A Quantitative Risk-based Approach to Integrity Maintenance Planning and Design Optimization for Offshore Pipelines

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Background to the PIRAMID Project

- A Multi-year Joint Industry Program

- Sponsors
  - BC Gas Utility
  - Enbridge Inc. (Interprovincial)
  - Foothills Pipe Lines
  - Kinder Morgan (KN Energy)
  - Southern California Gas
  - TransCanada Pipelines
  - Gas Research Institute
  - Canadian Geological Survey
  - U.S. Minerals Management Service
Program Goal

Develop Models and Software to:

- Make optimal maintenance decisions
  - Ensure acceptable risk levels
  - At the lowest possible cost
- Explain rationale behind decisions
  - Internally within company
  - Externally to regulators and the public
Issues To Be Addressed

- What is the operating risk associated with the pipeline in its present state
- What effect would each candidate maintenance strategy have on the operating risk
- What is the lowest cost maintenance option that meets acceptable safety & environmental constraints
PIRAMID Functions

Risk Ranking

Divide system into segments

Rank segments according to risk level

Determine optimal strategy for targeted segment

Repeat for each targeted segment

Implement optimal actions in order of refined ranking

Maintenance Optimization
Risk Ranking

For each Segment in System

1. Identify Hazards
2. Estimate Probability of Failure
3. Estimate Consequences of Failure
4. Estimate Total Operating Risk

Repeat for All Hazards
For each Targeted Segment

1. Identify Integrity Maintenance Options
2. Estimate Effect of Maintenance Strategy on the Probability of Failure
3. Calculate Risk reduction
4. Select Optimal Integrity Maintenance Strategy

Repeat for All Options

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PIRAMID Features

- Quantitative approach
- Extensive use of engineering models
- Calculates total risk
  - financial
  - safety
  - environmental
- Validated by real pipeline data
Probability Estimation Approaches

General

Information → Analysis → Failure Probabilities

Adjusted historical failure rate method

Failure rates → Adjustment factors → Failure Probabilities

Structural reliability method

Condition data → Reliability Models → Failure Probabilities
Adjusted Historical Failure Rate Method

\[ R_{ijkl} = R_{fb} \cdot MF_{kl} \cdot AF_{ijl} \]

1. Baseline failure rate per cause
2. Relative failure probability per mode
3. Adjustment factor for section and cause

Failure rate for section, mode and cause
Baseline Failure Rates by Cause

- **Mechanical damage**
- **External Corrosion**
- **Internal Corrosion**
- **Fabrication defects**
- **Ground movement**
- **Environmental cracking**
- **Other**
## Failure Rates by Mode

<table>
<thead>
<tr>
<th>Failure Cause</th>
<th>Mode Factor</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>small leak</td>
<td>large leak</td>
<td>rupture</td>
<td></td>
</tr>
<tr>
<td>Metal Loss Corrosion</td>
<td>???</td>
<td>???</td>
<td>???</td>
<td></td>
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<tr>
<td>Mechanical Damage</td>
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<tr>
<td>Ground Movement</td>
<td>???</td>
<td>???</td>
<td>???</td>
<td></td>
</tr>
<tr>
<td>Cracks</td>
<td>???</td>
<td>???</td>
<td>???</td>
<td></td>
</tr>
<tr>
<td>Other Causes</td>
<td>???</td>
<td>???</td>
<td>???</td>
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</tr>
</tbody>
</table>
Probability Adjustment Factors

E.g. - for External Corrosion

\[ AF = f(A, t, T) F_{SC} F_{CP} F_{CT} F_{CC} \]

- Adjustment factor
- Line age
- Wall thickness
- Operating temperature
- Soil corrosivity factor
- Cathodic protection factor
- Coating type factor
- Coating condition factor

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Adjusted Failure Rates - Summary

- Simple models utilizing
  - Statistical data
  - Engineering analysis
  - Judgment

- Suitable for segment ranking
Structural Reliability Approach

Load Distribution

Resistance Distribution

Mean Load

Mean Resistance

Overlap Leading to Failure Probability

Load or Resistance
Application to External Corrosion

Failure rate / km = No. Defects per km x Failure probability per defect
Failure Probability per Defect

Maximum operating pressure

- Data on pipe properties and dimensions
  - Frequency
  - Yield stress (MPa)

- Corrosion characteristics
  - Prob. density
  - Flaw depth (mm)

- Measurement uncertainties
  - Test results
  - Model results

- Corrosion model and test results
  - Prob. density
  - Growth Rate (mm/yr)

- Inspection Data
  - Data from repetitive inspections

Failure probability as a function of time

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Probability of Failure Versus Time

- Time (years): 1, 3, 5, 7, 9, 11, 13, 15, 17, 19
- Annual Probability of Failure:
  - Probability values: 0.0001, 0.0010, 0.0100, 0.1000
Effect of Maintenance

- **Mitigation philosophy**
  - Find and eliminate defects before they reach critical size

- **Maintenance options**
  - Inspection and repair
  - Hydro-testing

- **Maintenance impact**
  - Reduce number of defects per unit line length
  - Shift defect size distribution toward smaller values
Quantifying Effect of Maintenance

- Size of original defects
  - Inspection detection power
    - Size of undetected defects
      - Size of remaining detected defects
        - Size of all remaining defects
  - Size of detected defects
    - Measured size of detected defects
      - Inspection sizing accuracy
        - Repair criterion
Modified Defect Size Distributions

![Graph showing modified defect size distributions for different pressures: Detected, 1.25 MAOP, and 1.5 MAOP. The x-axis represents defect depth (mm), and the y-axis represents probability density. The graph illustrates the distribution of detected defects and defects at different MAOP levels.](image-url)
Effect on Probability

Annual Probability of Failure per km

Time to Next Inspection (years)

No repair
1.25 MAOP
1.5 MAOP

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Application to Mechanical Damage

\[ \text{Failure probability} = (\text{No. line hits}) \times (\text{Failure probability per hit}) \]
Probability of Failure Given Hit

Data on steel properties and pipe dimensions

Puncture model and test results

Data on equipment size and weight

Pipe properties

Model uncertainties

Outside force

Failure probability given hit

Yield stress (MPa)

Frequency

Test results

Model results

Load (kN)

Frequency
Frequency of Line Hits

Fault Tree Model (inductive logic)

Top event

Pipeline hit by dragged object

Seabed contact with dragged object

Vessel activity on sea surface

Dragged object deployed

Failure of on-bottom protection

Seabed disturbance exceeds cover depth

Failure of mechanical protection

Basic event probabilities (a function of line attributes)

Similar fault tree for vessel hull grounding
Effect of Maintenance

- Mitigation philosophy
  - Prevent potential line hits

- Example prevention options
  - Enhance awareness of pipeline location
  - Modify cover depth inspection frequency
  - Increase pipeline burial depth
  - Introduce mechanical protection

- Prevention Impact
  - Modify fault tree basic event probabilities
  - Reduce hit probability
Effect on Failure Probability

Annual probability of failure per km

- Status quo
- Increased cover depth inspection frequency
Structural Reliability Approach - Summary

- Calculate failure probability from
  - Structural behaviour models
  - Line and ROW information
    - Defect information (corrosion / SCC/ cracks / dent-gouges)
    - External forces (ground movement / mechanical damage)

- Suitable for maintenance optimization
### Consequence Estimation Approach

#### Consequence measures

<table>
<thead>
<tr>
<th>Category</th>
<th>Measure</th>
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</thead>
<tbody>
<tr>
<td>Financial impact</td>
<td>Dollars</td>
</tr>
<tr>
<td>Public safety impact</td>
<td>Number of people at risk</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>Effective residual spill volume</td>
</tr>
</tbody>
</table>
Consequences of Pipeline Failure

- Line Repair Cost
- Lost Product Cost
- Service Interrupt Cost

- Damage Thresholds
- Hazard Models
- Human Impact Thresholds

- Spill Decay & Clean-up Models
- Shoreline Impact Model

- Offshore Damage Cost
- Effective Shoreline Impact Volume

- Financial Cost
- Number of People at Risk
Consequence Analysis

Consequences of Acute Release Hazards

Step 1 - Use event tree analysis (logic model) to estimate relative likelihood of all conceivable release hazards

- Immediate ignition
  - Explosion
    - Fireball / Jet fire
    - Vapour cloud explosion
- Delayed ignition
  - No explosion
    - Vapour cloud fire
- No immediate ignition
  - No explosion
    - Toxic vapour cloud
  - No ignition

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Consequence Analysis

Consequence of Acute Release Hazards

Step 2 - Use hazard characterization models to estimate size of affected areas

- No Ignition
- Immediate Ignition
- Delayed Ignition

Toxic Vapour Cloud | Jet Fire | Vapour Cloud Fire | Vapour Cloud Explosion

Step 3 - Estimate offshore damage cost
(no. involved structures & vessels x property value)

Estimate number of people at risk
(no. involved structures & vessels x crew size)
Consequence Analysis

Long-term Consequences of Product Release Hazard

Step 1 - Spill Volume

Step 2 - Impact Volume
- Spill Decay Model
- Spill Trajectory Model

Step 3 - Shoreline Sensitivity Model
- Offshore Clean-up Model
- Shoreline Clean-up Model

Step 4 - Assess clean-up costs
Estimate degree of natural resource damage

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Spill Trajectory Model

Trajectory Analysis Results

Shoreline

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>#</td>
<td></td>
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<td>3</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
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</table>

Probability of Impact: 0 to 1

Time to Impact: days

Spill Trajectory Analysis

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## Segment Ranking Table

<table>
<thead>
<tr>
<th>Segment Description</th>
<th>Failure Cause</th>
<th>Total Risk ($/km²/yr)</th>
<th>Probability of Failure (/km²/yr)</th>
<th>Expected Cost ($/km²/yr)</th>
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<tbody>
<tr>
<td>Segment1.Sys; P4</td>
<td>External Metal Loss Corrosion</td>
<td>2.9671e+002</td>
<td>6.3732e-004</td>
<td>9.5698e+001</td>
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<tr>
<td>Segment1.Sys; P2</td>
<td>External Metal Loss Corrosion</td>
<td>2.9296e+002</td>
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<td>Segment1.Sys; P3</td>
<td>Other Causes</td>
<td>1.8852e+002</td>
<td>2.0000e-004</td>
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<td>Other Causes</td>
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<td>2.0000e-004</td>
<td>4.6770e+001</td>
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<tr>
<td>Segment1.Sys; P3</td>
<td>Mechanical Damage (Puncture)</td>
<td>1.2177e+002</td>
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<td>Ground Movement</td>
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<td>2.9980e+001</td>
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<td>Segment1.Sys; P3</td>
<td>External Metal Loss Corrosion</td>
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<td>Stress Corrosion Cracking</td>
<td>1.9291e+001</td>
<td>1.6228e-005</td>
<td>5.5745e+000</td>
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</table>
Risk Variations Along a Segment

Total Risk
All Causes Combined: Sections for Pipeline1
Sys; P1
Failure Rate Versus Time
Decision Analysis - Utility Chart
Summary

- Comprehensive user-friendly approach for risk-based integrity maintenance planning
- Quantitative and objective methodology
  - Historical incident data
  - Analytical models for
    - pipeline failure prediction
    - release hazard characterization
  - Pipeline condition data
- Benefits
  - Generates line-specific risk estimates
  - Quantifies the impact of maintenance actions
  - Identifies minimum cost solutions