Pipeline Risk Assessment Fundamentals

Banff Pipeline Workshop 2019

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Agenda

- Introductions
- Risk Definitions and Concepts
- Pipeline Risk Assessment Concepts
- Guidance from Standards
- Pipeline Risk and Reliability Modeling
  - Estimating Likelihood of Failure
  - Estimating Consequence of Failure
  - Case Studies
  - Societal Risk and Individual Risk
- Risk Presentation Methods
- Risk and Reliability Acceptance Criteria
- Integrating Risk Results into Integrity Management
Risk Definitions and Concepts
Risk Defined

- Risk is “The chance of loss”
  (Concise Oxford Dictionary)

- This definition involves:
  - Loss ➔ Adverse consequences
  - Chance ➔ Uncertainty regarding the loss
Risk Defined

Risk of a person dying in a car accident: 1 in 11,000 per year
Risk of a person dying in a plane crash: 1 in 300,000 per year
Risk of a person dying by lightning strike: 1 in 5,000,000 per year

- Recent 2018 Mariner East 2 Pipeline (NGL) report (public record) indicates that the average person’s exposure to a fatal traffic accident is about 20 times greater than the fatality risk to someone standing above the pipeline 24/7 in Delaware County.
Risk as Defined in CSA Z662

- CSA Z662-15 – Annex B
  - **Risk**: a compound measure, either qualitative or quantitative, of the frequency and severity of an adverse effect.
Risk as Defined in ASME B31.8S

- ASME/ANSI B31.8S
  - **Risk**: measure of potential loss in terms of both the incident probability (likelihood) of occurrence and the magnitude of the consequences.
Risk Measure

- **Risk** = **likelihood** of failure x **consequence** of failure

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Likelihood of Failure

**Likelihood**: The chance of something happening, whether defined, measured, or determined objectively or subjectively, qualitatively or quantitatively, and described using general terms or mathematically (such as a probability or frequency over a given time period).

*PHMSA Draft Pipeline Risk Modeling Report 2018*

- Likelihood index
- Probability
- Frequency
- Reliability
Likelihood: Probability & Frequency

- **Likelihood Index:** a non-quantitative relative ranking or rating number representing the likelihood of failure level.

- **Probability:** likelihood, or measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty.

- **Frequency:** Number of events or outcomes per defined unit of time. Frequency can be applied to past events or to potential future events, where it can be used as a measure of likelihood / probability.
Likelihood: Probability & Frequency

► **Probability:**
  - 2/10 chance (0.2, 20%) of failing

► **Frequency:** 2/10 chance (0.2, 20%) of failing per year
  - 2/10 chance of failing per year per kilometer
**Likelihood: Reliability**

- **Reliability**: the probability that a component or system will perform its required function without failure during a specified time interval (usually taken as one year), equal to 1.0 minus the probability of failure.

- Reliability = 1 - probability of failure
  - 8/10 chance (0.8, 80%) of not failing
**Consequence of Failure**

**Consequence:** Impact that a pipeline failure could have on the public, employees, property, the environment, or organizational objectives.

*PHMSA Draft Pipeline Risk Modeling Report 2018*
Pipeline Risk Assessment Concepts
Risk Assessment as Defined
In CSA Z662-15

- CSA Z662-15 – Annex B
  - Risk assessment: the process of risk analysis and risk evaluation.
Risk Assessment as Defined in ASME/ANSI B31.8S

- ASME/ANSI B31.8S
  - **Risk assessment**: systematic process in which potential hazards from facility operation are identified, and the likelihood and consequences of potential adverse events are estimated. Risk assessments can have varying scopes, and can be performed at varying level of detail depending on the operator’s objectives (see section 5).
Risk Assessment within Risk Management

- **Risk Management** is the integrated process of **Risk Assessment** and **Risk Control**

- **Risk Assessment** is a component of **Risk Management**

- **Risk Assessment** incorporates **Risk Analysis** and **Risk Evaluation**
Risk Assessment Objectives

- Identify highest risk pipeline segments
- Highlight pipeline segments where the risk is changing
- Identify gaps or concerns in data quality and completeness
- Support risk management:
  - Calculate the benefit of risk mitigation activities
  - Support decision making and program development
  - Improve system reliability
  - Minimize risk to as low as reasonably practicable and eliminate high impact events
Guidance from Standards
Guidance from Canadian Standards

Risk Assessment – Canadian Pipelines

- CSA Z662-15
  - Annex B – Guidelines for risk assessment of pipelines
  - Annex H - Pipeline failure records: provides a classification of the causes of pipeline failure incidents that can lead to hazards
CSA Z662 Annex H

- Hazard — a condition or event that might cause a failure or damage incident or anything that has the potential to cause harm to people, property, or the environment
Guidance from U.S. Standards

Risk Assessment - U.S. Pipelines

- 49 CFR Part 192 (Gas Pipelines)
  - Subpart O Section 192.917
    - Threat identification. An operator must identify and evaluate all potential threats to each covered pipeline segment. Potential threats that an operator must consider include, but are not limited to, the threats listed in ASME/ANSI B31.8S (incorporated by reference, see §192.7), section 2, which are grouped under the following four categories:
      1. Time dependent threats such as internal corrosion, external corrosion, and stress corrosion cracking;
      2. Static or resident threats, such as fabrication or construction defects;
      3. Time independent threats such as third party damage and outside force damage; and
      4. Human error.
Guidance from U.S. Standards

Risk Assessment - U.S. Pipelines

- 49 CFR Part 192 (Gas Pipelines)
  - Subpart O Section 192.917 (cont’d)
    
    (c) Risk assessment. An operator must conduct a risk assessment that follows ASME/ANSI B31.8S, section 5, and considers the identified threats for each covered segment. An operator must use the risk assessment to prioritize the covered segments for the baseline and continual reassessments (§§ 192.919, 192.921, 192.937), and to determine what additional preventive and mitigative measures are needed (§ 192.935) for the covered segment.
Guidance from N.A. Standards

ASME/ANSI B31.8S – Managing System Integrity of Gas Pipelines

- Provides general guidance on risk assessment approaches
- Provides specific guidance on threats, safety consequences and data elements to consider
- Incorporated by reference in 49 CFR Part 192
- Referenced in API 1160 (Managing System Integrity for Hazardous Liquid Pipelines)
Guidance from U.S. Standards

Risk Assessment – U.S. Pipelines

- 49 CFR Part 195 (Hazardous Liquid Pipelines)
  - Subpart F Section 195.452 and Appendix C to Part 195
    Provide guidance on risk factors to consider
Guidance from N.A. Standards

API 1160 - Managing System Integrity for Hazardous Liquid Pipelines

- Provides general guidance on risk assessment approaches
- Provides specific guidance on threats, spill consequences and data elements to consider
- References ASME/ANSI B31.8S
- Much overlap with API 1160 and ASME B31.8S; however, the fact that there are both physical and regulatory differences between gas and liquid pipelines makes it necessary to alter the threat categories to some extent.
Guidance from International Standards

International - ISO Risk Assessment Standards


- Using ISO 31000 can help organizations increase the likelihood of achieving objectives, improve the identification of opportunities and threats and effectively allocate and use resources for risk treatment.
Guidance from Standards

International - ISO Risk Assessment Standards (cont’d)

Questions?
Pipeline Risk and Reliability Modeling
Pipeline Risk Modeling Evolution

Before IM
- Cathodic protection
- Pigging
- Digging

Early days
- Framework of IM plan
- Event not a process
- Disconnected workflows

Maturing
- Relative risk models
- Ranking of HCA’s
- Data aggregation

Current
- Data integration
- Consequence modeling
- Calibration of risk models
- Looking beyond HCA

Desired
- Risk-based decision making
- Enterprise Risk Management
- Corporate Sustainability

Enabling changes
- Technology
- Data Integration
- ILI Inspection Results

2019 BANFF PIPELINE WORKSHOP
Pipeline Risk Modeling Overview

General Process Overview

- **Risk Evaluation**
  - Determine failure modes which materially contribute to failure
  - Data collection, integration and analysis
  - Determine failure likelihood
  - Determine consequences
  - Conduct risk assessment
  - Prioritize where to conduct risk mitigation

- **Risk Mitigation**
  - Determine risk acceptability
  - Identify segments requiring risk reduction
  - Perform risk mitigation
  - Establish performance metrics
  - Measure performance of IMP
Pipeline Risk Modeling Overview

Risk = f(Failure Likelihood, Consequences)

- **Failure Likelihood**
  - Consideration of all viable threats
    - External corrosion
    - Internal corrosion
    - 3rd party damage
    - Manufacturing
    - Incorrect operations
    - Etc.
  - Establish failure likelihood for each viable threat as function of design, installation and operating environment

- **Consequences**
  - Types of consequences:
    - Safety
    - Economic
    - Environmental
    - Regulatory
    - Corporate Image
  - Utilize impact chart as means of equating consequences from various sources and establishing quantifiable impacts
Pipeline Risk Assessment Scope

- Types of Risk Assessment:
  - Site or project specific (QRA)
  - System wide
  - New construction; risk based design
  - Asset acquisition; due diligence
  - Support of engineering assessment

*The risk assessment approach needs to align with the purpose of the assessment and the supporting data available.*
CSA Z662 requires consideration of risk assessment as part of engineering assessments for existing pipelines:

10.1 Engineering assessments of existing pipelines

There is a commentary available for this Clause.

10.1.1

Engineering assessments of existing pipeline systems shall be conducted and documented in accordance with the requirements of Clause 3.3 and the analysis shall include consideration of the following, as applicable:

- a) design basis of the pipeline system, including service fluid, operating pressure and temperature range, and the general and site-specific loading and operating conditions that are anticipated throughout its design life;
- b) material specifications and properties;
- c) manufacturing process and installation method;
- d) construction and testing specifications;
- e) the physical configuration and constraints of the part of the pipeline system that are the subject of the engineering assessment;
- f) condition of the piping, including types of imperfections, dimensions, and dimensional uncertainty;
- g) mechanism or mode of imperfection formation, growth, and failure;
- h) service, operating and maintenance history;
- i) appropriateness of repair methods;
- j) interaction of identified hazards; and
- k) risk assessment.

Notes:

1) Reference should be made to the records required in Clauses 5.7, 6.1.5, 7.6.3, 7.14.9, 7.15.11, 8.8.7, 9.8.4, 9.9.5, 10.4, and 16.5.2.
2) Risk assessment (see Annex B), pipeline system integrity management programs (see Annex N), and reliability-based design and assessment (RBD&A) (see Annex O) can provide valuable information and guidance for the engineering assessment.
Pipeline Risk Modeling Continuum

Risk Modeling Continuum:

- Risk modeling is a continuum utilizing a range of qualitative and quantitative approaches and measures of risk.

- Recent guidance on risk modeling (PHMSA Risk Modeling Work Group):

Pipeline Risk Modeling Continuum

- **Qualitative:**
  - Characterizes risk level without quantifying it

- **Quantitative**
  - Calculates risk level based on quantified estimates of probability and consequence

- **Semi-quantitative:**
  - One of either probability or consequence is based on quantified estimates while the other is not quantified
Pipeline Risk Modeling Continuum

**Qualitative**
- Simple
- Subjective
- Relative
- Judgmental

*Increased accuracy requires increased data availability, accuracy, resolution*

**Quantitative**
- Detailed
- Objective
- Absolute
- Analytical

**Index Methods** ➔ **Probabilistic Methods**
Pipeline Risk Modeling - Qualitative

Qualitative Methods:

- Risk Indices or Categories
  - Assign subjective scores based on pipeline attributes, e.g.:
    - Failure Likelihood:
      - Probability Score 1-10
      - Rare, Unlikely, Possible, Likely, Almost Certain
    - Consequence:
      - Impact Severity Score 1-10
      - Insignificant, Minor, Moderate, Major, Catastrophic
    - Risk:
      - Risk Score 1-100
      - Low, Moderate, High, Extreme
Pipeline Risk Modeling - Qualitative

▶ Advantages:
  - Easy to understand, use and communicate
  - Useful for prioritization
  - Readily accommodates a broad range of risk attributes

▶ Limitations:
  - Subjective assignment of attribute weights could be inaccurate
  - Difficult to establish acceptability thresholds
  - Provides relative measure only within a specific system; not comparable outside of the system
Pipeline Risk Modeling - Quantitative

Quantitative Methods:

- Failure Likelihood:
  - Failure Frequency (failures/km-yr or failures/yr)

- Consequences:
  - Numerical Consequences ($ Impact, Fatalities, etc.)

- Risk:
  - Numerical Impact ($/km-yr, fatalities/km-yr, barrels/km-yr)
Pipeline Risk Modeling - Quantitative

- Advantages:
  - Maximizes use of inspection data
  - Consistent basis for risk and feature response
  - Impact of design, material and mitigation measures on risk can be quantified

- Limitations:
  - Inaccurate or missing data has a large impact on results
  - Difficult to combine different measures of risk
Pipeline Risk Modeling - Quantitative

- Available approaches:
  - Reliability approaches
  - Fault-tree and event tree approaches
  - Incident data-based approaches
  - Exposure-mitigation-resistance approaches
  - Geohazard vulnerability approaches
Estimating Failure Likelihood
Pipeline Threats and Hazards

- **Threat:** Potential cause of failure, failure mechanism.

- **Hazard:** Hazard — a condition or event that might cause a failure or damage incident or anything that has the potential to cause harm to people, property, or the environment. [Used synonymously with “threat” by some references.]
Pipeline Threats and Hazards

Threats to Gas Pipelines (ASME B31.8S):

Time Dependent:
- External Corrosion
- Internal Corrosion
- SCC

Stable (Resident):
- Manufacturing-Related Defects
- Construction-Related Defects
- Equipment

Time Independent:
- Third Party/Mechanical Damage
- Incorrect Operational Procedure
- Weather Related and Outside Forces
Pipeline Threats and Hazards

Threats to Gas Pipelines (ASME B31.8S):

- Interactive nature of threats shall be considered
- Pressure cycling and fatigue shall be considered
Interactive Threats - Gas

Gas: DOT Incidents from Interacting Threats
Pipeline Threats and Hazards

Threats to Hazardous Liquid Pipelines (API 1160):

- External corrosion
- Internal corrosion
- Selective seam corrosion
- Stress corrosion cracking (SCC)
- Manufacturing defects
- Construction and fabrication defects
- Equipment failure (non-pipe pressure containing equipment)
- Immediate failure due to mechanical damage
- Time-dependent failure due to resident mechanical damage
- Incorrect operations
- Weather and outside force
- Activation of resident damage from pressure-cycle-induced fatigue
## Hazardous Liquids: DOT Incidents from Interacting Threats

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### Interactive Threats - Liquids

- **Hazardous Liquids Transmission Lines**
- **DOT Incident Database 1986-2010**
Pressure Cycling Considerations

- Impact on resident features
- Impact on crack growth
Pressure Cycling Considerations

![Graph showing the relationship between Cyclic Index and Specified Minimum Yield Strength (SMYS)].
Estimating Failure Likelihood

Threat Assessment:

- **Pipeline System Review**
  - System Maps (alignment, proximity to HCAs)
  - Installation Eras (modern vs. vintage materials)
  - Products Transported (liquid, gas, crude, refined, sour, sweet)
  - Design Variables (diameters, grades, w.t., stress levels)
  - Installation Procedures (welding, NDT, etc.)
  - Operating Factors (stress, pressure cycling, environmental conditions, Inspection data)
Estimating Failure Likelihood

Threat Assessment (cont’d):

- **Review Threat Attributes in Consideration of Data and System Review**
  - External Corrosion
    - Coating type, CP history, Inspection data, Interference, etc.
  - Internal Corrosion
    - Product composition, Hydraulic regime, Inspection data, etc.
  - Third Party Damage
    - Land use, patrol frequency, damage prevention measures, etc.

- **Quantitative**
  - Calculate risk level based on quantified estimates of probability and consequence
Estimating Failure Likelihood

**Case Study: Relative/Index Method for EC based on susceptibility factors (no ILI)**

\[
S = M \times \left( 1 - \left( 1 - \left( \frac{B}{10} \right) \right) \times \left( 1 - \left( \frac{C_F}{10} \right) \right) \times \left( 1 - \left( \frac{FH}{10} \right) \right) \right) \times A_F
\]

Where,

- \( M \) = Material Type Score (0 or 1);
- \( S \) = External Corrosion Score (0-10);
- \( B \) = Baseline Susceptibility Score (0-10);
- \( C_F \) = Stray Current / Interference Factor (0-10);
- \( FH \) = External Corrosion Failure History Score (0-10); and,
- \( A_F \) = Integrity Assessment Mitigation Factor (1-10)

**Baseline Score Weightings:**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Factor</th>
<th>Fractional Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>AF</td>
<td>0.20</td>
</tr>
<tr>
<td>Corrosion Allowance Factor</td>
<td>CAF</td>
<td>0.05</td>
</tr>
<tr>
<td>Coating System Type Score</td>
<td>MCT</td>
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</tr>
<tr>
<td>CP Compliance Score</td>
<td>CP</td>
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<tr>
<td>Coating Condition Score</td>
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</tr>
<tr>
<td>Casings</td>
<td>CAS</td>
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</tr>
</tbody>
</table>
Estimating Failure Likelihood

Case Study (cont’d): Relative/Index Method for EC based on susceptibility factors (no ILI)

Coating Type

Pipe Coating Type | Score | SCC Susceptible (Y/N)
---|---|---
Bare | 10 | Y
Unknown | 10 | Y
Coated | 7 | Y
Coal Tar (“Enamel”, “Hot Dope”) | 6 | Y
Reinforced Coal Tar (“Enamel – reinforced”) | 4 | Y
FBE | 2 | N
Thin Film | 2 | N
Pre-2000 Wax | 6 | Y
>= 2000 Wax | 3 | Y
Dual Coat | 1 | N
Paint (above ground paint) | 2 | Y
Paint – high temperature (above ground) | 2 | Y
Mastic | 5 | Y
Cold-applied PE tape with primer | 4 | Y
Liquid epoxy coating (“Powercrete”) | 1 | N
Extruded Polyethylene (“Yellow Coat”) | 3 | N
Line Travel PE Tape | 7 | Y

Coating Type

CP Compliance

\[ S_{cp} = \left\{ 1 - \left( \frac{NCR}{100} \right) \right\} \times 10 \]

Coating Age

<table>
<thead>
<tr>
<th>Coating Age [yrs]</th>
<th>&lt;=3</th>
<th>&gt;3 to &lt;=5</th>
<th>&gt;5 to &lt;=9</th>
<th>&gt;9 to &lt;=12</th>
<th>&gt;12 to &lt;=15</th>
<th>&gt;15 to &lt;=18</th>
<th>&gt;18 to &lt;=21</th>
<th>&gt;21 to &lt;=24</th>
<th>&gt;24 to &lt;=27</th>
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Corrosion Allowance

\[ t_{corr} = t_a - \left( \frac{PD}{2S} \right) \]

Calculated Value of \( t_{corr} \)

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<th>&gt;0.25</th>
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<th>&gt;0.15</th>
<th>&gt;0.12</th>
<th>&gt;0.10</th>
<th>&gt;0.07</th>
<th>&gt;0.05</th>
<th>&gt;0.02</th>
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<td>5 to &lt;= 0.2</td>
<td>5 to &lt;= 0.1</td>
<td>5 to &lt;= 0.1</td>
<td>5 to &lt;= 0.1</td>
<td>0 to &lt;= 0.1</td>
<td>0 to &lt;= 0.1</td>
<td>0 to &lt;= 0.1</td>
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<td>50</td>
<td>25</td>
<td>00</td>
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<td>25</td>
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</table>

Score

<table>
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<th>3</th>
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<th>5</th>
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</table>
Estimating Failure Likelihood

**Case Study: Relative/Index Method for EC based on ILI (Remaining Life)**

- Use failure pressure criteria such as Modified B31G and wall thickness threshold to determine critical depth for failure at MOP or wall thickness threshold (eg. 80%)
- Can incorporate Safety Factor
- Apply growth rate to feature depth from time of ILI to current
- Calculate feature specific remaining life
- Determine % RL consumed since last assessment
Estimating Failure Likelihood

Case Study (cont’d): Relative/Index Method for EC based on ILI (Remaining Life)

\[
\% \text{Remaining Life Consumed} = \frac{Y_{\text{risk}} - Y_{\text{ILI}}}{RL}
\]

Where,

- \(Y_{\text{risk}}\) = the current year
- \(Y_{\text{ILI}}\) = Year of ILI run
- \(RL\) = Remaining Life

Scores will be assigned using the following table:

<table>
<thead>
<tr>
<th>% of Remaining Life Consumed Since ILI</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 90%</td>
<td>10</td>
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<tr>
<td>&gt; 80% to ≤ 90%</td>
<td>9</td>
</tr>
<tr>
<td>&gt; 70% to ≤ 80%</td>
<td>8</td>
</tr>
<tr>
<td>&gt; 60% to ≤ 70%</td>
<td>7</td>
</tr>
<tr>
<td>&gt; 50% to ≤ 60%</td>
<td>6</td>
</tr>
<tr>
<td>&gt; 40% to ≤ 50%</td>
<td>5</td>
</tr>
<tr>
<td>&gt; 30% to ≤ 40%</td>
<td>4</td>
</tr>
<tr>
<td>&gt; 20% to ≤ 30%</td>
<td>3</td>
</tr>
<tr>
<td>&gt; 10% to ≤ 20%</td>
<td>2</td>
</tr>
<tr>
<td>≤ 10%</td>
<td>1</td>
</tr>
<tr>
<td>No anomalies</td>
<td>0</td>
</tr>
</tbody>
</table>
Estimating Failure Likelihood

**Case Study: Quantitative Methods based on Incident Data**

\[ FF_{s,t,m} = FF_{Baseline} \times W_t \times W_m \times AF_{t,s} \]

- **Failure frequency for segment by threat and mode**
- **Baseline failure frequency for type of asset (industry stats)**
- **Weighting by threat (industry stats)**
- **Weighting by mode [leak (size), rupture (industry stats)]**
- **Adjustment Factor for segment and threat [algorithm-based]**
## Estimating Failure Likelihood

### Case Study (cont’d): Quantitative Methods based on Incident Data

<table>
<thead>
<tr>
<th>Threat</th>
<th>Failure Frequency (failures/km*yr 2010-2017)</th>
<th>Leak Fraction</th>
<th>Rupture Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Corrosion</td>
<td>1.347E-05</td>
<td>0.49</td>
<td>0.51</td>
</tr>
<tr>
<td>Internal Corrosion</td>
<td>5.844E-06</td>
<td>0.57</td>
<td>0.43</td>
</tr>
<tr>
<td>Stress Corrosion Cracking</td>
<td>5.082E-06</td>
<td>0.35</td>
<td>0.65</td>
</tr>
<tr>
<td>Manufacturing Defects</td>
<td>5.844E-06</td>
<td>0.43</td>
<td>0.57</td>
</tr>
<tr>
<td>Construction Defects</td>
<td>8.131E-06</td>
<td>0.69</td>
<td>0.31</td>
</tr>
<tr>
<td>Equipment Failure</td>
<td>1.575E-05</td>
<td>0.95</td>
<td>0.05</td>
</tr>
<tr>
<td>Third Party Damage</td>
<td>3.202E-05</td>
<td>0.87</td>
<td>0.13</td>
</tr>
<tr>
<td>Incorrect Operations</td>
<td>3.049E-06</td>
<td>0.92</td>
<td>0.08</td>
</tr>
<tr>
<td>Natural Forces</td>
<td>5.336E-06</td>
<td>0.76</td>
<td>0.24</td>
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</tbody>
</table>

Natural Gas Pipelines (PHMSA 2010-2017)
## Hazardous Liquid Pipelines (PHMSA 2010-2017)

<table>
<thead>
<tr>
<th>Threat</th>
<th>Failure Frequency (failures/km*yr) 2010-2017</th>
<th>Leak Fraction</th>
<th>Rupture Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Corrosion</td>
<td>5.897E-05</td>
<td>0.9437</td>
<td>0.0563</td>
</tr>
<tr>
<td>Internal Corrosion</td>
<td>3.281E-05</td>
<td>0.9873</td>
<td>0.0127</td>
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<tr>
<td>Stress Corrosion Cracking</td>
<td>3.738E-06</td>
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<tr>
<td>Manufacturing Defects</td>
<td>2.741E-05</td>
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<td>Construction Threat</td>
<td>1.869E-05</td>
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<td>Equipment Failure</td>
<td>1.059E-04</td>
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<tr>
<td>Third Party Damage</td>
<td>4.361E-05</td>
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<tr>
<td>Incorrect Operations</td>
<td>4.195E-05</td>
<td>0.9406</td>
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</tr>
<tr>
<td>Natural Forces</td>
<td>7.060E-06</td>
<td>0.8235</td>
<td>0.1765</td>
</tr>
</tbody>
</table>
Incident Data Approaches:

- Useful when a reliability model cannot be employed or ILI cannot be leveraged
- Important to consider source of incident data
- Should match characteristics of system being modeled
  - Gas
  - Liquids
  - Products
  - Upstream/Midstream/Transmission/Distribution
Estimating Failure Likelihood

PoF approach from Exposure-Mitigation-Resistance:

- “…Exposure (attack) –...defined as an event which, in the absence of mitigation, can result in failure, if insufficient resistance exists...

- Mitigation (defense) –...type and effectiveness of every mitigation measure designed to block or reduce an exposure.

- Resistance – measure or estimate of the ability of the component to absorb the exposure force without failure, once the exposure reaches the component…”

Estimating Failure Likelihood

Exposure-Mitigation-Resistance Example:

\[ \text{PoF}_{\text{time-independent}} = \text{exposure} \times (1 - \text{mitigation}) \times (1 - \text{resistance}) \]

<table>
<thead>
<tr>
<th>Data Category</th>
<th>Examples of Data/Information</th>
<th>Example Units of Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PoF: Exposure</td>
<td>excavator activity, mpy external corrosion, mpy fatigue cracking, human error rates, etc.</td>
<td>events/mile-year</td>
</tr>
<tr>
<td>PoF: Mitigation</td>
<td>depth of cover, patrol, signage, coatings, procedures, training, etc.</td>
<td>% reduction in damage potential</td>
</tr>
<tr>
<td>PoF: Resistance</td>
<td>wall thickness, SMYS, toughness, weaknesses (dents, gouges, seam issues, etc.), etc.</td>
<td>% of damage resisted without leak/rupture OR effective wall thickness (inches)</td>
</tr>
<tr>
<td>CoF</td>
<td>population density, thermal radiation distance, dispersion distances, explosion potential, overland flow distances, soil permeability, etc.</td>
<td>Ft², Count/ft², value per unit (remediation costs), cost per incident, etc.</td>
</tr>
</tbody>
</table>
Estimating Failure Likelihood

Quantitative Methods based on Models

- Mechanistic models, combined with statistical analysis establishes probability of failure

\[(P_{\text{damage resistance}} < \text{load})\]

- Leverages ILI data, where available
- Often used in conjunction with Monte Carlo analysis
Estimating Failure Likelihood

Monte Carlo Analysis

- **Deterministic Approach**
  - Discrete Inputs → Discrete Outputs

- **Reliability Approach**
  - Probability of outcome a function of input distributions

- In Monte Carlo Analysis, mechanistic model is known as Limit State Equation
Estimating Failure Likelihood

Sample Limit State Equations:

- Modified B31G Equation (Corrosion)
  \[
  \sigma_f = \sigma \left[ \frac{1 - 0.85 \frac{d}{t}}{1 - 0.85 \frac{d}{M^{-1}}} \right]
  \]

- Q-Factor Equation (3rd Pty Damage)
  \[
  \sigma_h = \sigma_c \left( \frac{(Q - C_2)^{0.6}}{C_3} \right)
  \]

- NG18 Equation (Cracks)
  \[
  K_c^2 = \frac{8 \cdot c \cdot \sigma_c^2}{\pi} \ln \sec \left( \frac{\pi \cdot M_T \cdot \sigma_h}{2 \cdot \sigma_c} \right)
  \]

- EGIG Equation (Dents)
  \[
  N_f = 5620 \left( \frac{UTS}{\Delta \sum K_d K_e} \right)^{5.26}
  \]

All of these models support probabilistic analysis of ILI data
Estimating Failure Likelihood

Risk Evaluation Consistent With Feature Response

\[ d_{crit} = \frac{\left(\sigma_{MOP} - \bar{\sigma}\right) \cdot t}{0.85 \cdot \left(\sigma_{MOP} M \bar{\sigma} \right) - \bar{\sigma}} \]

<table>
<thead>
<tr>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>N</th>
<th>O</th>
<th>P</th>
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<tbody>
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</tbody>
</table>

POE Methodology
Estimating Failure Likelihood

Quantitative Methods based on Geohazard Vulnerability

<table>
<thead>
<tr>
<th>Category</th>
<th>Geohazard Type</th>
<th>Identifier</th>
<th>Geohazard Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrotechnical</td>
<td>Lateral Migration</td>
<td>LM</td>
<td>Lateral movement of a stream related to stream bank losses</td>
</tr>
<tr>
<td></td>
<td>Scour</td>
<td>SC</td>
<td>Downward erosion of the stream bed</td>
</tr>
<tr>
<td></td>
<td>Buoyancy</td>
<td>UP</td>
<td>Uplift of a pipeline related to buoyant conditions</td>
</tr>
<tr>
<td></td>
<td>Erosion</td>
<td>ER</td>
<td>Erosion of cover and/or confining materials around the pipe</td>
</tr>
<tr>
<td>Mass Movement</td>
<td>Deep-seated Landslide</td>
<td>DS</td>
<td>Deep landslide with rotational or complex slide surface</td>
</tr>
<tr>
<td></td>
<td>Creep</td>
<td>CR</td>
<td>Gradual downslope movement of soil or rock</td>
</tr>
<tr>
<td></td>
<td>Shallow Landslide</td>
<td>SL</td>
<td>Skin flows and shallow slides</td>
</tr>
<tr>
<td>Tectonics</td>
<td>Liqufaction</td>
<td>LQ</td>
<td>Loss of soil strength due to dynamic loading</td>
</tr>
<tr>
<td></td>
<td>Shaking</td>
<td>SK</td>
<td>Ground shaking due to seismic activity</td>
</tr>
<tr>
<td></td>
<td>Fault Displacement</td>
<td>FD</td>
<td>Differential movement of ground due to fault breaks</td>
</tr>
<tr>
<td>Geochemical</td>
<td>Acid Rock Drainage</td>
<td>ARD</td>
<td>Oxidation of sulphide bearing materials</td>
</tr>
<tr>
<td></td>
<td>Karst Collapse</td>
<td>KC</td>
<td>Collapse of ground into bedrock solution cavities</td>
</tr>
<tr>
<td>Freeze / Thaw</td>
<td>Frost Action</td>
<td>FA</td>
<td>Ground heave due to excess ice formations in frozen ground</td>
</tr>
</tbody>
</table>
Estimating Failure Likelihood

Geohazard FLOC Calculation

FLOC = Frequency of Loss of Containment

\[ FLOC = I \times F \times S \times V \times M \]

- **I** - Can it happen? (0 or 1)
- **F** - If so, how often? (/yr)
- **S** - When it happens, can it hit the pipe? (0-1)
- **V** - Will it cause the pipe to fail? (0-1)
- **M** - How will mitigation help? (0-1)
Estimating Failure Likelihood
Fault Tree Model for Third Party Damage

External Interference

- Probability of a hit

- Excavation on pipeline alignment
- Accidental interference with marked alignment
- Operator unaware of activity
- Third-party unaware of pipeline
- ROW signs not recognized
- Failure of permanent markers
- Third-party chooses not to notify
- Third-party fails to avoid pipeline
- Excavation prior to operation response
- Temporary markers removed
- Third-party fails to avoid alignment

- Failure of potential measures
- Excavation depth exceeds cover depth
- Alignment not properly marked
- Activity not detected by third party or other company employees
- Activity not notified by third party

- Failure of alignment markers
- Failure of temporary markers
## Estimating Failure Likelihood

<table>
<thead>
<tr>
<th>No</th>
<th>Event</th>
<th>Conditions</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>*Excavation on pipeline alignment (function of land use)</td>
<td>Commercial/Industrial</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High density residential</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low density residential</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Agricultural</td>
<td>0.076</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remote/Water Body</td>
<td>0.06</td>
</tr>
<tr>
<td>62</td>
<td>Third-party unaware of one-call (function of method of communicating one-call system)</td>
<td>Advertising via direct mail-outs and promotion among contractors</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Above + Community meetings</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Community meetings only</td>
<td>0.50</td>
</tr>
<tr>
<td>63</td>
<td>Right-of-way signs not recognized (function of placement frequency for signs)</td>
<td>Signs at selected crossings</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Signs at all crossings</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All crossings plus intermittently along route</td>
<td>0.17</td>
</tr>
<tr>
<td>64</td>
<td>Failure of permanent markers (warning tape)</td>
<td>No buried markers</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With buried markers</td>
<td>0.10</td>
</tr>
<tr>
<td>65</td>
<td>Third-party chooses not to notify (function of type of penalty for failure to advise of intent to excavate)</td>
<td>Voluntary</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mandatory</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mandatory plus civil penalty</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right-of-way agreement</td>
<td>0.11</td>
</tr>
<tr>
<td>66</td>
<td>Third-party fails to avoid pipeline</td>
<td>Default value</td>
<td>0.40</td>
</tr>
<tr>
<td>67</td>
<td>ROW patrols fail to detect activity (function of patrol frequency)</td>
<td>Semi-daily patrols</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily patrols</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bi-daily patrols</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weekly patrols</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bi-weekly patrols</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Monthly patrols</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Semi-annual patrols</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Annual patrols</td>
<td>0.996</td>
</tr>
<tr>
<td>68</td>
<td>Activity not detected by other employees</td>
<td>Default value</td>
<td>0.97</td>
</tr>
<tr>
<td>69</td>
<td>Excavation prior to operator’s response (function of response time following advice of intent to excavate)</td>
<td>Response at the same day</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Response within two days</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Response within three days</td>
<td>0.20</td>
</tr>
<tr>
<td>70</td>
<td>Temporary mark incorrect (function of marking method)</td>
<td>By company records</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>By magnetic techniques</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>By pipe locators/probe bars</td>
<td>0.01</td>
</tr>
<tr>
<td>71</td>
<td>Accidental interference with marked alignment (function of means of conveying information pertaining to location of pipeline during excavation by others)</td>
<td>Provide route information</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Locate/mark</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Locate/mark/site supervision</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pipe exposed by hand</td>
<td>0.06</td>
</tr>
<tr>
<td>72</td>
<td>Excavation depth exceeding cover depth (function of depth of cover)</td>
<td>Cover depth &lt;= 0.8 m (2.5 ft)</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8 m (2.5 ft) &lt; Cover depth &lt;=0.9 m (3 ft)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9 m (3 ft) &lt; Cover depth &lt;=1.2 m (4 ft)</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2 m (4 ft) &lt; Cover depth &lt;=1.5 m (5 ft)</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cover depth &gt; 1.5 m (5 ft)</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Questions?
Estimating Consequence of Failure
Estimating Consequence of Failure

- Consequence factors most commonly modeled
  - Safety
  - Economic
  - Environmental
  - Regulatory
  - Corporate Image
  - Outage

- Computer models/empirical relationships to establish
  - Release Rate
  - Hazard Area
  - Spill Area
  - Damage Area

- Consideration of failure mode:
  - Small Leak
  - Large Leak
  - Rupture
Estimating Consequence of Failure

Main Steps

- Identify fluid properties and parameters
- Estimate release rate
- Model hazard area and probability of hazard (ignition)
- Establish public impact
Estimating Consequence of Failure

\[ PIR = 0.69 \sqrt{P.D^2} \]
Estimating Consequence of Failure

- Environmental impact determined by modelling liquid outflow and overland spill
- Spill plume intersects are identified
  - HCAs, ESAs
  - Waterbodies
  - Areas of Habitation
  - Native territorial lands and reserves
Estimating Consequence of Failure

No regulatory body or standard has adopted a means to quantify environmental impact

No acceptance criteria based on quantitative end points

Challenges*:

- Limits on ability to accurately model complex ecosystems
- Temporal / seasonal impacts
- Lack of agreement on assumptions
- Lack of data on response of environmental receptors to toxic loads
- Appropriate units to quantify ecosystem value
- Variability in perception of value (native / non-native / commercial / recreational user)
- Social / cultural considerations in valuation
- Intangible value of habitat preservation among species

* European Commission Land Use Planning Guidelines
Estimating Consequence of Failure

Consequence Assessment; Environmental Consequence

- **Outflow volume**
  - Product type
  - MOP
  - Flow rate
  - Hole size
  - Leak detection capabilities

- **Pump shutdown time**
- **Valve design & configuration**
- **Valve actuation time**
- **Valve section profile**
Estimating Consequence of Failure

Consequence Assessment; Environmental Consequence

Overland spill potential (direct / indirect intersect)

Practical solution is employment of consequence index that accounts for above factors

\[ CI_{Watercourse} = F_{W1}S_{Watercourse} + F_{W2}S_{Sp} + F_{W3}S_{Dw} \]

Where,
- \( CI_{Watercourse} \) = Consequence Index for Watercourse Intersects (10-100)
- \( F_W \) = Weighting Factors (0-1)
- \( S_{Watercourse} \) = Outflow Volume Score for Watercourse Intersects (10-100)
- \( S_{Sp} \) = Watercourse Sensitivity Rating Score (10-100)
- \( S_{Dw} \) = Drinking Water Source Score (10-100)

\[ CI_{Non-watercourse} = F_{NW1}S_{Non-watercourse} + F_{NW2}S_{Ls} \]

Where,
- \( CI_{Non-watercourse} \) = Consequence Index for Non-Watercourse Intersects (1-10)
- \( F_{NW} \) = Weighting Factors (0-1)
- \( S_{Non-watercourse} \) = Outflow Volume Score for Non-Watercourse Intersects (1-10)
- \( S_{Ls} \) = Land use Severity Score (1-10)
Risk Assessment Case Studies
Quantitative Risk Analysis - Case Study

Straits of Mackinac Enbridge Line 5 Study

- Client: State of Michigan contracted study (public record)
- Project: detailed assessment of alternatives to controversial oil pipeline crossing
  - 64-year-old twin 20-inch diameter lines on bottom of the straits
  - Transporting ≈540,000 bbl/day of light crude oil/natural gas liquids
- Alternatives analyzed
  - Construction of a new pipeline along a different route
  - Moving oil by rail
  - A new "trenched" crossing
  - Tunnel under the straits
  - Outright closure and decommissioning of Line 5
- Assessment included
  - Design-based cost estimates
  - Economic feasibility, socioeconomic and market impacts
  - Operational risk including consequences associated with an oil spill
Risk-based Design - Case Study

QRA for Planned Pipeline Interconnect

- Client: Diversified energy company operating more than 18,000 miles of liquids and natural gas pipelines
- Project: quantitative risk assessment for planned pipeline project

Threat Assessment

- Reviewed design, materials, construction, operating practices, and environment
- Identified principal failure threats
- Identified data to support failure frequency analysis

Failure Frequency Analysis

- Developed threat-based calculation of probability of failure per year of operation

Consequence Analysis

- Overland spill modeling and spatial assessment of impact
- Safety, Environment, Economic impacts considered

Risk Analysis

- Developed a compound measure of likelihood and consequences
- Recommended risk mitigation options to achieve acceptable risk level
Societal Risk and Individual Risk
Societal Risk

- Represented by an F-N curve, which is a plot of the frequency F, of incidents resulting in N or more fatalities
- An F-N curve is associated with a specified length of pipeline
Societal Risk

- Probability of failure
- Probability of ignition
- Probability of fatality
Societal Risk

F-N Curve:

Unacceptable Societal Risk

Criteria developed by the Advisory Committee on Major Hazards (ACMAH) in response to the Piper Alpha disaster. This criteria defines an acceptable societal risk as 1 death per million years. The risk from a single facility is considered 'just tolerable' if it results in an annual number of fatalities of 10 or less. For multiple facilities, the risk is considered 'just tolerable' if it results in an annual number of fatalities of 100 or less.

Criteria developed by the HSE to reflect what they felt the public might deem as 'acceptable' related to a large number of deaths from a nuclear incident - 500 latent cancer deaths within 10,000 years (COP, pg 15). In addition, in 2001, the HSE scaled the societal risk criteria from the 'just tolerable' risk from the multiple hazardous facility criteria to a single hazardous facility (1/20 of the N value) which is equivalent to the latent cancer death criteria.
Societal Risk

- CSA Z662-15 Annex O: Reliability Targets for Ultimate Limit States:

\[
R_T = \begin{cases} 
1 - \frac{1650}{(PD)^{0.66}} & \text{for } \rho = 0 \\
1 - \frac{197}{(\rho PD)^{0.66}} & \text{for } 0 < \rho PD^3 \leq 1.16 \times 10^7 \\
1 - \frac{49700}{\rho PD^3} & \text{for } 1.16 \times 10^7 < \rho PD^3 \leq 7.1 \times 10^9 \\
1 - \frac{4.05 \times 10^{10}}{(\rho PD)^{1.6}} & \text{for } \rho PD^3 > 7.1 \times 10^9 
\end{cases}
\]

where
\(\rho\) = the population density (people per hectare)
\(P\) = the pressure, MPa
\(D\) = the diameter, mm
Societal Risk

- CSA Z662-15 Annex O: Reliability Targets for Ultimate Limit States:

Figure 0.2
Reliability targets for ultimate limit states
(See Clauses 0.1.5.2.1 and 0.1.5.2.4.)
Individual Risk

- Defined as the probability of fatality for a person at a particular location due to a pipeline failure.
- Calculated for locations where individuals can be present for extended periods of time.
- Varies with the distance from the pipeline and the likelihood of individuals being present.
Individual Risk

\[ IR = \left( f_{p_1} \times pf_{at_1} \right) \cdot U \left( f_{p_2} \times pf_{at_2} \right) \cdot U \left( f_{p_3} \times pf_{at_3} \right) \cdot U \ldots \cdot U \left( f_{p_n} \times pf_{at_n} \right) \]
# Individual Risk

## CSChE Guidelines:

**APPENDIX A1 – COMMON RISKS**

In evaluating levels of individual risk, and putting the risk acceptability criteria into perspective, it is useful to keep in mind the risk levels encountered in other activities. Some common risks are presented in Table A1.1 for this purpose.

### Table A1.1 Common Risks in Canada

| Cause                                 | Individual Risk \(^{(b)}\) (Chances in a million of death per year) |
|---------------------------------------|------------------------------------------------|---|
| Motor Vehicle Accident                | 109                                          |
| Falls                                 | 82                                           |
| Poisoning\(^{(c)}\)                   | 25                                           |
| Dwelling Fires                        | 7.9                                          |
| Water Transport Accidents             | 3.6                                          |
| Air & Space Transport Accidents       | 3.2                                          |
| Excessive Cold                        | 3                                            |
| Electrical Current                    | 1.1                                          |
| Railway Accidents                     | 1.1                                          |
| Drowning in Bathtub                   | 0.8                                          |
| Earth Movements                       | 0.4                                          |
| Lightning                             | 0.2                                          |
| Cataclysmic Storm                     | 0.03                                         |

\(^{(a)}\) Data are Canada-wide and were derived from information in “Causes of Death” Statistics Canada Publication #84-208 (1995).

\(^{(b)}\) These are average individual risk values, based on a population of ~29.600,000. Data are rounded.

\(^{(c)}\) Poisoning includes accidental poisoning due to poisonous and other substances, surgical complications and misadventures to patients.
Presentation of Risk Results
## Qualitative Risk Matrix Examples

<table>
<thead>
<tr>
<th>Consequence</th>
<th>0 to 2</th>
<th>2 to 4</th>
<th>4 to 6</th>
<th>6 to 8</th>
<th>8 to 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 to 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 to 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 to 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 to 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Increasing Risk

- The matrix shows the relationship between the probability of an event occurring and the potential impact or consequence.
- The color coding indicates different levels of risk, with red representing the highest risk and green representing the lowest risk.
- The arrows in the diagram illustrate the increasing risk as the probability and consequence increase.
Qualitative Risk Matrix Examples

<table>
<thead>
<tr>
<th>Likelihood level</th>
<th>Descriptor</th>
<th>Consequence level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Almost certain</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Likely</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Possible</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Unlikely</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Rare</td>
<td>1</td>
</tr>
</tbody>
</table>

Risk rating:
- Extreme
- High
- Moderate
- Low
Qualitative Risk Matrix Examples

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No injury or health effects</td>
</tr>
<tr>
<td>2</td>
<td>Minor to moderate injury or health effects</td>
</tr>
<tr>
<td>3</td>
<td>Moderate to severe injury or health effects</td>
</tr>
<tr>
<td>4</td>
<td>Permanently disabling injury or fatality</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not expected to occur during life of process/system/facility</td>
</tr>
<tr>
<td>2</td>
<td>May occur once during life of process/system/facility</td>
</tr>
<tr>
<td>3</td>
<td>May occur several times during life of process/system/facility</td>
</tr>
<tr>
<td>4</td>
<td>Expected to occur more than once in a year</td>
</tr>
</tbody>
</table>
# Semi-Quantitative Risk Matrix Example

<table>
<thead>
<tr>
<th>Likelihood of Failure (ruptures/mile²)</th>
<th>From 0</th>
<th>From 2</th>
<th>From 4</th>
<th>From 8</th>
<th>From 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>From 0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 1.0E-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 1.0E-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Consequence of Failure Severity Index

1. MINOR
2. MODERATE
3. MAJOR
4. CRITICAL
5. CATASTROPHIC
Other Displays of Risk
Failure Frequency and Impact Severity
Risk Distribution

- Useful tool for testing and calibrating risk assessment approach
- Need an approach that provides for focused risk reduction
Risk Acceptance Criteria
Risk Acceptance Criteria

- Industry Activities:
  - PHMSA Paper Study on Risk Tolerance
  - CSA Annex B Risk Management Task Force (proposed updates for 2023 standard)
  - Operators developing their own reliability targets
  - Comparison to other industries that have criteria:
    - Nuclear
    - Aeronautical
    - Aerospace
    - Chemical
  - Employing ALARP principles
Risk Acceptance Criteria

- ALARP (as low as reasonably practicable):
**Risk Acceptance Criteria**

- **ALARP**: As Low as Reasonably Practicable is the level of risk that represents the point, objectively assessed, at which the time, difficulty and cost of further reduction measures become *unreasonably disproportionate* to the additional risk reduction obtained.

  (ref. CSA Z276-15 LNG)
Risk Acceptance Criteria

- IGEM/TD/1 Sample F-N curve criteria for natural gas pipelines (1.6 km):
Risk Acceptance Criteria

- County of Santa Barbara County Planning and Development Department criteria
Risk Acceptance Criteria

Discrete (step-wise) Qualitative Risk Matrix

- Likely
  - High
  - Extreme
  - Extreme
  - Extreme

- Possible
  - Medium
  - Extreme
  - Extreme

- Unlikely
  - Low
  - Low
  - Medium
  - High

- Very Unlikely
  - Low
  - Low
  - Medium
  - High

- Minor
- Moderate
- Major
- Critical

Continuous Quantitative Risk Criteria

- Probability of Occurrence
- Number of Persons Affected

- Unacceptable
- Acceptable
- May be acceptable

Thresholds in F-N curve and risk matrices
Using the Risk Results
Using the Risk Results

- Goal: risk-based decision making
- Supports integrity management activities and prioritizations
- Eliminate high consequence events
- Regulatory expectation to integrate risk results
- Recognize that integrity management and risk assessment approaches may not always be aligned
- Need to gain trust in the results across the organization
Integration of Risk Assessment into IMP

- Compares the calculated risk to established measures
- Combines Probability of failure and Consequence meaningfully
- Prioritizes preventative & maintenance (P&M) activities
Questions?