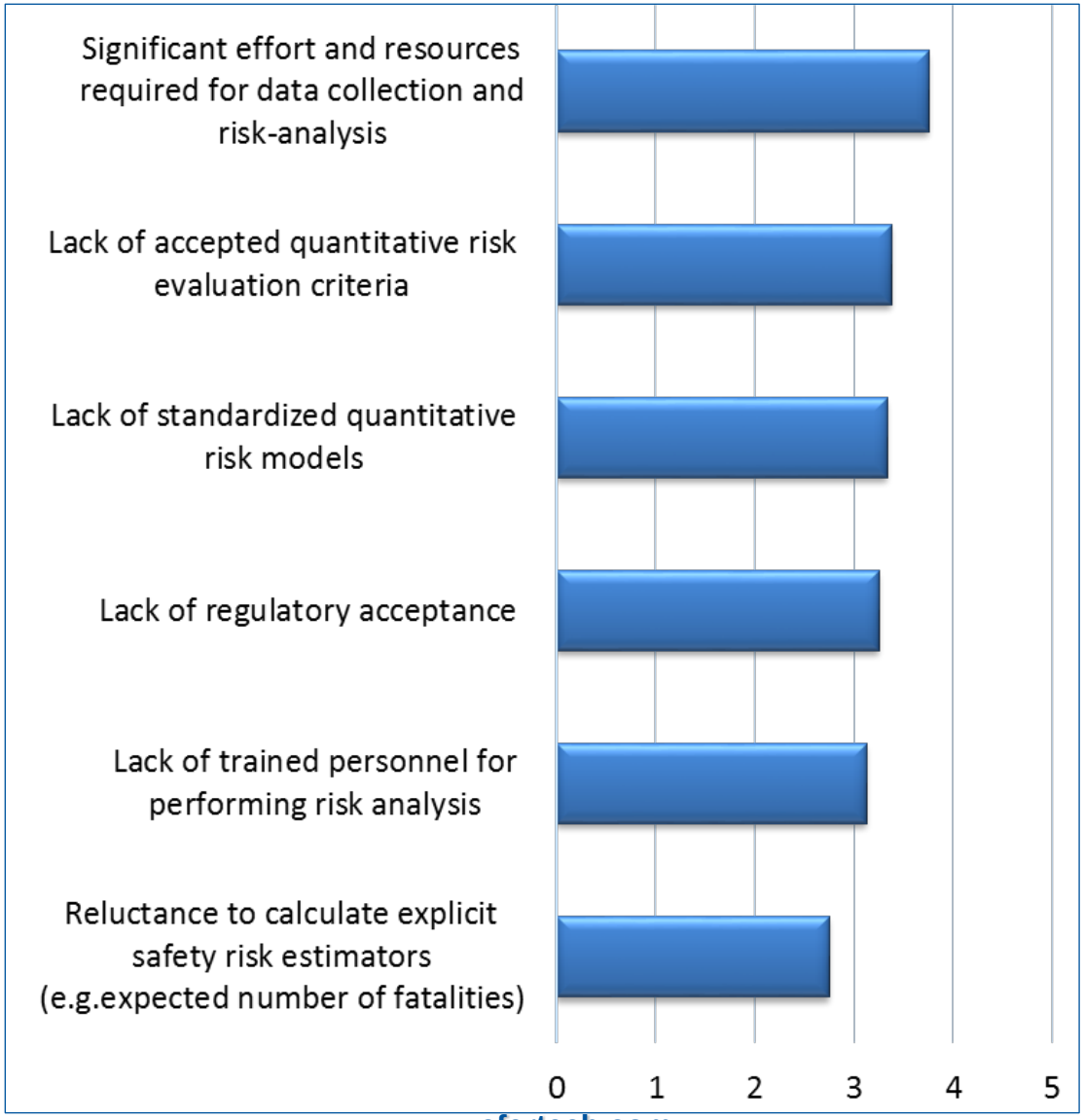
Model Applications



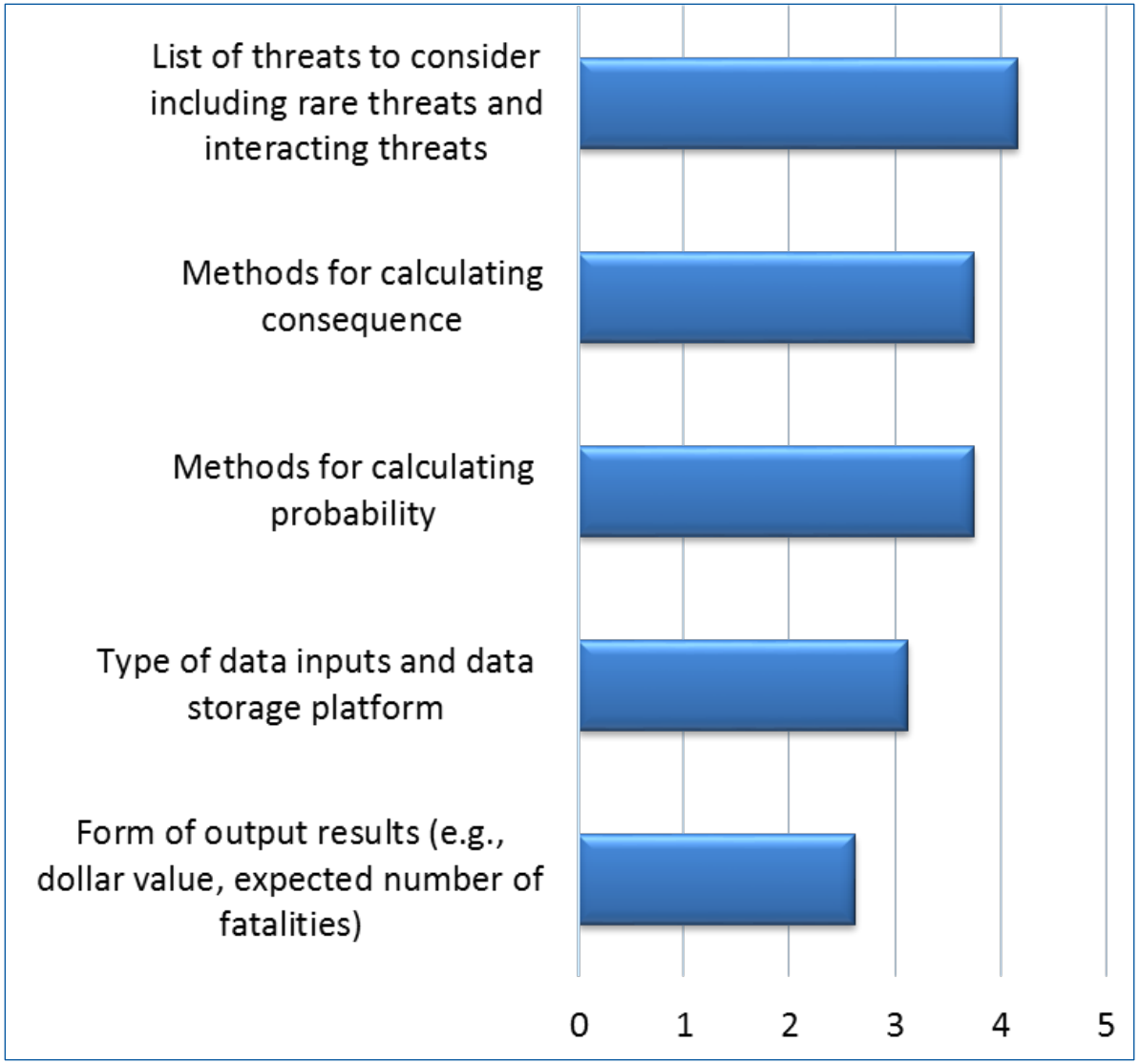
Ideal Model Attributes



Obstacles to QRA Adoption



Standardization



Survey Key Learnings

- Quantitative models have not replaced qualitative models – they are used when qualitative models are inadequate
  - Excavation selection, hydrostatic test simulation, evaluation of class location changes, fitness-for-service assessments, pipeline design and route selection
- All desirable model attributes were scored high
- All of the respondents using QRA to evaluate risk used an acceptance criteria despite the lack of a universally accepted criteria
- The use of existing data in all available formats was preferred over standardizing the data inputs and the data storage platform

Literature Review

Literature Sources

- 34 Engineering and Technology Databases
  - SciSearch (6,000+ science journals)
  - Inspec (15M papers – engineering and physics)
  - Ei Compendex (17M papers – engineering)

- Prior C-FER expertise

- 70 publications reviewed
  - 8 system wide, 33 likelihood, 29 consequences

Pipeline Industry

- QRA used extensively in the pipeline industry
- Well-established probability models for common threats
- ‘Weakest link’ methodology and failure rate are fundamentally different, but provide similar results for small probabilities
- Probabilistic frequency estimation incorporated into pipeline codes in Canada and Europe
- Individual risk and societal risk are common life safety measures for gas transmission pipelines
- Hazardous liquids pipeline consequences are expressed as environmental impacts (equivalent dollar value). There is no standardized methodology for life safety

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Other Industries

- QRA is the most common decision-making approach for integrity management actions
- Varying levels of uncertainty are handled using appropriate conservatism in the risk acceptance criteria
- Well established risk acceptance criteria and risk measures facilitate the selection of an appropriate modelling approach
- The nuclear and aviation industries have detailed guidelines to quantify knowledge uncertainties
- A common data collection platform shared by the industry improves hazard identification

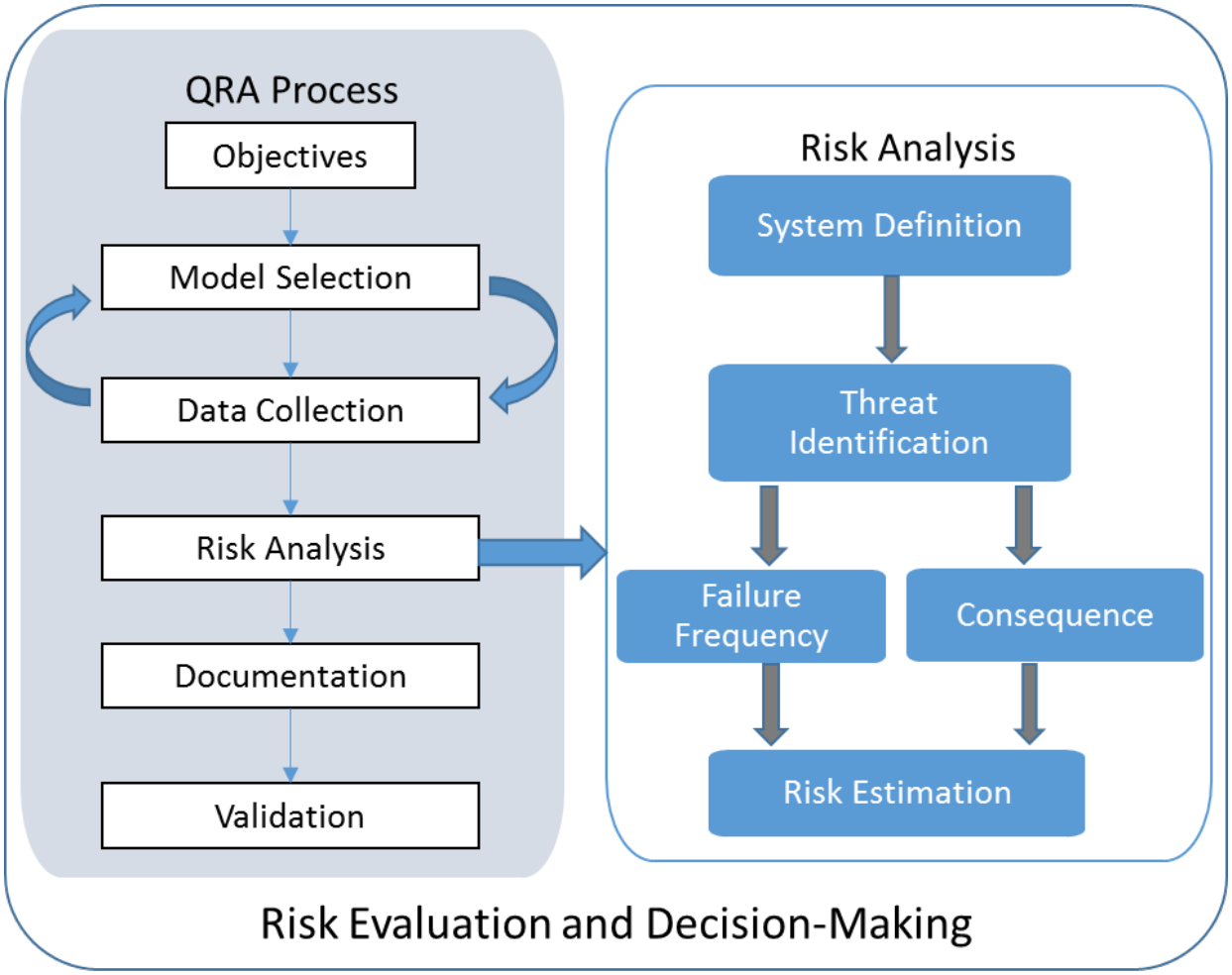
Risk Guidelines

- Purpose
  - provide a framework for performing QRA
  - assist operators in developing new QRA models
  - identify gaps in existing models
  - help to evaluate the accuracy, completeness, and effectiveness of the QRA models

Scope of the Guidelines

- Quantitative methods only
- Failure frequency: an estimated rate of failure events (*per mile-yr)*
- Consequence: a physical quantifiable parameter (dollar value, number of fatalities, spill volume, or impact on area affected)
- Not within guideline scope
  - Hazard identification methodologies
  - Risk acceptance criteria
  - Risk mitigation strategies

QRA Process


QRA Process
Objectives
Model Selection
Data Collection
Risk Analysis
Documentation
Validation
Risk Analysis
System Definition
Threat Identification
Failure Frequency
Consequence
Risk Estimation
Risk Evaluation and Decision-Making

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QRA Objectives

- Identify high-risk locations and the main contributing threats
- Evaluate the risk against an acceptance criterion
- Evaluate changes in risk over time
- Make integrity management decisions
- Demonstrate regulatory compliance

Failure Frequency

Based on the use of objective data and engineering models:

- Level 1: Subject matter experts (SME) opinion
  - Quantified to probability values
- Level 2: Historical data
  - Based on adjustment factors
  - Use of regression equations
- Level 3: Probabilistic/Engineering models
  - Structural reliability methods
  - Graphical models (Fault-tree methods/Bayesian Networks)

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SME Opinion

Advantages

- Requires limited resources and is simple to implement
- Uses SME experience to compensate for data gaps
- Does not require an engineering model

Disadvantages

- Validation is difficult
- High uncertainty due to subjective nature
- Difficult to quantify the level of conservatism in the results
- Influence of uncertainty cannot be quantified
- Effects of mitigation are difficult to estimate

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SME Guidelines

- Estimate the failure frequency as a product of the rate of occurrence of an initiating event and a series of conditional probabilities of intermediate events
- Separate failure frequency estimates by threat category
- Express failure frequencies as a function of three elements representing exposure, mitigation, and resistance
- Use structured approaches to elicit SME opinion (e.g. the Delphi method, the guidelines for expert elicitation used by the U.S. Nuclear Regulatory Commission)

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Historical Data

Types

- *Generic Failure Frequencies*: historical data from industry-wide failure databases is used to estimate the failure frequency for individual threats and combinations of attributes

- *Failure Frequencies with Modification Factors*: modification factors applied to the historical data to estimate pipeline-specific failure frequencies. Modification factors can be developed using engineering models, statistical analysis or SME opinion

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Historical Data

Advantages

- Improves objectivity compared to SME opinion
- Based on actual incident occurrence
- Pipeline specific factors can be considered

Disadvantages

- Significant effort required to develop realistic modification factors
- Pipeline-specific adjustment factors may be subjective
- Lack of data to address new and emerging threats
- May not represent future probability of failure

Historical Data Guidelines

- Develop modification factors based on engineering models and probabilistic methods
- Consider the guidelines for SME opinion if expert opinion is used in the development of modification factors
- Consider other levels of analysis for rarely occurring threats because the small sample size of the data can underestimate frequency

Probabilistic Models

- ***Structural reliability methods***: Input parameters of deterministic engineering models and model errors are characterized as random variables and the frequency of failure is estimated using standard reliability methods

- ***Graphical Models***: Fault tree methods are a logical representation basic events connected with 'AND' and 'OR' gates combined to estimate the frequency of failure. Bayesian networks are a graphical representation of the causal links between basic events leading to failure

- ***Other Methods***: Novel mathematical approaches to estimate failure rate, such as fuzzy logic, do not have well-established mathematical and theoretical basis compared to probability theory. The advantages of these approaches is not clear

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Probabilistic Models

Advantages

- Most objective compared to other levels
- Based on recognized engineering models
- Uses all types of pipeline specific evidence as input
- Directs data collection efforts
- Can address rare and interacting threats
- Accounts for specific integrity maintenance actions
- Allows for sensitivity analysis and uncertainty reduction efforts

Disadvantages

- Needs more effort to characterize inputs
- Requires greater computational resources
- Skepticism of outputs due to the complexity of models

Probabilistic Model Guidelines

- Include all possible sources of uncertainty
- Consider input parameter bounds when selecting probability distributions
- Ensure goodness-of-fit in the tails of the distributions
- Consider the guidelines for SME opinion if subjective judgement is used to characterize model inputs
- Apply appropriate probabilistic techniques (sample size, model convergence)

Consequences Models

Consequence: the effect of a pipeline failure on individuals or populations, property, or the environment. Models are often divided into:

- Life safety
- Environmental impact
- Financial impact

Life Safety Models

- Natural Gas: Jet fires
  - Simplified models: potential impact radius (PIR) model
  - Detailed proprietary models: PIPESAFE and DNV PHAST
- HVP Liquids: Flash fires, toxic effects and blast pressure
  - General purpose consequence software models: CANARY, DNV PHAST, EFECTS by TNO, and TRACER by Safer Systems.
  - CFD modelling: IOGP (2010) and the Norwegian Standard NORSOK Z-13 Annex F (NORSOK 2010)
- Flammable LVP Liquids: Pool fires
  - proprietary software and CFD models

Environmental Impact Models

Levels of analysis:

1. SME opinion
2. Historical data models
   - Recorded data often limited to clean up costs
3. Detailed models
   - Release volume
   - Area affected
   - Habitat assessment

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Failure Modes

- The magnitude of the consequences associated with each failure mode is very different
- The frequency and risk associated with each failure mode is calculated separately and added up to arrive at an estimate of total risk
- Failure Modes: release as a function of size:
  - small leak
  - large leak
  - rupture

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Risk Measures

- Life Safety:
  - Expected number of casualties (including injuries)
  - Individual Risk (IR): the probability of fatality for a person at a particular location. It varies with the distance from the pipelines and the likelihood that the person will be present at the location being considered
  - Societal Risk (SR) as is represented by an F-N curve, a plot of the frequency of incidents resulting in N or more fatalities associated with a specified length of pipeline

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Risk Measures

- Environmental Impact:
  - Monetary costs that account for environmental sensitivity and include clean-up costs, and second order socio-economic impact.
  - Spill volumes adjusted for site sensitivity.
  - Habitat recovery time estimated as the time for restoration of an environmental resource. The estimation of habitat recovery is ideally based on a clearly-defined natural resource and a quantified measure of restoration (e.g. population density of a particular aquatic species or the allowable residual spill volume in the soil).

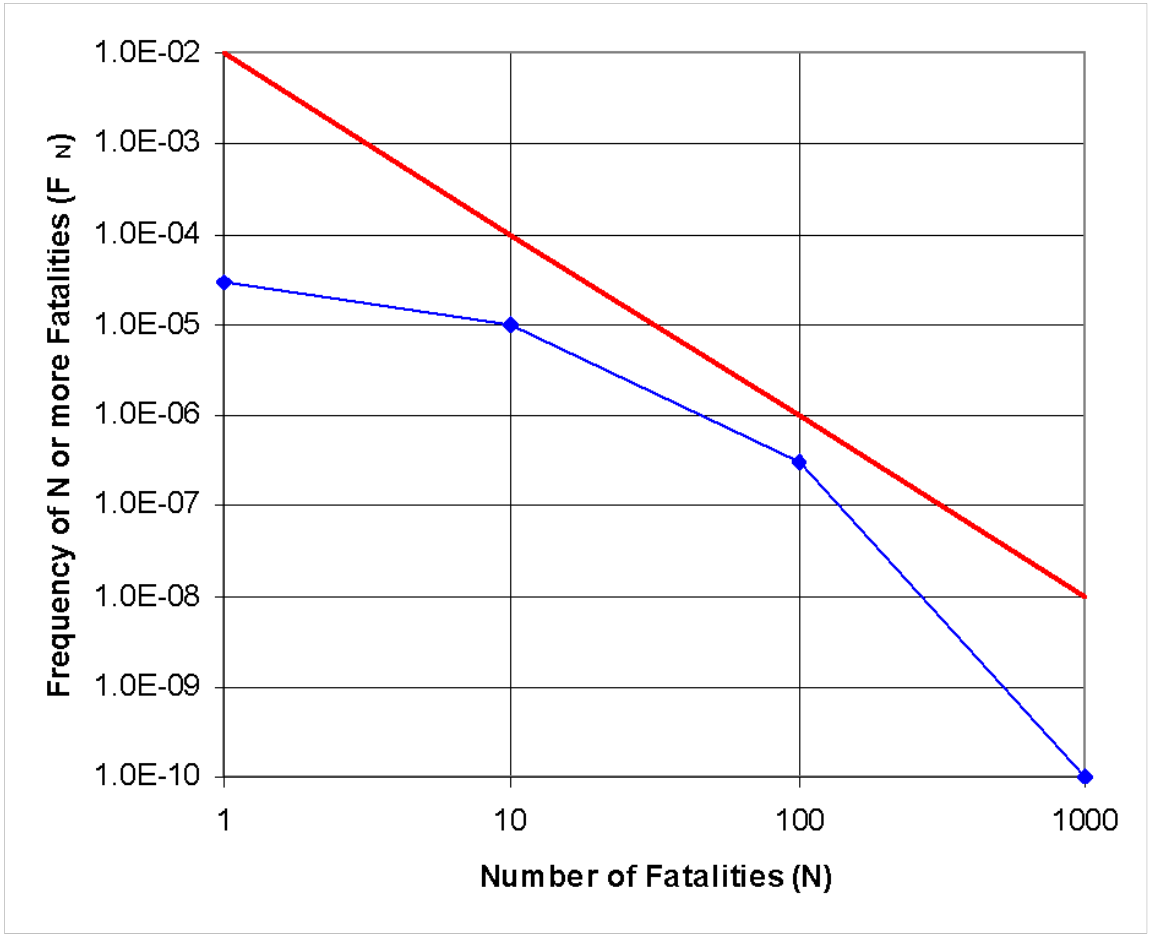
Risk Measures

- Financial impact:
  - Monetary costs including third-party property damage and other business impacts. Acceptance criteria depends on the business priority of the operator

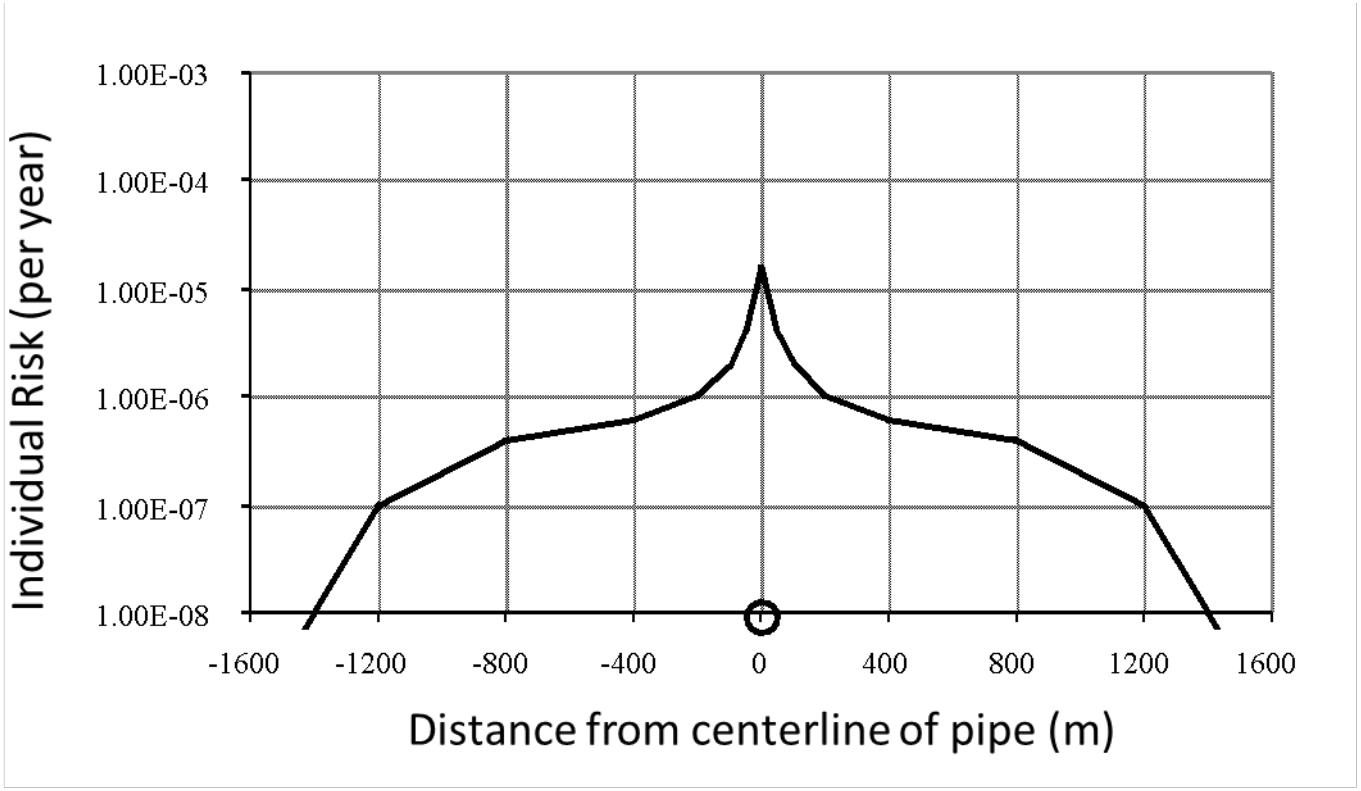
Risk Model Validation

- The standard validation - comparing their results to empirical data is not applicable to risk models unless large sets of data are available
- Statistical estimates of the frequencies of occurrence for rare or moderately rare events is often not possible
- Alternative validation approaches include:
  - component verification
  - hindcasting
  - error bounds
  - benchmarking
  - sensitivity analysis

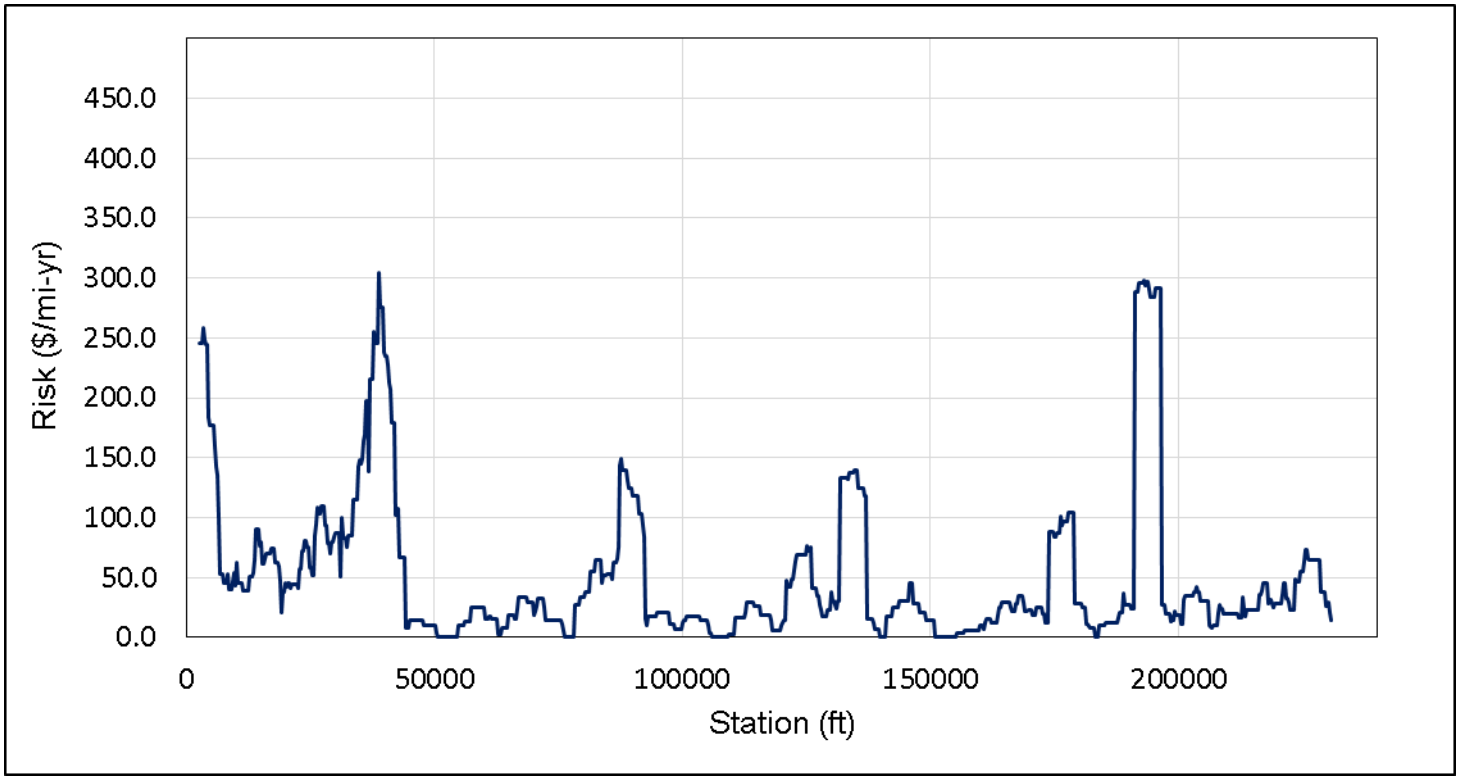
Example: FN Curve



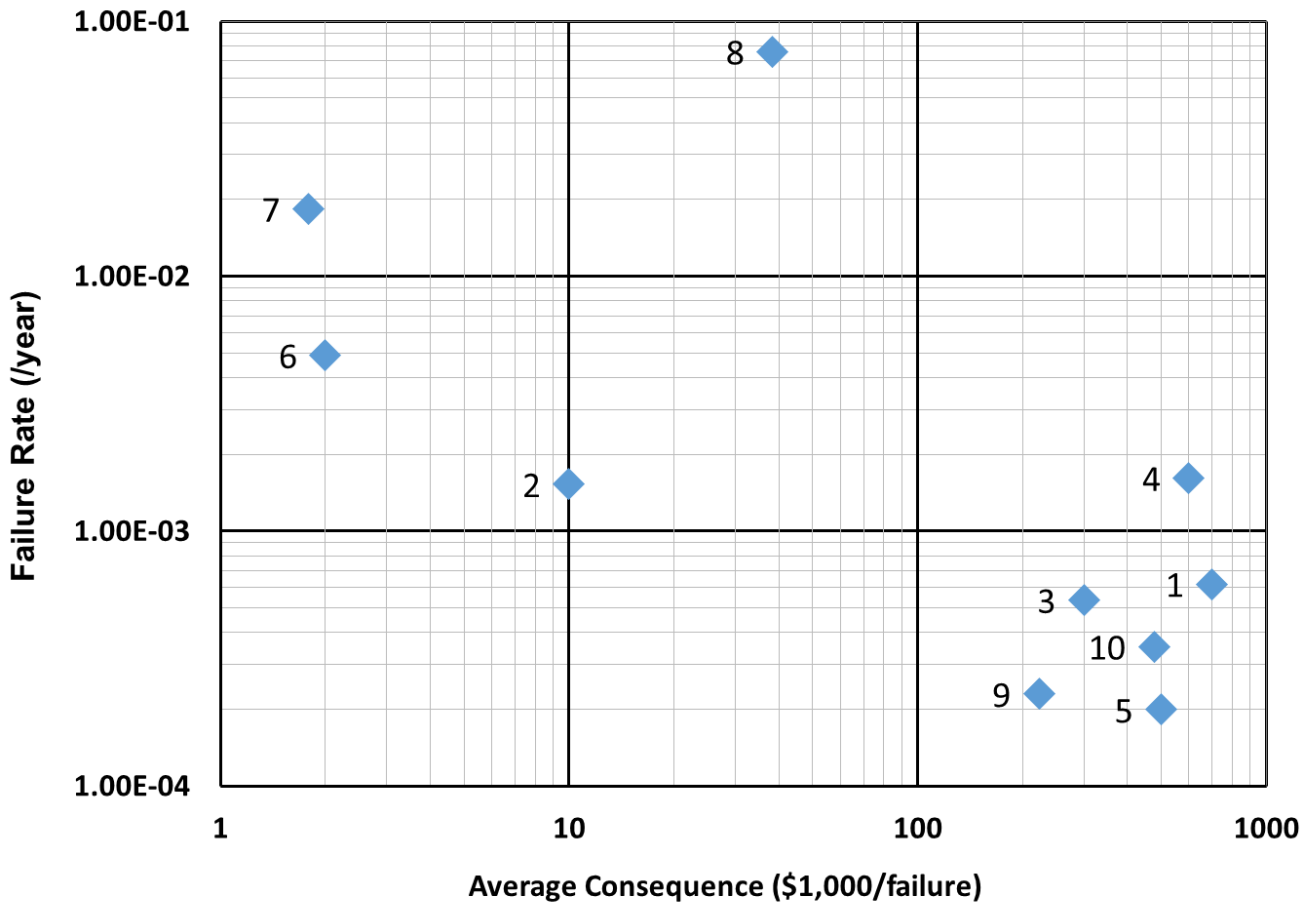
Example: Risk Contour



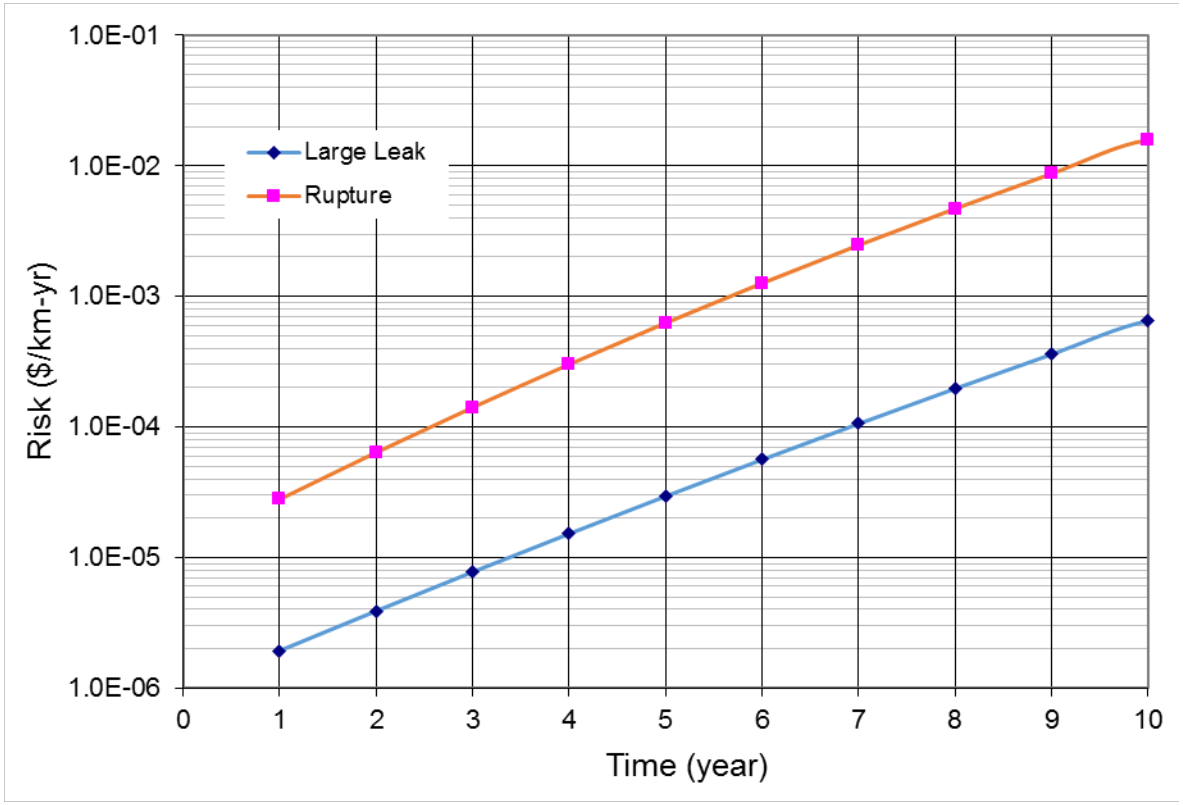
Example: Risk Profile



Example: Risk Matrix



Example: Risk Over Time



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Summary

- QRA uses:
  - Evaluate risk against a criteria
  - Monitor the change in risk over time
  - Identify high risk locations
  - Making integrity management decisions

- Desirable QRA model attributes:
  - Flexibility to use data in all formats
  - Identify risk by threat and location
  - Produce results that support decision-making

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Summary

- QRA Models:
  - Address 9 threat categories (ASME B31.8S)
  - Use structural reliability and fault tree methods
  - Well-established consequence models for gas pipelines
  - Liquid consequence models not standardized

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Recommendations

- Develop model components to address gaps:
  - A standardized list of interacting threats;
  - Risk measures for environmental impacts; and
  - Simplified life safety models for hazardous liquids pipelines
- A pilot study for the application of guidelines to a quantitative risk model
- Development of a suite of benchmark problems to facilitate independent risk model validations by a third party

Thankyou!