Pipeline Risk Assessment/Management

Mini-Workshop
The Basics – PL Risk Management

Objective:
Understand the essential elements of an effective pipeline risk assessment and its role in risk management

Agenda
- Background
- Regulations/standards
- Risk Assessment
  - What to look for
  - Essential Elements
- Risk Mgmt Implications

<table>
<thead>
<tr>
<th>Element</th>
<th>Index/Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth cover</td>
<td>shallow = 8 pts</td>
</tr>
<tr>
<td>wrinkle bend</td>
<td>yes = 6 pts</td>
</tr>
<tr>
<td>coating condition</td>
<td>fair = 3 pts</td>
</tr>
<tr>
<td>soil</td>
<td>moderate = 4 pts</td>
</tr>
</tbody>
</table>
Kalamazoo River, 2010

$1,000,000,000 spent

10ft creek

PoF: 1/1000yr
CoF: $1B
Expected Loss: $1M/yr/10ft!
Overall Example
## Overview Data Collection

<table>
<thead>
<tr>
<th>beg</th>
<th>end</th>
<th>event</th>
<th>code</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8</td>
<td>pipe wall</td>
<td></td>
<td>inches</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>pipe wall</td>
<td></td>
<td>inches</td>
</tr>
<tr>
<td>18</td>
<td>20</td>
<td>pipe wall</td>
<td></td>
<td>inches</td>
</tr>
<tr>
<td>0</td>
<td>15</td>
<td>soil</td>
<td></td>
<td>mpy</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>soil</td>
<td></td>
<td>mpy</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>pop</td>
<td></td>
<td>$/event</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>pop</td>
<td></td>
<td>$/event</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>pop</td>
<td></td>
<td>$/event</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
<td>coat/CP</td>
<td></td>
<td>% effective</td>
</tr>
</tbody>
</table>

**How to segment?**
## Overview Risk Calcs

<table>
<thead>
<tr>
<th>beg</th>
<th>end</th>
<th>pipe_wall</th>
<th>soil</th>
<th>pop</th>
<th>mpy mit</th>
<th>TTF, yrs</th>
<th>PoF, yr1</th>
<th>EL, $/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5</td>
<td>0.25</td>
<td>5</td>
<td>10000</td>
<td>0.5</td>
<td>500</td>
<td>0.002</td>
<td>$ 20</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>0.25</td>
<td>5</td>
<td>100000</td>
<td>0.5</td>
<td>500</td>
<td>0.002</td>
<td>$ 200</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>0.25</td>
<td>5</td>
<td>10000</td>
<td>0.5</td>
<td>500</td>
<td>0.002</td>
<td>$ 20</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>0.5</td>
<td>5</td>
<td>10000</td>
<td>0.5</td>
<td>1000</td>
<td>0.001</td>
<td>$ 10</td>
</tr>
<tr>
<td>15</td>
<td>18</td>
<td>0.5</td>
<td>10</td>
<td>10000</td>
<td>1</td>
<td>500</td>
<td>0.002</td>
<td>$ 20</td>
</tr>
<tr>
<td>18</td>
<td>20</td>
<td>0.25</td>
<td>10</td>
<td>10000</td>
<td>1</td>
<td>250</td>
<td>0.004</td>
<td>$ 40</td>
</tr>
</tbody>
</table>

coat/CP 90%

CoF = pop
TTF = pipe_wall / mpy mit
PoF = 1 / TTF
EL = PoF × CoF
Overall Example

1.3% PoF Corr Ext for 20 km
EL = $310 / year

**Demonstrations of**
Centerlines
Efficient data collection
Data management
Dynamic segmentation
Risk estimates
Risk aggregation
High tech on a ‘scratch pad’
Background
Reality Check

- RM is not new; requires RA

- Risk-based decision-making is complex
  - Because the real world is complex, measuring risk is complex
    - 200+ variables & 200+ calculations for every inch of pipe
    - real factors, real considerations
  - RM is even more complex than RA

- Dealing with the complexity is worthwhile
  - increases understanding
  - shows full range of options; many opportunities to impact risk
  - cheaper than prescriptive ‘solutions’
  - Improves decision-making
If you put tomfoolery into a computer, nothing comes out of it but tomfoolery. But this tomfoolery, having passed through a very expensive machine, is somehow ennobled and no-one dares criticize it.

- Pierre Gallois

The Illusion of Knowledge
IMP RA Regulations & Standards
Pertinent Regulatory/Standards

- 49 CFR Parts 192, 195
- Advisory Bulletin (Jan 2011)
- Public Presentations (June 2011)
- ASME B31.8s
- API STANDARD 1160
  - Managing Pipeline System Integrity
- API Risk Based Inspection (RBI) RP’s
- NACE DA RP’s
- CSA Z662
  - Annex O
- ISO
RA is the Centerpiece of IMP
Gas IM Rule Objectives

- Prioritize pipeline segments
- Evaluate benefits of mitigation
- Determine most effective mitigation
- Evaluate effect of inspection intervals
- Assess the use of alternative assessment
- Allocate resources more effectively
Gas IM Rule RA

- Account for relevant attributes
- Use conservative defaults for unknown data
- Identify significant risk-driving factors
- Sufficient segment discretization or resolution
- Predictive or “what-if” capability
- Updateable to reflect changes or new information
- Populating risk model is resource intensive
- Validate model, show to be plausible with respect to known history and significance of threats

ASME B31.8S, Section 5
B31.8S Threat Categories

- ASME B31.8 supplement considers 3 categories of threat:
  - *Time dependent* – may worsen over time; require periodic reassessment
  - *Time stable* – does not worsen over time; one-time assessment is sufficient (unless conditions of operation change)
  - *Time independent* – occurs randomly; best addressed by prevention
• External corrosion
• Internal corrosion
• Stress-corrosion cracking (SCC)
Threat Categories: Time Independent (Random) Threats

- Third-party/Mechanical damage
  - Immediate failure
  - Delayed failure (previously damaged)
  - Vandalism

- Incorrect operations

- Weather related
  - Cold weather
  - Lightning
  - Heavy rain, flood
  - Earth movement
Threat Categories:

**Time Stable Threats—Resistance**

- Manufacturing-related flaws in
  - Pipe body
  - Pipe seam
- Welding / Fabrication-caused flaws in
  - Girth welds
  - Fabrication welds
  - Wrinkled / buckled bend
  - Threads / couplings
- Defects present in equipment
  - Gaskets, O-rings
  - Control / relief devices
  - Seals, packing
  - Other equipment
ASME B31.8s

- Subject Matter Experts
- Relative Assessments
- Scenario Assessments
- Probabilistic Assessments

Confusion: tools vs models
IMP Objectives vs RA Techniques

Objectives

(a) prioritization of pipelines/segments for scheduling integrity assessments and mitigating action
(b) assessment of the benefits derived from mitigating action
(c) determination of the most effective mitigation measures for the identified threats
(d) assessment of the integrity impact from modified inspection intervals
(e) assessment of the use of or need for alternative inspection methodologies
(f) more effective resource allocation

Numbers Needed

• Failure rate estimates for each threat on each PL segment
• Mitigation effectiveness for each contemplated measure
• Time to Failure (TTF) estimates (time-dep threats)

Techniques

• Subject Matter Experts
• Relative Assessments
• Scenario Assessments
• Probabilistic Assessments
PL RA Methodologies

ASME B31.8s
- Subject Matter Experts
- Relative Assessments
- Scenario Assessments
- Probabilistic Assessments

Index/Score

<table>
<thead>
<tr>
<th>Feature</th>
<th>Index/Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth cover</td>
<td>shallow = 8 pts</td>
</tr>
<tr>
<td>wrinkle bend</td>
<td>yes = 6 pts</td>
</tr>
<tr>
<td>coating condition</td>
<td>fair = 3 pts</td>
</tr>
<tr>
<td>soil</td>
<td>moderate = 4 pts</td>
</tr>
</tbody>
</table>

Probabilistic
Mechanistic
Deterministic

Qualitative
Quantitative
Semi-quantitative

QRA
PRA
Indexing
Scoring
PL Risk Modeling Confusion

Types of Models
- Absolute Results
- Relative Results

Ingredients in All Models
- Probabilistic methods
  - Scenarios, trees
  - Statistics
- SME (input and validation)

ASME B31.8s
- Subject Matter Experts
- Relative Assessments
- Scenario Assessments
- Probabilistic Assessments

Qualitative
Quantitative
Semi-quantitative
Probabilistic
Absolute Risk Values

Frequency of consequence
- Temporally
- Spatially

• Incidents per mile-year
• Fatalities per mile-year
• Dollars per km-decade

Ingredients
- Events/yr
- Events/mile-year
- Mpy corrosion
- Mpy cracking
- TTF = pipe wall / mpy
- % reduction in events/mi-yr
- % reduction in mpy
- % damage vs failure
ASME B31.8S Summary of Updates Needed

- The stated objectives of risk assessment cannot be effectively accomplished using some of the risk assessment techniques that are currently acceptable according to ASME B31.8s.
- The ASME B31.8s threat list confuses failure mechanisms and vulnerabilities.
- The ASME B31.8s methodology discussion confuses risk models with characteristics of risk models or tools used in risk analyses.
- The use of weightings is always problematic, rarely appropriate, but appears to be mandated in inspection protocols based on ASME B31.8S language.
Inspecting a Risk Assessment
Easy to Spot (and Correct!) Methodology Weaknesses

<table>
<thead>
<tr>
<th></th>
<th>Index/Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth cover</td>
<td>shallow = 8 pts</td>
</tr>
<tr>
<td>wrinkle bend</td>
<td>yes = 6 pts</td>
</tr>
<tr>
<td>coating condition</td>
<td>fair = 3 pts</td>
</tr>
<tr>
<td>soil</td>
<td>moderate = 4 pts</td>
</tr>
</tbody>
</table>
What does that mean?

ASME B31.8s
- Subject Matter Experts
- Relative Assessments
- Scenario Assessments
- Probabilistic Assessments

QRA
PRA
Indexing
Scoring

Qualitative
Quantitative
Semi-quantitative

Probabilistic
Mechanistic
Deterministic
Hazard ID & Risk Analyses Tools

- Scenarios
- Event / fault trees
- Safety reviews / Checklists
- Matrix
- What-if analysis
- FMEA
- PHA, HAZOPS
- LOPA
Judging a Risk Assessment

- “Technically justifiable . . .”
- “Logical, structured, and documented . . .”
- “Assurance of completeness . . .”
- “…incorporates sufficient resolution . . .”
- “Appropriate application of risk factors . . .”
- “Explicitly accounts for . . .” and combines PoF and CoF factors
- “Process to validate results . . .”
- P&M based on risk analyses
Passing the ‘Map Point’ Test

Risk Profiles
Receiver Operating Characteristic (ROC) Curve

<table>
<thead>
<tr>
<th>statistical perspective</th>
<th>management perspective</th>
<th>public perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td>false positive</td>
<td>false alarm</td>
<td>crying wolf</td>
</tr>
<tr>
<td>false negative</td>
<td>missed alarm</td>
<td>wolf in sheep's clothing</td>
</tr>
<tr>
<td>true positive</td>
<td>actual alarm</td>
<td>wolf in plain sight</td>
</tr>
<tr>
<td>true negative</td>
<td>no alarm</td>
<td>no wolf</td>
</tr>
</tbody>
</table>

Can you tolerate 20% FP in exchange for only missing one in one-hundred?
PHMSA Concerns

**Inspections Identify Weaknesses in Risk Analysis**
- Current **challenge** is for industry to develop
  - More rigorous quantitative risk analyses
  - More investigative approach
  - Engineering critical assessment
  - Robust approach for P&M measures
- Technically sound risk-based criteria

**Recent Events Illustrate Weaknesses in Risk Analysis**
- Effective risk analysis might have prevented or mitigated recent high consequence accidents
- **Weaknesses** include inadequate:
  - Knowledge of pipeline risk characteristics
  - Processes to analyze interactive threats
  - Evaluation of way to reduce or mitigate consequences
  - Process to select P&M measures
- Lack of **objective, systematic approach**

**Limitations of Simple Index Models**
- Ineffective analysis of complex risk factor interactions
- Output not useful for identifying previously unrecognized threats/risks
- Not proven as adequate basis for evaluating P&M measures
- Poor capability to identify risk drivers
- Uncertainties (due to quantifying risk scores based on opinion) are not appropriately considered

**PHMSA Risk Assessment Concerns**
- Weaknesses of Simple Relative Index Models
- Records (Availability and Quality of Data)
- Data Integration
- Interacting Threats
- Vintage/Legacy Pipe
- Connection to Real Decision-Making
- Uncertainties
Relative, Index, Scoring Models

- Intuitive
- Comprehensive
- Ease of setup and use
- Optimum for prioritization
- Mainstream
- Served us well in the past
Scoring Model Issues

- Artificial, inefficient layer
- Not designed for IMP
- Difficult to anchor
- Potential for masking
- Technical compromises
  - Weightings
  - Scale direction
  - Interactions of variables (dep vs indep)
- Validation (reg reqmt)
- New uses
Common Complaints:

“We’ve been waiting for two years to start generating results we can trust”

“We have a risk assessment, but we can’t use the results for anything”

“We purchased a sophisticated off-the-shelf solution, but we’re not really sure how it calculates risk”

“Our risk assessment methodology was developed internally ages ago, how do we know if it’s still acceptable?”
Myths: Data Availability vs Modeling Rigor

Myth:
- Some RA models are better able to accommodate low data availability

Reality:
- Strong data + strong model = accurate results
- Weak data + strong model = uncertain results
- Weak data + weak model = meaningless results
Myth: QRA / PRA Requirements

Myth:

- QRA requires vast amounts of incident histories

Reality:

- QRA ‘requires’ no more data than other techniques
- All assessments work better with better information

Footnotes:
- Some classical QRA does over-emphasize history
- Excessive reliance on history is an error in any methodology
Risk Assessment Maturity

Risk Assessment Maturity

Relative

Absolute
Modern RA Modeling Approach

- High resolution
- Measurements instead of scores
- Accurate/Appropriate mathematical relationships
- Direct use of inspection results
- Ability to express results in absolute terms
Modern Pipeline Risk Assessment

<table>
<thead>
<tr>
<th>System</th>
<th>Product</th>
<th>Length (miles)</th>
<th>Risk (Total Annual Exposure)</th>
<th>Risk (Expected Loss $/m-yr)</th>
<th>PoF (Incident Rate, failures per m-yr)</th>
<th>CoF (Probability-weighted $/failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elvira</td>
<td>gasoline</td>
<td>120</td>
<td>$142,080</td>
<td>$1,184</td>
<td>0.001</td>
<td>$1,184,000</td>
</tr>
<tr>
<td>Scaramonga</td>
<td>crude oil</td>
<td>408</td>
<td>$342,720</td>
<td>$840</td>
<td>0.0015</td>
<td>$560,000</td>
</tr>
<tr>
<td>Perseus</td>
<td>natural gas</td>
<td>23</td>
<td>$33,810</td>
<td>$1,470</td>
<td>0.007</td>
<td>$210,000</td>
</tr>
</tbody>
</table>
Essential Elements
Essential Elements

- The Essential Elements are meant to
  - Be common sense ingredients that make risk assessment meaningful, objective, and acceptable to all stakeholders
  - Be concise yet flexible, allowing tailored solutions to situation-specific concerns
  - Lead to *smarter risk assessment*
  - Avoid need for ‘one size fits all’ solutions
  - Response to stakeholder criticisms
  - Stepping stone towards RP

- The elements are meant to supplement, not replace, guidance, recommended practice, and regulations already in place
- The elements are a basis for risk assessment certifications
- www.pipelinerrisk.net
The Essential Elements

- Measurements in Verifiable Units
- Proper Probability of Failure Assessment
- Characterization of Potential Consequences
- Full Integration of Pipeline Knowledge
- Sufficient Granularity
- Bias Management
- Profiles of Risk
- Proper Aggregation
Measure in Verifiable Units

- Must include a definition of “Failure”
- Must produce *verifiable* estimates of PoF and CoF in commonly used measurement units
- PoF must capture effects of length and time
- Must be free from intermediate schemes (scoring, point assignments, etc)

“Measure in verifiable units” keeps the process transparent by expressing risk elements in understandable terms that can be calibrated to reality
Verifiable Risk Values

Risk = Frequency of consequence
- Temporally
- Spatially

<table>
<thead>
<tr>
<th>Index/Score</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth cover</td>
<td>shallow = 8 pts</td>
</tr>
<tr>
<td>wrinkle bend</td>
<td>yes = 6 pts</td>
</tr>
<tr>
<td>coating condition</td>
<td>fair = 3 pts</td>
</tr>
<tr>
<td>soil</td>
<td>moderate = 4 pts</td>
</tr>
</tbody>
</table>

- Incidents per mile-year
- Fatalities per mile-year
- Dollars per km-decade

TTF = pipe wall / mpy
% reduction in events/mi-yr
% reduction in mpy
% damage vs failure

Measure in Verifiable Units

conseq  prob
Why measurements instead of scores?

- Less subjective
- Anchored in ‘real world’ (incl orders magnitude, OR gates, etc)
- Defensible, verifiable over time
- Avoids need for ‘cook book’
- Avoids erosion of score definitions
- Allows calculation of costs and benefits
- Supports better decisions
- Auditable
All plausible failure mechanisms must be included in the assessment of PoF

Each failure mechanism must have the following elements independently measured:
- Exposure
- Mitigation
- Resistance

For each time dependent failure mechanism, a theoretical remaining life estimate must be produced
Proper PoF Characterization

- **Exposure**: likelihood and aggressiveness of a failure mechanism reaching the pipe when no mitigation applied (ATTACK)

- **Mitigation**: prevents or reduces likelihood or intensity of the exposure reaching the pipe (DEFENSE)

- **Resistance**: ability to resist failure given presence of exposure (SURVIVABILITY)
Information Use--Exposure, Mitigation, or Resistance?

<table>
<thead>
<tr>
<th>Pipe wall thickness</th>
<th>maintenance pigging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air patrol frequency</td>
<td>surge relief valve</td>
</tr>
<tr>
<td>Soil resistivity</td>
<td>casing pipe</td>
</tr>
<tr>
<td>Coating type</td>
<td>flowrate</td>
</tr>
<tr>
<td>CP P-S voltage reading</td>
<td>depth cover</td>
</tr>
<tr>
<td>Date of pipe manufacture</td>
<td>training</td>
</tr>
<tr>
<td>Stress level</td>
<td>SMYS</td>
</tr>
<tr>
<td>Operating procedures</td>
<td>one-call system type</td>
</tr>
<tr>
<td>Nearby traffic type and volume</td>
<td>SCADA</td>
</tr>
<tr>
<td>Nearby AC power lines (2)</td>
<td>pipe wall lamination</td>
</tr>
<tr>
<td>ILI date and type</td>
<td>wrinkle bend</td>
</tr>
<tr>
<td>Pressure test psig</td>
<td></td>
</tr>
</tbody>
</table>
PoF: Critical Aspects

Exposure ➔ Mitigation ➔ Resistance
Probability of Damage or Failure—Simple Math

- Probability of Damage (PoD) = exposure \times (1 \text{ - mitigation})

- Probability of Failure (PoF) = PoD \times (1 \text{ - resistance})

\{PoF = \text{exposure} \times (1 \text{ - mitigation}) \times (1 \text{ - resistance})\}

- PoF (time-dependent) = \frac{1}{TTF}

  = \text{exposure} \times (1 \text{ - mitigation}) \div \text{resistance} \text{ (example only)}

<table>
<thead>
<tr>
<th>Exposure</th>
<th>PoD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitigation</td>
<td></td>
</tr>
<tr>
<td>Resistance</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PoF</th>
</tr>
</thead>
</table>
Estimating Threat Exposure

- **Events per mile-year (km-yr)** for time independent mechanism
  - third party
  - incorrect operations
  - weather & land movements

- **MPY (mm/yr)** for degradation mechanisms
  - Corrosion (Ext, Int)
  - Cracking (EAC / fatigue)
List the Exposures
Example: Exposures Offshore RA
Sample Exposure Estimates

- Vehicle impact; 1 mile along busy highway
  0.1 to 10 events/mile-year

- excavation; 530 ft heavy construction
  ~400 events/mile-year

- vehicle impact; 1 mile along RR
  ~0.01 events/mile-year

- power pole falling
  0.05 to 2 events/mile-year
## Rates: Failures, Exposures, Events, etc

<table>
<thead>
<tr>
<th>Failures/yr</th>
<th>Years to Fail</th>
<th>Approximate Rule Thumb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td>0.000001</td>
<td>Continuous failures</td>
</tr>
<tr>
<td>100,000</td>
<td>0.00001</td>
<td>fails ~10 times per hour</td>
</tr>
<tr>
<td>10,000</td>
<td>0.001</td>
<td>fails ~1 times per hour</td>
</tr>
<tr>
<td>1,000</td>
<td>0.01</td>
<td>fails ~3 times per day</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>fails ~2 times per week</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>fails ~1 times per month</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>fails ~1 times per year</td>
</tr>
<tr>
<td>0.1</td>
<td>100</td>
<td>fails ~1 per 10 years</td>
</tr>
<tr>
<td>0.01</td>
<td>1,000</td>
<td>fails ~1 per 100 years</td>
</tr>
<tr>
<td>0.001</td>
<td>10,000</td>
<td>fails ~1 per 1000 years</td>
</tr>
<tr>
<td>0.0001</td>
<td>100,000</td>
<td>fails ~1 per 10,000 years</td>
</tr>
<tr>
<td>0.00001</td>
<td>1,000,000</td>
<td>fails ~1 per 100,000 years</td>
</tr>
<tr>
<td>0.000001</td>
<td>1,000,000,000</td>
<td>One in a million chance of failure</td>
</tr>
<tr>
<td>0.000000001</td>
<td>1,000,000,000</td>
<td>Effectively, it never fails</td>
</tr>
</tbody>
</table>
Advantages of Estimates as Measurements

- Estimates can often be validated over time
- Estimate values from several causes are directly additive. E.G. Falling objects, landslide, subsidence, etc, each with their own frequency of occurrence can be added together
- Estimates are in a form that consider segment-length effects and supports PoF estimates in absolute terms
- Avoids need to standardize qualitative measures such as “high”, “medium”, “low” avoids interpretation and erosion of definitions over time and when different assessors become involved.
- Can directly incorporate pertinent company and industry historical data.
- Forces SME to provide more considered values. It is more difficult to present a number such as 1 hit every 2 years
Estimating Mitigation Measure Effectiveness

- Exposure
  - Coating system
  - Depth of cover
  - Casing
  - Patrol
  - Public Education
  - Training & Competency
  - Cathodic protection system
  - Maint Pigging
  - Chem Inhibition

Damage
Measuring Mitigation

Strong, single measure

Or

Accumulation of lesser measures

Mitigation % = 1 - (remaining threat)

Remaining threat = (remnant from mit1) AND (remnant from mit2) AND (remnant from mit3) …
Measuring Mitigation

Mitigation % = \( 1 - [(1 - \text{mit1}) \times (1 - \text{mit2}) \times (1 - \text{mit3}) \ldots] \)

In words:

\[ \text{Mitigation \%} = 1 - \text{(remaining threat)} \]
\[ \text{Remaining threat} = \text{(remnant from mit1)} \ \text{AND} \ \text{(remnant from mit2)} \ \text{AND} \ \text{(remnant from mit3)} \ \ldots \]

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Mitigation</th>
<th>Reduction</th>
<th>freq damage</th>
<th>prob damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>events/mi-yr</td>
<td></td>
<td></td>
<td>events/mi-yr</td>
<td>Prob/mi-yr</td>
</tr>
<tr>
<td>10</td>
<td>90.0%</td>
<td>10</td>
<td>1</td>
<td>63.2%</td>
</tr>
<tr>
<td>10</td>
<td>99.0%</td>
<td>100</td>
<td>0.1</td>
<td>9.52%</td>
</tr>
<tr>
<td>10</td>
<td>99.9%</td>
<td>1000</td>
<td>0.01</td>
<td>1.00%</td>
</tr>
</tbody>
</table>
Measuring Mitigation

What is the overall mitigation effectiveness if:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth cover</td>
<td>50%</td>
</tr>
<tr>
<td>One call</td>
<td>60%</td>
</tr>
</tbody>
</table>
# Reported Mitigation Benefits

<table>
<thead>
<tr>
<th>Mitigation</th>
<th>Impact on risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase soil cover</td>
<td>56% reduction in mechanical damage when soil cover increased from 1.0 to 1.5 m</td>
</tr>
<tr>
<td>Deeper burial</td>
<td>25% reduction in impact failure frequency for burial at 1.5 m; 50% reduction for 2 m; 99% for 3 m</td>
</tr>
<tr>
<td>Increased wall thickness</td>
<td>90% reduction in impact frequency for &gt;11.9-mm wall or &gt;9.1-mm wall with 0.3 safety factor</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>Same effect as pipe wall thickness increase</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>Reduces risk of mechanical damage to “negligible”</td>
</tr>
<tr>
<td>Underground tape marker</td>
<td>60% reduction in mechanical damage</td>
</tr>
<tr>
<td>Additional signage</td>
<td>40% reduction in mechanical damage</td>
</tr>
<tr>
<td>Increased one-call awareness and response</td>
<td>50% reduction in mechanical damage</td>
</tr>
<tr>
<td>Increased ROW patrol</td>
<td>30% reduction in mechanical damage</td>
</tr>
<tr>
<td>Increased ROW patrol</td>
<td>30% heavy equipment-related damages; 20% ranch/farm activities; 10% homeowner activities</td>
</tr>
<tr>
<td>Improved ROW, signage, public education</td>
<td>5–15% reduction in third-party damages</td>
</tr>
</tbody>
</table>
Level of Protection Analysis

LOPA
ANSI/ISA-84.00.01-2004, IEC 61511 Mod

http://www.plg.com/svc_opRisk_LOPA.html

SIL selection requirements of the American National Standards Institute (ANSI)/Instrumentation, Systems, and Automation Society (ISA) standard 84.00.01 – 2004
Damage Vs Failure

- Probability of damage (PoD) = \( f \) (exposure, mitigation)

- Probability of failure (PoF) = \( f \) (PoD, resistance)

\[
\begin{align*}
\text{Exposure} & \quad \text{PoD} \\
\text{Mitigation} & \quad \text{PoF} \\
\text{Resistance} & \quad \text{PoF}
\end{align*}
\]
Resistance

Figure 1. Photographs of the two fracture pipe segments and crater. Photograph on the upper page is looking north. Composite photograph at the lower portion of the page is looking west. The origin of the fracture was determined to be located in the area indicated by arrow “O”. General direction of fracture propagation is indicated by white unmarked arrows.
Estimating Resistance

- Pipe spec (original)
- Historical issues
  - Low toughness
  - Hard spots
  - Seam type
  - Manufacturing

- Pipe spec (current)
  - ILI measurements
  - Calcs from pressure test
  - Visual inspections
  - Effect of estimated degradations

- Required pipe strength
  - Normal internal pressure
  - Normal external loadings
Best Estimate of Pipe Wall Today

Measurement error  Degradation Since Meas  Today’s Estimate

Press Test
15 yrs ago
(inferred)  +/- 5%  8 mpy x 15 yrs = 120 mils

ILI
2 yrs ago
 +/- 15%  8 mpy x 2 yrs = 16 mils
Best Estimate of Pipe Wall Today

Press Test 1
ILI 1
Bell Hole 1
Press Test 2
Bell Hole 2
ILI 2
NOP
Pipe Wall Available

Pipe eff wall
0.240"

Pipe NOP
0.110"

Pipe thick
0.300 - 10% - (15 yrs x 2 mpy)

Pipe adj

Pipe meas
0.300" - 10% = 0.270"
0.300" - 100% crack = 0"

Pipe est wall
0.170"

15 yrs x 10 mpy

Metal loss
8 mpy

Cracking
2 mpy

Pipe nom = 0.320"
Loads & Stresses

- Stress capacity
- Load capacity
- Effective wall thickness
- Fraction of damage events that do not result in failure

Full solution: ...formal reliability assessment to study the relation of tensile strain resistance distribution to tensile strain demand distribution
Comprehensive

- Pipe specification;
- Last measured wall thickness;
- Age of last measured wall thickness;
- Wall thickness "measured" (implied) by last pressure test;
- Age of last pressure test;
- Detection capabilities of last inspection (ILI, etc), including data analyses and confirmatory digs;
- Maximum depth of a defect remaining after last inspection; age of last inspection
- Estimated metal loss mpy since last measurement;
- Estimated cracking mpy since last measurement;
- Maximum depth of a defect surviving at last pressure test and/or normal operating pressure (NOP) or last known pressure peak;
- Penalties for possible manufacturing/construction weaknesses
Why Exp-Mit-Res?

- Implicit, if not explicit, categorization because:
  - knowledge of all 3 is required for PoF

- Benefits of explicit categorization
  - without all 3, inability to diagnose
  - without diagnosis, inability to optimize P&M

- Eg, Corr in sand vs swamp
Upgrading Old RA’s

- **Exposure**  (events per year)
- **Mitigation**  (% of avoided events)
- **Resistance**  (% damage events that do not result in failure)

<table>
<thead>
<tr>
<th></th>
<th>Index/Score</th>
<th>New</th>
<th>Measurement/Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth cover</td>
<td>shallow = 8 pts</td>
<td>mitigation</td>
<td>15%</td>
</tr>
<tr>
<td>wrinkle bend</td>
<td>yes = 6 pts</td>
<td>resistance</td>
<td>-0.07&quot; pipe wall</td>
</tr>
<tr>
<td>coating condition</td>
<td>fair = 3 pts</td>
<td>mitigation</td>
<td>0.01 gaps/ft2</td>
</tr>
<tr>
<td>soil</td>
<td>moderate = 4 pts</td>
<td>exposure</td>
<td>4 mpy</td>
</tr>
</tbody>
</table>
Fully Characterize Consequence of Failure

- Must identify and acknowledge the full range of possible consequence scenario hazard zones
- Must consider ‘most probable’ and ‘worst case’ scenarios

Diagram:
- HCA
- Hazard Zone
- Spill path
- PL
Common Consequences of Interest

- Human health
- Environment
- Costs

Choose receptors and CoF units
A Guiding Equation

\[ \text{CoF} = \text{ProdHaz} \times \text{Spill} \times \text{Spread} \times \text{Receptors} \]
Liquid Releases
Particle Trace Analysis
Why are DEM and structures so important??
Thermal Radiation—Pool Fire
### Hazard Zone Scenarios

**Figure 5-4 Example of a Post-Incident Event Tree**

<table>
<thead>
<tr>
<th>Initial Release ($F_L$)</th>
<th>Immediate Ignition</th>
<th>Delayed Ignition</th>
<th>VCE</th>
<th>Final Event</th>
<th>Probability of Final Event</th>
<th>Frequency of Final Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>0.4</td>
<td></td>
<td></td>
<td>Fireball</td>
<td>0.4</td>
<td>0.4 $F_L$</td>
</tr>
<tr>
<td>No</td>
<td>0.6</td>
<td></td>
<td></td>
<td>VCE</td>
<td>0.0144</td>
<td>0.0144 $F_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12*</td>
<td></td>
<td>Flash Fire</td>
<td>0.0576</td>
<td>0.0576 $F_L$</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td>Unignited Release</td>
<td>0.528</td>
<td>0.528 $F_L$</td>
</tr>
</tbody>
</table>

* Example for Suburban Population Density
GRI PIR Documentation

Figure 1.1 Event tree for high pressure gas pipeline failure (adapted from Bilo and Kinsman 1997).

* ignoring hazard potential of overpressure and flying debris
Hazard Zone Criteria
### Table A2.2  Effects of Thermal Radiation (CCPS, 1989a)

<table>
<thead>
<tr>
<th>Radiation intensity ($kW/m^2$)</th>
<th>Observed effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5</td>
<td>Sufficient to cause damage to process equipment</td>
</tr>
<tr>
<td>12.5</td>
<td>Minimum energy required for piloted ignition of wood, melting of plastic tubing</td>
</tr>
<tr>
<td>9.5</td>
<td>Pain threshold reached after 8 s; second degree burns after 20 s</td>
</tr>
<tr>
<td>4</td>
<td>Sufficient to cause pain to personnel if unable to reach cover within 20 s; however, blistering of the skin (second degree burns) is likely; 0% lethality</td>
</tr>
<tr>
<td>1.6</td>
<td>Will cause no discomfort for long exposure</td>
</tr>
</tbody>
</table>

### Table A2.3  Exposure Time Necessary to Reach the Pain Threshold (API 521)

<table>
<thead>
<tr>
<th>Radiation intensity ($Btu/hr/ft^2$)</th>
<th>$kW/m^2$</th>
<th>Time to pain threshold (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.74</td>
<td>60</td>
</tr>
<tr>
<td>740</td>
<td>2.33</td>
<td>40</td>
</tr>
<tr>
<td>920</td>
<td>2.90</td>
<td>30</td>
</tr>
<tr>
<td>1500</td>
<td>4.73</td>
<td>16</td>
</tr>
<tr>
<td>2200</td>
<td>6.94</td>
<td>9</td>
</tr>
<tr>
<td>3000</td>
<td>9.46</td>
<td>6</td>
</tr>
<tr>
<td>3700</td>
<td>11.67</td>
<td>4</td>
</tr>
<tr>
<td>6300</td>
<td>19.87</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 2.1 Conceptual fire hazard model.
PIR Calculations

Table 7.1  Summary of Potential Impact Radius Formulae

<table>
<thead>
<tr>
<th>Product</th>
<th>PIR Formula</th>
<th>PIR Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene</td>
<td>1 psi Overpressure</td>
<td>( r = 0.021 \cdot (d^2 \cdot p)^{1/3} )</td>
</tr>
<tr>
<td>Anhydrous Ammonia (Liquefied under pressure)</td>
<td>1 psi Overpressure</td>
<td>( r = 0.014 \cdot (d^2 \cdot p)^{1/3} )</td>
</tr>
<tr>
<td></td>
<td>Rural Conditions</td>
<td>( r = 0.08 \cdot (d^2 \cdot p)^{0.48} )</td>
</tr>
<tr>
<td></td>
<td>Urban Conditions</td>
<td>( r = 0.07 \cdot (d^2 \cdot p)^{0.45} )</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>1 psi Overpressure</td>
<td>( r = 0.012 \cdot (d^2 \cdot p)^{1/3} )</td>
</tr>
<tr>
<td></td>
<td>Rural Conditions</td>
<td>( r = 0.04 \cdot (d^2 \cdot p)^{0.5} )</td>
</tr>
<tr>
<td></td>
<td>Urban Conditions</td>
<td>( r = 0.03 \cdot (d^2 \cdot p)^{0.45} )</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Rural Conditions</td>
<td>( r = 0.38 \cdot (d^2 \cdot p)^{0.49} )</td>
</tr>
<tr>
<td></td>
<td>Urban Conditions</td>
<td>( r = 0.16 \cdot (d^2 \cdot p)^{0.5} )</td>
</tr>
<tr>
<td>Ethylene</td>
<td>1 psi Overpressure</td>
<td>( r = 0.021 \cdot (d^2 \cdot p)^{1/3} )</td>
</tr>
<tr>
<td>Hydrogen Sulfide</td>
<td>1 psi Overpressure</td>
<td>( r = 0.015 \cdot (d^2 \cdot p)^{1/3} )</td>
</tr>
<tr>
<td></td>
<td>Rural Conditions</td>
<td>( r = 0.37 \cdot (d^2 \cdot p)^{0.45} )</td>
</tr>
<tr>
<td></td>
<td>Urban Conditions</td>
<td>( r = 0.27 \cdot (d^2 \cdot p)^{0.46} )</td>
</tr>
<tr>
<td>Methane</td>
<td>1 psi Overpressure</td>
<td>( r = 0.019 \cdot (d^2 \cdot p)^{1/3} )</td>
</tr>
<tr>
<td>Rich Gas</td>
<td>1 psi Overpressure</td>
<td>( r = 0.020 \cdot (d^2 \cdot p)^{1/3} )</td>
</tr>
</tbody>
</table>

Note 1: See discussion in Section 4.8.5
Grouping of Distance Estimates

Threshold distances

Hazard Zone
\( \text{CoF} = f \{ \text{Hazard Zones} \} \)
## Hazard Zone Exercise

<table>
<thead>
<tr>
<th>prod</th>
<th>hole size</th>
<th>prob</th>
<th>ignition scenario</th>
<th>prob</th>
<th>dist</th>
<th>therm haz zone</th>
<th>overpress haz</th>
<th>contam haz zone</th>
<th>haz zone</th>
<th>prob of haz zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel oil</td>
<td>rupt</td>
<td>2%</td>
<td>immediate ignition</td>
<td></td>
<td></td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>med</td>
<td>8%</td>
<td>immediate ignition</td>
<td></td>
<td></td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>small</td>
<td>90%</td>
<td>immediate ignition</td>
<td></td>
<td></td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td></td>
</tr>
</tbody>
</table>

- **Fuel Oil**
  - **Rupture**
    - 2% probability
    - Immediate ignition
    - Delayed ignition
    - No ignition
  - **Medium**
    - 8% probability
    - Immediate ignition
    - Delayed ignition
    - No ignition
  - **Small**
    - 90% probability
    - Immediate ignition
    - Delayed ignition
    - No ignition
## Hazard Zones

<table>
<thead>
<tr>
<th>Product</th>
<th>Hole size probability</th>
<th>Ignition scenario</th>
<th>Ignition probability</th>
<th>Distance from source (ft)</th>
<th>thermal hazard zone (ft)</th>
<th>Contamination hazard zone (ft)</th>
<th>Total (ft)</th>
<th>Probability of hazard zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>oil</td>
<td>4%</td>
<td>immediate ignition</td>
<td>5%</td>
<td>0</td>
<td>400</td>
<td>0</td>
<td>400</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>10%</td>
<td>0</td>
<td>500</td>
<td>400</td>
<td>1100</td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no ignition</td>
<td>85%</td>
<td>0</td>
<td>0</td>
<td>900</td>
<td>1500</td>
<td>3.4%</td>
</tr>
<tr>
<td>oil</td>
<td>16%</td>
<td>immediate ignition</td>
<td>2%</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>200</td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>5%</td>
<td>0</td>
<td>300</td>
<td>200</td>
<td>500</td>
<td>0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no ignition</td>
<td>93%</td>
<td>200</td>
<td>0</td>
<td>500</td>
<td>700</td>
<td>14.9%</td>
</tr>
<tr>
<td>oil</td>
<td>80%</td>
<td>immediate ignition</td>
<td>1%</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>50</td>
<td>0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>2%</td>
<td>80</td>
<td>100</td>
<td>0</td>
<td>180</td>
<td>1.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no ignition</td>
<td>97%</td>
<td>80</td>
<td>0</td>
<td>80</td>
<td>160</td>
<td>77.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.0%</td>
</tr>
<tr>
<td>LPG</td>
<td>16%</td>
<td>immediate ignition</td>
<td>20%</td>
<td>0</td>
<td>400</td>
<td>0</td>
<td>400</td>
<td>3.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>20%</td>
<td>0</td>
<td>2000</td>
<td>0</td>
<td>2500</td>
<td>3.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no ignition</td>
<td>60%</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>9.6%</td>
</tr>
<tr>
<td>LPG</td>
<td>24%</td>
<td>immediate ignition</td>
<td>15%</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>200</td>
<td>3.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>15%</td>
<td>200</td>
<td>1200</td>
<td>0</td>
<td>1400</td>
<td>3.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no ignition</td>
<td>70%</td>
<td>200</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>16.8%</td>
</tr>
<tr>
<td>LPG</td>
<td>60%</td>
<td>immediate ignition</td>
<td>10%</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>50</td>
<td>6.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>10%</td>
<td>30</td>
<td>100</td>
<td>0</td>
<td>130</td>
<td>6.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no ignition</td>
<td>80%</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>48.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.0%</td>
</tr>
</tbody>
</table>
Receptor Characterization

- fatalities
- injuries
- prop damage
- waterways
- ground water
- wetlands
- T&E wildlife
- preserves
- historical sites
Population Characterization

- Building density
- Building characterization
- Occupancy rate
- Mobility

\[ O_f = D \times R \]

Where,
- \( O_f \) = The occupancy factor, which is an indication of the number of people within a hazard zone;
- \( D \) = building density of land use areas within the hazard zone (includes buildings or other areas that define a class location or HCA); and,
- \( R \) = The expected average occupancy rate per building within the land use area
Damage State Estimates

• Create Zones Based on Threshold Distances
• Estimate Damage States (or PoD) for Each Zone

<table>
<thead>
<tr>
<th>Hazard Zone</th>
<th>injury rate</th>
<th>fatality rate</th>
<th>environ damage rate</th>
<th>service interruption rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;100'</td>
<td>80%</td>
<td>8%</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>100'-50% PIR</td>
<td>50%</td>
<td>5%</td>
<td>30%</td>
<td>90%</td>
</tr>
<tr>
<td>50% -100% PIR</td>
<td>20%</td>
<td>2%</td>
<td>10%</td>
<td>80%</td>
</tr>
</tbody>
</table>
CoF at Facilities

- Hazard Zone Assessment

\[
\text{Potential Loss} = \text{Hazard Area} \times \Sigma (\text{receptor unit value} \times \text{receptor density} \times \text{receptor damage rate})
\]

* Probability-adjusted area
## Sample CoF Calculations

<table>
<thead>
<tr>
<th>Hole Size</th>
<th>Ignition Scenario</th>
<th>Maximum Distance (ft)</th>
<th>Probability of Maximum Distance</th>
<th>Hazard Zone Group</th>
<th># people</th>
<th>Human Injury Costs</th>
<th>Human Fatality Costs</th>
<th># Environ units</th>
<th>Environ Damage Costs</th>
<th>Probability weighted dollars per failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>rupture</td>
<td>immediate</td>
<td>400</td>
<td>4.8%</td>
<td>100'-50% PIR</td>
<td>5</td>
<td>$3,600</td>
<td>$12,600</td>
<td>1</td>
<td>$720</td>
<td>$16,920</td>
</tr>
<tr>
<td></td>
<td>delayed</td>
<td>1500</td>
<td>1.6%</td>
<td>50% -100% PIR</td>
<td>10</td>
<td>$960</td>
<td>$3,360</td>
<td>1</td>
<td>$80</td>
<td>$4,400</td>
</tr>
<tr>
<td></td>
<td>no ignition</td>
<td>300</td>
<td>1.6%</td>
<td>100'-50% PIR</td>
<td>5</td>
<td>$1,200</td>
<td>$4,200</td>
<td>1</td>
<td>$240</td>
<td>$5,640</td>
</tr>
<tr>
<td>medium</td>
<td>immediate</td>
<td>300</td>
<td>1.8%</td>
<td>100'-50% PIR</td>
<td>5</td>
<td>$1,350</td>
<td>$4,725</td>
<td>1</td>
<td>$270</td>
<td>$6,345</td>
</tr>
<tr>
<td></td>
<td>delayed</td>
<td>600</td>
<td>1.8%</td>
<td>100'-50% PIR</td>
<td>5</td>
<td>$1,350</td>
<td>$4,725</td>
<td>1</td>
<td>$270</td>
<td>$6,345</td>
</tr>
<tr>
<td></td>
<td>no ignition</td>
<td>100</td>
<td>8.4%</td>
<td>100'-50% PIR</td>
<td>5</td>
<td>$6,300</td>
<td>$22,050</td>
<td>1</td>
<td>$1,260</td>
<td>$29,610</td>
</tr>
<tr>
<td>small</td>
<td>immediate</td>
<td>50</td>
<td>8.0%</td>
<td>&lt;100'</td>
<td>1</td>
<td>$1,920</td>
<td>$6,720</td>
<td>0.5</td>
<td>$1,000</td>
<td>$9,640</td>
</tr>
<tr>
<td></td>
<td>delayed</td>
<td>80</td>
<td>8.0%</td>
<td>&lt;100'</td>
<td>1</td>
<td>$1,920</td>
<td>$6,720</td>
<td>0.5</td>
<td>$1,000</td>
<td>$9,640</td>
</tr>
<tr>
<td></td>
<td>no ignition</td>
<td>30</td>
<td>64.0%</td>
<td>&lt;100'</td>
<td>1</td>
<td>$15,360</td>
<td>$53,760</td>
<td>0.5</td>
<td>$8,000</td>
<td>$77,120</td>
</tr>
</tbody>
</table>

100.0% Total expected loss per failure at this location $165,660
## Final EL Value

At a specific location along a pipeline:

<table>
<thead>
<tr>
<th>Failure Rate (failures per mile-year)</th>
<th>Probability of Hazard Zone$^{1,2}$</th>
<th>Probability weighted dollars$^{2,3}$</th>
<th>Probability weighted dollars per mile-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>4.80%</td>
<td>$16,920</td>
<td>$0.81</td>
</tr>
<tr>
<td></td>
<td>1.60%</td>
<td>$4,400</td>
<td>$0.07</td>
</tr>
<tr>
<td></td>
<td>1.60%</td>
<td>$5,640</td>
<td>$0.09</td>
</tr>
<tr>
<td></td>
<td>1.80%</td>
<td>$6,345</td>
<td>$0.11</td>
</tr>
<tr>
<td></td>
<td>1.80%</td>
<td>$6,345</td>
<td>$0.11</td>
</tr>
<tr>
<td></td>
<td>8.40%</td>
<td>$29,610</td>
<td>$2.49</td>
</tr>
<tr>
<td></td>
<td>8.00%</td>
<td>$9,640</td>
<td>$0.77</td>
</tr>
<tr>
<td></td>
<td>8.00%</td>
<td>$9,640</td>
<td>$0.77</td>
</tr>
<tr>
<td></td>
<td>64.00%</td>
<td>$77,120</td>
<td>$49.36</td>
</tr>
<tr>
<td>100.00%</td>
<td>$165,660</td>
<td></td>
<td>$54.59</td>
</tr>
</tbody>
</table>

### Table Notes
1. after a failure has occurred
2. from Table 2 above, per event
3. (damage rate) x (value of receptors in hazard zone), per event
Step 1: Determine On-Line Sampling Interval

...identify model and pipeline specifications (e.g., product)

determine the interval spacing or read point locations from a stored file of X,Y points
Step 2: Establish Hazard Zones

...determine the # of zones and reach defining each zone
Step 3: Determine Number of Houses in Each Zone (Point Features)

...count the number of houses within each zone
Step 4: **Determine Length of Waterways in Each Zone**

(Line Features)

...calculate the length of waterway within each zone
Step 5: **Determine Area of HCAs in Each Zone**

(Polygon Features)

...calculate the area of each HCA within each zone
Summarize Impacted Receptors (Data Table)

...convert the counts, lengths, and areas of impacted features into estimated impacts within each hazard zone.
## Expected Loss Calcs

*(Probability * Impacted Feature Valuation)*

Each row represents one pipeline release location.

Expected Loss is a function of each Zone’s Probability of occurring and the Zone’s Potential Loss:

\[
\text{Expected Loss} = (Z1_{\text{Prob}} \times Z1_{\text{PLoss}}) + (Z2_{\text{Prob}} \times Z2_{\text{PLoss}}) + (Z3_{\text{Prob}} \times Z3_{\text{PLoss}})
\]

For row 20:

\[
\text{EL}_{20} = (0.88 \times 101660) + (0.07 \times 15812) + (0.07 \times 28609) = 146,081 \quad \text{considerable risk exposure at this location}
\]
Consequence Estimation Overview

**Sequence of Analysis**

1. Chance of failure (threat models)
2. Chance of failure hole size
3. Spill size (considering leak detection and reaction scenarios)
   - *Volume Out*
4. Chance of ignition
   - Immediate
   - Delayed
   - None
5. Spill dispersion
   - Pipeline/product characteristics
   - Topography (if liquid release)
   - Meteorology (if gaseous release)
6. Hazard area size and probability (for each scenario)
7. Chance of receptor(s) being in hazard area (counts, density, or area)
8. Chance of various damage states to various receptor (including consequence mitigation)
9. Calculate Expected Loss (Prob x Consequence $)

### Table: Ignition Scenario Probabilities

<table>
<thead>
<tr>
<th>Product</th>
<th>Hole size</th>
<th>Hole size probability</th>
<th>Ignition scenario</th>
<th>Ignition probability</th>
<th>Distance from source (ft)</th>
<th>thermal hazard zone (ft)</th>
<th>Contamination hazard zone (ft)</th>
<th>Total (ft)</th>
<th>probability of hazard zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>oil</td>
<td>rupture</td>
<td>4%</td>
<td>immediate ignition</td>
<td>5%</td>
<td>0</td>
<td>400</td>
<td>0</td>
<td>400</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>10%</td>
<td>600</td>
<td>500</td>
<td>400</td>
<td>1100</td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>no ignition</td>
<td>85%</td>
<td>600</td>
<td>0</td>
<td>900</td>
<td>1500</td>
<td>3.4%</td>
</tr>
<tr>
<td>medium</td>
<td></td>
<td>16%</td>
<td>immediate ignition</td>
<td>2%</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>200</td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>5%</td>
<td>200</td>
<td>300</td>
<td>200</td>
<td>500</td>
<td>0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>no ignition</td>
<td>93%</td>
<td>200</td>
<td>0</td>
<td>500</td>
<td>700</td>
<td>14.9%</td>
</tr>
<tr>
<td>small</td>
<td></td>
<td>80%</td>
<td>immediate ignition</td>
<td>1%</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>50</td>
<td>0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>delayed ignition</td>
<td>2%</td>
<td>80</td>
<td>100</td>
<td>0</td>
<td>180</td>
<td>1.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>no ignition</td>
<td>97%</td>
<td>80</td>
<td>0</td>
<td>80</td>
<td>160</td>
<td>77.6%</td>
</tr>
</tbody>
</table>
Other Consequences

- Service Interruption
- Production/transportation loss
- Repair costs
- Resumption of service
- Contract penalties
- Legal costs
- Increased regulatory oversight
- Corp reputation
Risk Of Service Interruption

Service interruption risk

\[ = (\text{Upset potential}) \times (\text{impact factor}) \]

Where:

\[ \text{Upset potential} = (\text{PSD} + \text{DPD}) \]
Service Interruptions

- **Product spec deviation (PSD)**
  - Product origin
  - Equipment
  - Dynamics
  - Other

- **Delivery parameter deviation (DPD)**
  - Pipeline failures
  - Blockages
  - Equipment
  - Operator error

- Intervention adjustment

- Upset potential
Integrate Pipeline Knowledge

- The assessment must include complete, appropriate, and transparent use of all available information
- ‘Appropriate’ when model uses info as would an SME
How much is enough?

- The risk assessment should use all the information in substantially the same way that an SME uses information to improve the understanding of risk.
External Corrosion Model

EC POF (prob/mile-yr)

EC TTF (Years –assuming a per mile basis)

Available Pipe Wall (in) & Estimate x Adjustment

Estimate (in)

Max based on:
1. NOP
2. Hydrotest
3. NDE/ILI
2&3 adjusted for mpy growth since measurement

Adjustments (%)

Cumulative:
1. Joint Type
2. Reinforcements
3. Manuf & Const
4. Pipe Type
5. Toughness
6. Flaws
7. External Loads
8. Spans

Environment (mpy) & Sum

1. Above/Below Ground
2. Atmospheric CGR (mpy)
3. Electrical Isolation (%)
4. Soil based CGR (mpy)
5. Mitigated AC Induced CGR (mpy)

Mitigation (%) based on Active Corrosion Locations

Growth Rate (mpy)

Total mpy x (1-Mitigation)

Measured (mpy)

Direct measurements adjusted by confidence

External Coating Holiday Rate

Estimated (defects/mi)
1. Defects/mi adjusted by confidence

Measured (defects/mi)
1. Defects/mi adjusted by confidence and age

CP Gaps (Prob of gaps/ft)

Sum of gaps/mi converted to probability

CP Effectiveness

CP Interference

Locations/mi:
1. DC Sources (mitigated)
2. Coating Shielding
3. Casing Shielding

Measured Gaps /mi
1. CP Readings adjusted by confidence
2. CP Readings adjusted by confidence and age

Estimated Gaps/mi
1. Distance from test station
2. PL Age
3. Criteria
4. Rectifier out of service history
Risk assessment must divide the pipeline into segments where risks are unchanging.

Compromises involving the use of averages or extremes can significantly weaken the analysis and are to be avoided.
Dynamic Segmentation

Due to the numerous and constantly-varying factors effecting the risk to the pipeline, proper analysis will require at least 10-100 segments per mile*

- **1995**: Steel Pipe wall 0.320”
- **1961**: Pipe wall 0.500”
- **Landslide Threat**
- **Population Class 3**

*thousands of segments per mile is not unusual today*
Facility Risks

<table>
<thead>
<tr>
<th>Facility</th>
<th>Expected Loss ($/yr)</th>
<th>Total PoF</th>
<th>Max CoF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck Loading</td>
<td>$814</td>
<td>1.13E-02</td>
<td>$72,000</td>
</tr>
<tr>
<td>Pig Launchers</td>
<td>$41</td>
<td>4.20E-04</td>
<td>$98,000</td>
</tr>
<tr>
<td>Pump</td>
<td>$5,708</td>
<td>1.07E-01</td>
<td>$98,000</td>
</tr>
<tr>
<td>Tankage</td>
<td>$4,831</td>
<td>9.46E-02</td>
<td>$68,000</td>
</tr>
</tbody>
</table>

Total Facility

<table>
<thead>
<tr>
<th>Expected Loss ($/yr)</th>
<th>$5,708</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total PoF</td>
<td>1.07E-01</td>
</tr>
<tr>
<td>Max CoF</td>
<td>$98,000</td>
</tr>
</tbody>
</table>
Control the Bias

- Risk assessment must state the level of conservatism employed in all of its components.
- Assessment must be free of inappropriate bias that tends to force incorrect conclusions.
“ABSOLUTE CERTAINTY IS THE PRIVILEGE OF FOOLS AND FANATICS.”
Dealing With Uncertainty

Error 1: call it ‘good’ when its really ‘bad’

Error 2: call it ‘bad’ when its really ‘good’
Understanding Conservatism and Uncertainty

A way to measure and communicate conservatism in risk estimates

- PXX
  - P50
  - P90
  - P99.9

Useful in conveying intended level of conservatism
The Role of Historical Incidents

Problems:

- Historical data usefulness in current situation
- Small amount of data in rare-event situations
- Representative population
- Behavior of the individual vs population

Control the Bias
Profile the Risk Reality

- The risk assessment must be performed at all points along the pipeline

- Must produce a continuous profile of changing risks along the entire pipeline

- Profile must reflect the changing characteristics of the pipe and its surroundings
Profile to Characterize Risk

**Scenario 1**
100 km oil pipeline
widespread coating failure
river parallel
remote

**Scenario 2**
50 km gas pipeline
2 shallow cover locations
high population density
high pressure, large diameter
Risk Characterization

**Scenario 1**
100 km oil pipeline
widespread coating failure
river parallel
remote location

**Scenario 2**
50 km gas pipeline
2 shallow cover locations
high population density
high pressure, large diameter

Very different risk profiles
Risk Characterization

**Scenario 1**
100 km oil pipeline
widespread coating failure
river parallel
remote location

**Scenario 2**
50 km gas pipeline
2 shallow cover locations
high population density
high pressure, large diameter

What is best action to take?
ProperAggregation

- Proper process for aggregation of the risks from multiple pipeline segments must be included.
- Summarization of the risks from multiple segments must avoid simple statistics or weighted statistics that mask the actual risks.
Aggregating Risks for Collection of Pipe Segments

Simple sum only works when values are very low.

\[
\text{PoF total} = \text{PoF1} + \text{PoF2} + \text{PoF3} + \text{PoF4} + \ldots + \text{PoFn}
\]

PoF total = 137% . . . ?
Aggregating Risks

PoF total = Avg(PoF1, PoF2, ...PoFn)

Avg PoF = Avg PoF
But

PoF
KM
PoF
KM
≠
Aggregating Risks

PoF total = Max(PoF1, PoF2, …PoFn)

Max PoF = Max PoF
But

PoF

KM

PoF

KM
Aggregating Risks

PoF total = Max(PoF1, PoF2, …PoFn)

Max PoF = Max PoF
 But

PoF total ≠ PoF KM

Unmask Aggregation
Aggregating Failure Probabilities

Overall pf is prob failure by [(thd pty) OR (corr) OR (geohaz)…]

Ps = 1 - pf

Overall ps is prob surviving [(thd pty) AND (corr) AND (geohaz)….]

So…

\[ Pf_{overall} = 1 - [(1-pf_{thdpty}) \times (1-pf_{corr}) \times (1-pf_{geohaz}) \times (1-pf_{incops})] \]
The Essential Elements

- Measurements in Verifiable Units
- Proper Probability of Failure Assessment
- Characterization of Potential Consequences
- Full Integration of Pipeline Knowledge
- Sufficient Granularity
- Bias Management
- Profiles of Risk
- Proper Aggregation
Managing Risks

Situations in life often permit no delay; and when we cannot determine the action that is certainly the best, we must follow the action that is probably the best.

If the action selected is indeed not good, at least the reasons for selecting it are excellent.
Participating in Important Discussions

How safe is ‘safe enough’?
Canadian Risk-Based Land Uses

CSChE Risk Assessment – Recommended Practices, MIACC risk acceptability
Acceptable Risk

- **UNACCEPTABLE REGION**
  - Risk cannot be justified save in extraordinary circumstances

- **ALARP REGION**
  - Risk is undertaken only if a benefit is desired
  - Tolerable only if risk reduction is impracticable or if its cost is grossly disproportionate to the improvement gained

- **BROADLY ACCEPTABLE REGION**
  - No need for detailed working to demonstrate ALARP
  - Tolerable if cost of reduction would exceed the improvement

- **Negligible risk**
  - Necessary to maintain assurance that risk remains at this level
Reliability Targets

Target reliability (per km-yr)

Class 3 Target
Class 2 Target
Individual Risk
Class 1 Target

$PD^3$ (psi-in$^3$)

1 - 1E-07
1 - 1E-06
1 - 1E-05
1 - 1E-04
1 - 1E-03
1 - 1E-02
1.E+06 1.E+07 1.E+08
Modern PL RA is Specialized QRA-PRA

![Graph showing probability of failure (PoF) adjusted and unitized with corresponding frequency and bin]

<table>
<thead>
<tr>
<th>System</th>
<th>Product</th>
<th>Length</th>
<th>Risk</th>
<th>Risk</th>
<th>PoF</th>
<th>CoF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>miles</td>
<td>Total Annual Exposure</td>
<td>Expected Loss $/m-yr</td>
<td>Incident Rate, failures per m-yr</td>
<td>Loss Exposure, Probability-weighted $/failure</td>
</tr>
<tr>
<td>Elvira</td>
<td>gasoline</td>
<td>120</td>
<td>$142,080</td>
<td>$1,184</td>
<td>0.001</td>
<td>$1,184,000</td>
</tr>
<tr>
<td>Scaramonga</td>
<td>crude oil</td>
<td>408</td>
<td>$342,720</td>
<td>$840</td>
<td>0.0015</td>
<td>$560,000</td>
</tr>
<tr>
<td>Perseus</td>
<td>natural gas</td>
<td>23</td>
<td>$33,810</td>
<td>$1,470</td>
<td>0.007</td>
<td>$210,000</td>
</tr>
</tbody>
</table>
Application of EE’s—benefits realized

- Efficient and transparent risk modeling
- Accurate, verifiable, and complete results
- Improved understanding of actual risk
- Risk-based input to guide integrity decision-making: *true risk management*

**Optimized resource allocation leading to higher levels of public safety**

- Appropriate level of standardization facilitating smoother regulatory audits
  - Does not stifle creativity
  - Does not dictate all aspects of the process
  - Avoids need for (high-overhead) prescriptive documentation
- Expectations of regulators, the public, and operators fulfilled
If you don’t have a number, you don’t have a fact, you have an opinion.
Key Takeaways

- Significant confusion and errors in terminology and current guidance documents
- Threat interaction requires no special treatment in a modern, complete RA
- Multiple models are not necessary
- Mandating a methodology is not needed—a short list of essential elements ensures acceptability
- RA model certification has begun
Hawthorne Effect

“Anything that is studied, improves.”

Anticipate enormously more useful information
Appendix
Protocols

- **C.03.c.** Verify that the risk assessment explicitly accounts for factors that could affect the likelihood of a release and for factors that could affect the consequences of potential releases, and that these factors are combined in an appropriate manner to produce a risk value for each pipeline segment.

- The risk assessment approach contains a defined logic and is structured to provide a complete, accurate, and objective analysis of risk [ASME B31.8S-2004, Section 5.7(a)];
  - ii. The risk assessment considers the frequency and consequences of past events, using company and industry data [ASME B31.8S-2004, Section 5.7(c)];
  - iii. The risk assessment approach integrates the results of pipeline inspections in the development of risk estimates [ASME B31.8S-2004, Section 5.7(d)];
  - iv. The risk assessment process includes a structured set of weighting factors to indicate the relative level of influence of each risk assessment component [ASME B31.8S-2004, Section 5.7(i)];
  - v. The risk assessment process incorporates sufficient resolution of pipeline segment size to analyze data as it exists along the pipeline [ASME B31.8S-2004, Section 5.7(k)].
Surface Facilities Assessment
CoF at Facilities

Hazard Zone Assessment

Potential Loss

\[ \text{Potential Loss} = \text{Hazard Area} \times \sum (\text{receptor unit value} \times \text{receptor density} \times \text{receptor damage rate}) \]

* Probability-adjusted area
Application to Facilities

- Dynamic Segmentation is applied to find equipment items with similar characteristics.

- Using the same assessment methodology for pipelines and facilities ensures apples-to-apples comparisons.
# Application to Facilities

## Equipment Specific Risk

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Expected Loss ($/yr)</th>
<th>PoF</th>
<th>CoF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading Rack</td>
<td>$813.60</td>
<td>1.13E-02</td>
<td>$72,000</td>
</tr>
<tr>
<td>Pig Launcher 1</td>
<td>$11.76</td>
<td>0.00012</td>
<td>$98,000</td>
</tr>
<tr>
<td>Pig Launcher 2</td>
<td>$23.52</td>
<td>0.00024</td>
<td>$98,000</td>
</tr>
<tr>
<td>Pig Launcher 3</td>
<td>$5.88</td>
<td>0.00006</td>
<td>$98,000</td>
</tr>
<tr>
<td>Pump 102</td>
<td>18</td>
<td>0.0015</td>
<td>$12,000</td>
</tr>
<tr>
<td>Pump 103</td>
<td>2.59</td>
<td>0.0007</td>
<td>$3,700</td>
</tr>
<tr>
<td>Pump 201</td>
<td>1.92</td>
<td>0.00006</td>
<td>$32,000</td>
</tr>
<tr>
<td>Tank 10</td>
<td>$630</td>
<td>0.015</td>
<td>$42,000</td>
</tr>
<tr>
<td>Tank 11</td>
<td>$26</td>
<td>0.0007</td>
<td>$37,500</td>
</tr>
<tr>
<td>Tank 12</td>
<td>$105</td>
<td>0.002</td>
<td>$52,300</td>
</tr>
<tr>
<td>Tank 13</td>
<td>$206</td>
<td>0.005</td>
<td>$41,250</td>
</tr>
<tr>
<td>Tank 14</td>
<td>$28</td>
<td>0.0005</td>
<td>$55,000</td>
</tr>
<tr>
<td>Tank 15</td>
<td>$78</td>
<td>0.0012</td>
<td>$65,000</td>
</tr>
<tr>
<td>Tank 16</td>
<td>$620</td>
<td>0.02</td>
<td>$31,000</td>
</tr>
<tr>
<td>Tank 17</td>
<td>$53</td>
<td>0.002</td>
<td>$26,500</td>
</tr>
<tr>
<td>Tank 18</td>
<td>$10</td>
<td>0.0006</td>
<td>$15,900</td>
</tr>
<tr>
<td>Tank 19</td>
<td>$168</td>
<td>0.0056</td>
<td>$30,000</td>
</tr>
<tr>
<td>Tank 20</td>
<td>$392</td>
<td>0.0087</td>
<td>$45,000</td>
</tr>
<tr>
<td>Tank 21</td>
<td>$2,516</td>
<td>0.037</td>
<td>$68,000</td>
</tr>
</tbody>
</table>
Application to Facilities

- **Total Risk from a facility**

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Expected Loss ($/yr)</th>
<th>Total PoF</th>
<th>Max CoF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig Launchers Truck Loading</td>
<td>$5,708</td>
<td>1.07E-01</td>
<td>$98,000</td>
</tr>
<tr>
<td>Pumps</td>
<td>$41</td>
<td>4.20E-04</td>
<td>$98,000</td>
</tr>
<tr>
<td>Tankage</td>
<td>$4,831</td>
<td>9.46E-02</td>
<td>$68,000</td>
</tr>
</tbody>
</table>

**Total Facility**

- **Expected Loss ($/yr)**: $5,708
- **Total PoF**: 1.07E-01
- **Max CoF**: $98,000
Application to Facilities

- Utilizes the same models developed for pipelines
- Each equipment item is assessed for threats that may lead to a loss of containment

Example

1) **What components can lead to a loss of containment?**

2) **What threats apply to those components?**
Absolute Facility Risk

<table>
<thead>
<tr>
<th>Component</th>
<th>Expected Loss ($/yr)</th>
<th>Total PoF</th>
<th>Max CoF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig Launchers Truck Loading</td>
<td>$814</td>
<td>1.13E-02</td>
<td>$72,000</td>
</tr>
<tr>
<td>Pumps</td>
<td>$41</td>
<td>4.20E-04</td>
<td>$98,000</td>
</tr>
<tr>
<td>Tankage</td>
<td>$4,831</td>
<td>9.46E-02</td>
<td>$68,000</td>
</tr>
<tr>
<td>Total Facility</td>
<td>$5,708</td>
<td>1.07E-01</td>
<td>$98,000</td>
</tr>
</tbody>
</table>

Same models used in PLs
“...when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be.”

Lord Kelvin
Sample Audit Questions

- What is maximum and average segment length?
  - If less than 20 segs per mile, then only appropriate if very low variations along route, including hydraulic profile

- How do you discriminate between low-exp and low-mit vs high-exp and high-mit?

- Show how non-HCA data is being used.

- Obtain counts and ranges (min, max, average):
  - Inputs
  - Defaults & assignments
  - Threats
  - Equations


- Show how risk assessment is driving risk management (P&M).

- Show where remaining life (TTF) is used to set integrity re-assessment intervals.
Practice PoD, PoF

What is PoD and PoF when . . .

- Exposure = 10 events/mile-year
- Mitigation = 99%
- Resistance = 90%

PoD = Exposure x (1 - mitigation)
   = 10 x (1 - 0.99)
   = 0.1 damages/mile-year = damage incident every 10 yrs

PoF = PoD x (1 - resistance)
   = 0.1 x (1 - 0.9)
   = 0.01 failures/mile-year = failure every 100 years
Practice PoD, PoF

What is PoD and PoF when . . .

- Exposure = 1 events/mile-year
  - Mitigation = 50%
  - Resistance = 50%

- Exposure = 2 events/mile-year
  - Mitigation = 90%
  - Resistance = 80%

- Exposure = 10 events/mile-year
  - Mitigation = 99.9%
  - Resistance = 90%

- Exposure = 0.01 events/mile-year
  - Mitigation = 99.99%
  - Resistance = 95%
What is TTF and PoF when . . .

- Exposure = 10 mpy
- Mitigation = 50%
- Resistance = 0.100”

Damage rate = Exposure x (1 - mitigation)
= 10 x (1 - 0.5)
= 5 mpy

TTF = Resistance / Damage rate
= 100 mils / 5 mpy = 20 years

PoF = 1 / TTF
= 1 / 20 years = 0.05 / year = 5% prob failure in year one
Practice TTF, PoF

What is TTF and PoF when . . .

- Exposure = 5 mpy
- Mitigation = 80%
- Resistance = 0.100”

- Exposure = 10 mpy
- Mitigation = 90%
- Resistance = 0.100”
**Example**

### CoF

<table>
<thead>
<tr>
<th>Hazard Zone (ft²)</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receptors ($/ft²)</td>
<td>500</td>
</tr>
<tr>
<td>Damage Rate (%)</td>
<td>1%</td>
</tr>
<tr>
<td>EL ($/incid)</td>
<td></td>
</tr>
</tbody>
</table>

### Ext Corr

1995 4" steel, 0.250", coated, CP

<table>
<thead>
<tr>
<th>Exposure (mpy)</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitigation (%)</td>
<td>80%</td>
</tr>
<tr>
<td>coat</td>
<td>50%</td>
</tr>
<tr>
<td>CP</td>
<td>60%</td>
</tr>
<tr>
<td>Resistance (in)</td>
<td>0.22</td>
</tr>
<tr>
<td>TTF (yrs)</td>
<td>110</td>
</tr>
<tr>
<td>PoF (%/yr)</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

### Thd Pty

Excavations 2/yr in this area

<table>
<thead>
<tr>
<th>Exposure (events/yr)</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitigation (%)</td>
<td>95%</td>
</tr>
<tr>
<td>cover</td>
<td>90%</td>
</tr>
<tr>
<td>one-call</td>
<td>50%</td>
</tr>
<tr>
<td>Resistance (%)</td>
<td>50%</td>
</tr>
<tr>
<td>PoD (%/yr)</td>
<td>10.0%</td>
</tr>
<tr>
<td>PoF (%/yr)</td>
<td>5%</td>
</tr>
</tbody>
</table>

### Risk

<table>
<thead>
<tr>
<th>Ext Corr</th>
<th>0.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thd Pty</td>
<td>5%</td>
</tr>
<tr>
<td>CoF</td>
<td>$5,000</td>
</tr>
<tr>
<td>PoF (%/yr)</td>
<td>5.9%</td>
</tr>
<tr>
<td>EL ($/yr)</td>
<td>$293</td>
</tr>
</tbody>
</table>

Risk (relative) scaled from EL

### Risk (relative)

- Ext Corr: 0.9%
- Thd Pty: 5%
- CoF: $5,000
- PoF (%/yr): 5.9%
- EL ($/yr): $293

Risk (relative) scaled from EL
PoF: TTF & TTF99

![Graph showing PoF and TTF99 over time]

- PoF: 1% and 100%
- TTF99
Examples

- $TTF = 0.160'' / [(16 \text{ mpy}) \times (1 - 0.9)] = 100 \text{ years}$
- $TTF_{99} = 0.160'' / (16 \text{ mpy}) = 10 \text{ years}$
- $PoF \Rightarrow \text{lognormal or other} \Rightarrow 0.001\% \text{ for year 1}$

- $TTF = 0.016'' / [(16 \text{ mpy}) \times (1 - 0.9)] = 10 \text{ years}$
- $TTF_{99} = 0.016'' / (16 \text{ mpy}) = 1 \text{ year}$
- $PoF = 1/TTF = 10\% \text{ for year 1}$
Final Pof

$$Pof_{overall} = pof_{thdpty} + pof_{ttf} + pof_{theftsab} + pof_{incops} + pof_{geohazard}$$

$$Pof_{overall} = 1 - [(1 - pof_{thdpty}) \times (1 - pof_{ttf}) \times (1 - pof_{theftsab}) \times (1 - pof_{incops}) \times (1 - pof_{geohazard})]$$

Guess pof if 1%, 4%, 2%, 2%, 0%

Calc: