PHMSA Pipeline Risk Model Working Group

Critical Review of Candidate Pipeline Risk Models

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Overview

1. Project Objectives
2. Summary & Recommendations
3. Industry Survey – Key Model Attributes
4. Literature Review – Pipeline Industry
5. Literature Review – Other Industries
6. Probabilistic Risk Guidelines
Project Objectives

Create guidelines for developing and assessing probabilistic quantitative pipeline risk models based on the following:

- A survey of the industry participant, regulators and subject matter experts on the attributes of a quantitative pipeline risk assessment
- A critical review of existing quantitative risk models (including models used in other industries)

The guidelines define:

- **Standard requirements** – for example:
  - Minimum risk model attributes
  - Minimum list of threats considered
  - Risk measures to be evaluated by the model

- **Levels of analysis**
  - Ability to achieve desirable attributes
  - Degree of analytical rigor and data completeness
Scope

- Quantitative models
- Failure frequency
- Consequence in measurable units
- Identifying various modelling categories
- Not within scope:
  - develop or validate a model
  - develop risk criteria
  - Identify rare-event threats
**Summary I**

**Literature Review**
- Extensive use of QRA models
- Frequency methods: SME opinion, historical data and probabilistic models
- Established risk measures for life safety
- Established consequence models for natural gas releases
- Proprietary consequence models for hazardous liquids
- Environmental risk measures are not standardized

**Other Industries: Nuclear, Offshore, Aviation and Power Transmission**
- Common methods to quantify frequency
- Consequence models are not common between industries
- Criteria for frequency and consequence may be defined separately
- Standardization of methods eases use
- Standardization of data collection allows for aggregate analysis
- Integration pipeline and facility QRA is possible for some risk measures
Guidelines

- **Purpose**: develop, improve or evaluate QRA models
- **Are consistent with the international risk assessment standards**
- **Describes methodologies to estimate failure frequency and consequences**
- **Suggest various outputs for risk estimates**
- **Enables models that are repeatable, traceable, and treat uncertainties consistently**
- **Describes levels of analysis to use available information, identify areas of incremental improvement and to move towards more objective risk models**
Recommendations for Future Work

• Development of the necessary model components to address the 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
Industry Survey

Purpose
• Find quantitative risk models not in open literature
• Determine what industry considers as key attributes of the ideal quantitative risk model
• Evaluate readiness of industry to adopt quantitative risk models

Question Types
• Current models
• Model uses
• Key attributes of ideal quantitative model
  – Ease of use, analytical rigor, model outcomes
• Obstacles to the application of quantitative risk assessment
• Desirable attributes for standardization
Industry Survey - Overview

• Requests for survey participation – 17
  – Operators & Consultants
  – Follow-up twice

• Responses – 8
  – 6 different operating companies

• Models described – 13
  – Qualitative : 4
  – Quantitative: 9
Industry Survey – Model Uses

- Rank pipeline segments by risk
- Identify significant failure threats at specific locations
- Identify high risk locations
- Evaluate the risk against a defined acceptance criteria
- Evaluate changes in risk over time
- Demonstrate regulatory compliance
- Determine inline inspection intervals
- Evaluate mechanical damage prevention strategies
- Evaluate the risk mitigation strategies associated with road crossings or river crossings
- Compare pipeline risk to the risk associated with other assets within the company
- Select excavations
- Evaluate the benefits of a hydrostatic test
- Evaluate the impact of class location changes
- Evaluate pipeline fitness for service
- Evaluate pipeline design options
- Inform route-selection for the new pipelines or pipeline re-route

Quantitative
Qualitative
Most Common Uses – All Models

- Rank pipeline segments by risk
- Identify significant failure threats at specific locations
- Identify high risk locations

Quantitative
Qualitative
## Survey Results – Model Uses

<table>
<thead>
<tr>
<th>Model Uses</th>
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<tbody>
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*PHMSA Pipeline Risk Model Working Group, Sept 4-6*
Most Common Uses – Quantitative

- Identify high-risk locations
- Evaluate the risk against a defined acceptance criteria
- Evaluate changes in risk over time
Ideal Model Attributes

• **Inputs**: Considers all forms of evidence available
• **Defaults**: Suggests appropriate defaults
• **Transparency**: Documented algorithms
• **Flexibility**: Considers pipeline-specific factors
• **Repeatability**: Produces consistent results
• **Threats**: Covers the standard threats
• **Rare threats**: Covers interacting threats and rare threats
• **Validation**: Has been validated, allows validation by a third party
• **Output type**: Results that can be compared to a criteria
• **Resolution**: Risk by location and by threat
• **Decision-making**: Results used for decision-making;
• **Uncertainty**: Uncertainty is properly handled
• **Value of new data**: Assess whether additional effort is beneficial
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Obstacles to Implementation

- Significant effort and resources required for data collection and risk-analysis
- Lack of accepted quantitative risk evaluation criteria
- Lack of standardized quantitative risk models
- Lack of regulatory acceptance
- Lack of trained personnel for performing risk analysis
- Reluctance to calculate explicit safety risk estimators (e.g. expected number of fatalities)
List of threats to consider including rare threats and interacting threats
Methods for calculating consequence
Methods for calculating probability
Type of data inputs and data storage platform
Form of output results (e.g., dollar value, expected number of fatalities)
Survey Key Learnings

• Several quantitative risk models already in use
• Qualitative models for ranking pipeline segments by risk and for identifying locations of high risk segments
• Quantitative risk models are used for the selection of excavations, hydrostatic test simulation, the evaluation of class location changes, fitness-for-service assessments, and pipeline design and route selection
• All desirable model attributes were scored high
• Lack of a quantitative risk criteria was ranked as the second highest obstacle
• All of the respondents using QRA use a defined acceptance criteria
• Reluctance to standardize the data inputs and the data storage platform – the use of existing data in all available formats to reduce the data collection effort, was preferred instead
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
QRA Uses

• **Purpose**
  – Meeting regulatory requirements
  – Integrity management
  – Asset risk management
  – Comparison of design options

• **Granularity**
  – System-wide assessments
    • Dynamic segmentation
    • Individual pipe joints
  – Annualized probabilities

• **Failure modes**
  – Loss of containment as failure
  – Distinction between leak and rupture is rare – usually only rupture considered

• **Risk Measures and Presentation**
  – Total risk profile of all threats combined
  – Separate risk profiles for each threat
Standard Threats (ASME B31.8S)

- External corrosion
- Internal corrosion
- Stress corrosion cracking
- Manufacturing-related defects
- Welding/Fabricated related
- Equipment
- Third party/Mechanical damage
- Incorrect operations
- Weather-related and outside force
Threats

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- External corrosion
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Cracks

Earth movements
Threats

Standard Threats (ASME B31.8S)

- External corrosion
- Internal corrosion
- Stress corrosion cracking
- Manufacturing-related defects
- Welding/Fabricated related
- Equipment

- Third party/Mechanical damage
- Incorrect operations
- Weather-related and outside force

Non-Standard

- Theft
- Sabotage
- Seismic shaking
- Interacting threats

Vandalism

Floods
Risk Outputs

• **Life safety measures**
  – Individual risk (IR)
    • Risk to specific individuals near a pipeline
  – Societal risk (SR): F-N curves
    • Risk as a set of frequency of incidents and a number of fatalities resulting from the incident
  – Expected number of fatalities
  – IR and SR are commonly estimated

• **Financial measures**
  – Dollar values including all costs
  – Conversion of environmental impacts to dollar amounts
  – Conversion of fatalities to dollar amounts

• **Environmental Measures**
  – Volume lost, receptor sensitivity, size of area affected
• Approaches for combining probabilities from different threats

  – Summation of frequencies of failures
    • Assumes that all threats are mutually exclusive
    • Occurrence of failure due to one threat does not prevent occurrence of failure due to a different threat
    • Multiple failures possible for a given segment
    • Accounts for risk of each threat and total risk is a direct summation of risks from individual threats

  – “Weakest-link” methodology
    • Assumes that all threats are statistically independent
    • Accounts for risk due to occurrence of the first failure due to any threat
    • Possibility of a second failure on the same segment is ruled out
    • Total risk is not a direct summation of risks from individual threats

• Both approaches give same result for total risk at small values of probability
‘Weakest Link’ vs Failure Rate

Probability of one or more failures
  – the probability that none happen:
    \[ P_1 = (1-a)(1-b)\ldots \]
  – The probability that at least one happens
    \[ P = 1 - P_1 \]
  – Does not scale with length

Failure Rate for a given length
  \[ P_1 = a + b + \ldots \]
  – Scales with length
Summary of Other Industries

• Methods for quantitative risk analysis
  – Probability estimation methods similar to pipeline industry
  – Consequence models specific to each industry

• Levels of analysis
  – Based on the availability of well-developed models
  – Purpose of assessment

• Human reliability analysis
  – Human error quantified as probabilities
  – Detailed methodologies for expert elicitation

• Establishing risk or reliability criteria
  – Reliability criteria for high consequence triggering events
  – Risk criteria for consequence mitigation
Nuclear Industry

• Standardization of models and analysis approaches for selected threats

• Guidelines on sources of uncertainties and strategies to reduce them

• Approaches for setting criteria
  • Risk criteria
  • Reliability criteria

• Stages in risk evaluation
  • Availability of standardized models
  • Level of uncertainty in the analysis
Offshore Industry

DNV: Marine Risk Assessment (2001)
Offshore Industry

• Guidance on levels of analysis based on assessment objectives
  – Risk screening
  – Broadly focused detailed analysis
  – Narrowly focused detailed analysis

• Identifying key factors in selection of assessment methods

• Examples of assessment methodologies based on decision contexts

• Approaches to characterize environmental impact from oil spill volumes
Aircraft Industry

• Methods of probability estimation similar to pipeline industry
  – SME opinion
  – Probabilistic/Engineering models

• Common threats for integrity
  – Fatigue crack growth
  – Stress corrosion cracking
  – Models not directly applicable due to material differences

• Operations and safety systems
  – Detailed data recording methods to facilitate human factors analysis
  – Standardization of data collection methods specific to industry
Power Transmission

• Primary threat: network failure
  – Hidden component interdependency
  – Component failures are triggering events for system failure

• Methods of probability estimation similar to pipeline industry
  – SME opinion
  – Historical data
  – Graphical network methods

• Guidelines for risk assessment
  – Limited to qualitative and semi-quantitative methods
  – Component failure risk is well defined
  – Network failure risks methods
Summary of Literature Review

- Extensive use of quantitative risk models in the pipeline industry
  - Well-established probability estimation for frequently occurring threats
  - ‘Weakest link’ methodology and failure rate are fundamentally different, but provide similar results for small probabilities
  - Some standardized QRA incorporated into codes in Canada and Europe
  - Consequences are specific to industry and product type
  - Life safety measures for gas transmission pipelines: individual risk and societal risk
  - Hazardous liquids pipeline consequences are expressed as environmental impacts (equivalent dollar value). There is no standardized methodology for life safety

- Other Industries
  - Guidelines, standards, best practices
  - Structured examples of levels of analysis
  - Human reliability analysis
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
Risk Guidelines

• Guidelines scope
  – Quantitative methods only
  – Failure frequency: an estimated rate of failure events
    • defined in units *per mile-yr*
  – Consequence: a physical quantifiable parameter
    • dollar value, number of fatalities, spill volume, or area affected

• Not within guideline scope
  – Hazard identification methodologies
  – Risk acceptance criteria
  – Risk mitigation strategies
Risk Framework

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
Purpose of a QRA

Purpose

- 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
Model Selection – Failure Frequency

Based on the degree of objective data and the use of 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)
SME Opinion

• Approaches
  – Rule-based conversion
    • Risk index scores \(\rightarrow\) quantitative conditional probabilities
  – Direct evaluation of failure rates
  – Assessment of damage rates
    • Damage rates \(\rightarrow\) e.g., dents, coating holidays
    • Conversion to required failure rates
    • Rule-based algorithms on combination of damage rates
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
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:
- the Delphi method - an iterative process used to reach a consensus amongst a panel of experts, resulting in a reduction of bias in the opinion of any single expert; and
- the guidelines for expert elicitation used by the U.S. Nuclear Regulatory Commission - a simplified version of the Delphi method with guidance on developing customized questionnaires for expert opinion elicitation.
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.
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 fully represent future probability of failure
Historical Data Guidelines

• Develop modification factors based on engineering models and probabilistic methods where possible

• 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; the frequency of failure is estimated using standard reliability methods.

- **Graphical Models**: Fault tree methods are a logical representation of 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.
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 is necessary 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)
Model Selection - Consequences

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 Hazards

• 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, EFFECTS by TNO, and TRACER by Safer Systems.

• Flammable LVP Liquids: Pool fires
  – proprietary software and CFD models
Environmental Impact

Environmental impact is dependent on:
• product type
• exposure of receptors
• toxicity of the product for each receptor
• socio-economic importance of the affected resources

Important Factors:
• total volume released
• receptor identification
• pathway to receptors
• habitat recovery and duration of recovery
Environmental Impact

Levels of analysis:

• SME opinion

• Historical data models
  – Recorded data often limited to clean up costs

• Detailed models
  – Release volume
  – Area affected
  – Habitat assessment
The appropriate cost components and models depend on the operator’s corporate values and the objectives of the QRA

Direct costs:
• cost of lost product
• repair cost
• costs associated with downtime (e.g. lost revenues, penalties and restart costs)
• third-party property damage costs
• legal costs

Indirect costs:
• loss of customer satisfaction
• loss of reputation
• costs of increased regulatory oversight.
Summary of Consequence Models

Natural Gas
- Life safety
  - PIPESAFE
  - Potential impact radius (PIR) formula
  - Other proprietary models
- Environmental impact
  - No standard quantification
  - Proprietary models in equivalent dollar value
- Financial impact
  - Proprietary models (available for licensing)
  - Company-specific models

Liquids
- Life safety
  - Proprietary models
  - No standardized methodology
- Environmental impact
  - No standard quantification
  - Proprietary models in equivalent dollar value
- Financial impact
  - Proprietary models (available for licensing)
  - Company-specific models
Risk Analysis – 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
Risk Analysis – Risk Measures

• Life Safety:
  
  – Expected number of casualties (includes injuries and fatalities)
  
  – Individual Risk (IR) is defined as 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.
Risk Analysis – 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).
• 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
QRA results facilitate decision-marking in the following ways:

- comparing pipeline risk to risks to the risks associated with other facilities
- ranking segments within a pipeline system
- identifying dominant failure threats
- cost-benefit analyses
Decision Making

- IR contours and F-N curves enable the evaluation of risks against recognized acceptance criteria.
- Risk profiles along the pipeline length enable identification of high-risk locations by threat categories.
- Risk matrices can be used to display the failure frequencies and failure consequences.
- A plot of risk as a function of time enables risk forecasting and decision-making regarding time-dependent threat mitigation including inspection intervals and defect repair planning.
Example: FN Curve
Example: Risk Contour

![Graph showing individual risk over distance from centerline of pipe (m)]
Example: Risk Profile

![Risk Profile Graph]

- **Risk** ($/mi-yr)
- **Station (ft)**

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www.cfertech.com
Example: Risk Matrix

![Risk Matrix Diagram]

Failure Rate (year) vs. Average Consequence ($1,000/failure) matrix with data points marked.
Example: Risk Over Time

![Graph showing risk over time with two lines representing Large Leak and Rupture](image-url)
Thankyou!