Attachment A
Software Updating

- Implement modifications requested by participants
  - dual units (metric or imperial)
  - hole size specification options (absolute vs. fraction of line diameter)

- Implement improvements identified by C-FER
  - convert to 32 bit environment (remove model size limitations)
  - refine release rate / volume calculation algorithms
  - improve program calculation speed
Prioritization of Offshore Pipeline Segments for Integrity Maintenance
Review of Risk Methodology

System Definition
- divide system into segments
- define segment attributes

Segment Prioritization
- conduct quantitative risk analysis
- rank segments by est. risk level

Decision Analysis
- assess maintenance options
- identify optimal strategy

Maintenance Prioritization
- revise segment ranking based on cost of risk reduction

Repeat for All Targeted Segments
PIRAMID Offshore - Prioritization

- Provides a quantitative estimate of operating risk for each segment within pipeline system
- Ranks segments by estimated level of risk
- Risk estimates:
  - linked to specific line attributes
  - failure cause specific
  - provides a combined measure of
    » financial risk
    » life safety risk
    » environmental risk

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Software Program - modules
System Definition

Program divides each segment into sections having consistent attribute values

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## Segment Attributes - Affecting Failure Probability

<table>
<thead>
<tr>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Line diameter</td>
<td>- Vessel traffic density</td>
</tr>
<tr>
<td>- Wall thickness</td>
<td>- Water depth range</td>
</tr>
<tr>
<td>- Yield strength</td>
<td>- Enviro. corrosivity</td>
</tr>
<tr>
<td>- Joint type</td>
<td></td>
</tr>
<tr>
<td>- Line age</td>
<td></td>
</tr>
<tr>
<td>- Line pressure</td>
<td></td>
</tr>
<tr>
<td>- Line temperature</td>
<td></td>
</tr>
<tr>
<td>- Depth of cover</td>
<td></td>
</tr>
<tr>
<td>- Land use type</td>
<td></td>
</tr>
<tr>
<td>- Soil corrosivity</td>
<td></td>
</tr>
<tr>
<td>- Coating type</td>
<td></td>
</tr>
<tr>
<td>- Coating condition</td>
<td></td>
</tr>
<tr>
<td>- Cathodic protection level</td>
<td></td>
</tr>
<tr>
<td>- SCC potential</td>
<td></td>
</tr>
<tr>
<td>- Product corrosivity</td>
<td></td>
</tr>
<tr>
<td>- Ground movement potential</td>
<td></td>
</tr>
<tr>
<td>- Failure potential given ground movement</td>
<td></td>
</tr>
</tbody>
</table>

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# Probability Estimation

Program adjusts baseline failure rates to reflect segment attributes

## Baseline Failure Rate Estimates

<table>
<thead>
<tr>
<th>Failure Cause</th>
<th>Failure Rate (incidents/km-yr)</th>
<th>Relative Failure Probability by Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Metal Loss Corrosion</td>
<td>0.00010000</td>
<td>small leak 0.85, large leak 0.10, rupture 0.05</td>
</tr>
<tr>
<td>Internal Metal Loss Corrosion</td>
<td>0.00044000</td>
<td>small leak 0.85, large leak 0.10, rupture 0.05</td>
</tr>
<tr>
<td>Mechanical Damage</td>
<td>0.00015000</td>
<td>small leak 0.25, large leak 0.50, rupture 0.25</td>
</tr>
<tr>
<td>Natural Hazard Damage</td>
<td>0.00008000</td>
<td>small leak 0.25, large leak 0.50, rupture 0.25</td>
</tr>
<tr>
<td>Ground Movement</td>
<td></td>
<td>small leak 0.20, large leak 0.40, rupture 0.40</td>
</tr>
<tr>
<td>Environmentally Induced Cracks [SCC]</td>
<td></td>
<td>small leak 0.60, large leak 0.30, rupture 0.10</td>
</tr>
<tr>
<td>Mechanically Induced Cracks [girth weld fatigue]</td>
<td></td>
<td>small leak 0.60, large leak 0.30, rupture 0.10</td>
</tr>
<tr>
<td>Other Causes</td>
<td>0.00016000</td>
<td>small leak 0.80, large leak 0.10, rupture 0.10</td>
</tr>
</tbody>
</table>

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Probability Estimation Approach

Probability of failure for a given section

\[ P_{f_{ijkl}} = Rf_{ijkl} L_{sec_{ij}} \]

- Section length
- Adjustment factor for section and cause

\[ Rf_{ijkl} = Rfb_{l}MF_{kl}AF_{ijl} \]

- Section failure probability for given mode and given cause
- Failure rate for section, mode and cause
- Baseline failure rate per cause
- Relative failure probability per mode

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Adjustment Factor - External Corrosion

\[ AF = K_{EC} \left( \frac{A}{D} \right) (T + 17.8)^{2.28} \]

- \( K_{EC} \): Rate adjustment factor
- \( A/D \): Scaling factor
- \( T + 17.8 \): Line age
- \( (T + 17.8)^{2.28} \): Operating temperature
- \( F_{CE} \): Environment corrosivity factor
- \( F_{CP} \): Coating type factor
- \( F_{CT} \): Coating condition factor
- \( F_{CC} \): Centre For Engineering Research Inc.
Adjustment Factor - Mechanical Damage

\[ AF = \frac{K_{MD}}{D^{0.72}} \cdot F_{MA} \cdot F_{MD} \cdot F_{MC} \]

Scale factor

Rate adjustment factor

Line diameter

Traffic density factor

Soil cover factor

Water depth factor

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Consequence Evaluation

Program estimates loss components based on segment attributes

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Consequence Evaluation Approach

Based on analytical models

Line Repair Cost

Lost Product Cost

Service Interrupt Cost

Failure

Damage Thresholds

Hazard Characterization Models

Fatality Thresholds

Spill Trajectory and Clean-up Models

Spill Impact Factor

Damage & Restoration Costs

Effective Residual Spill Volume

Number of Fatalities

Equivalent Cost

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Consequence Evaluation - Loss Estimate

Total loss

Loss_{ijk} = \bar{c}_{ijk} + \alpha_n \bar{n}_{ijk} + \alpha_v \bar{v}_{ijk}

Cost

Number of fatalities

Equivalent spill volume

Equivalent Costs

The amount that society would be willing to pay to:
- prevent the loss of a statistical life
  ($1000's/fatality)
- prevent the spill of the reference product at the reference location ($/m^2)

2,000
5,000

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Risk Ranking

Calculate total risk = Expected loss

\[ \text{ExpLoss} = Pf \cdot \text{Loss} \]
### Segment Risk Ranking

**System:** Greek tragedy  
**Date:** 15th March 1996

#### Failure Causes Considered:

<table>
<thead>
<tr>
<th>Failure Cause</th>
<th>SCC</th>
<th>Mechanical Damage</th>
<th>Natural Hazard Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Corrosion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal Corrosion</td>
<td>Material Defects</td>
<td>Ground Movement</td>
<td>Other</td>
</tr>
</tbody>
</table>

**All Causes Combined**

#### Segment Ranking Approach:

<table>
<thead>
<tr>
<th>Risk Ranking</th>
<th>Segment Designation</th>
<th>Failure Cause</th>
<th>Expected Cost /km²yr</th>
<th>Expected Cost /seg²yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Delta</td>
<td>Mechanical Damage</td>
<td>1223</td>
<td>61166</td>
</tr>
<tr>
<td>2</td>
<td>Gamma</td>
<td>Mechanical Damage</td>
<td>1175</td>
<td>117571</td>
</tr>
<tr>
<td>3</td>
<td>Delta</td>
<td>External Corrosion</td>
<td>882</td>
<td>40099</td>
</tr>
<tr>
<td>4</td>
<td>Alpha</td>
<td>Mechanical Damage</td>
<td>602</td>
<td>60240</td>
</tr>
<tr>
<td>5</td>
<td>Beta</td>
<td>External Corrosion</td>
<td>547</td>
<td>41044</td>
</tr>
<tr>
<td>6</td>
<td>Beta</td>
<td>Mechanical Damage</td>
<td>371</td>
<td>27895</td>
</tr>
<tr>
<td>7</td>
<td>Alpha</td>
<td>External Corrosion</td>
<td>351</td>
<td>35104</td>
</tr>
</tbody>
</table>

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Risk Ranking Options

Segment Ranking Approach
- Expected cost per km/yr
- Expected cost per segment/yr

Failure Causes Considered in Ranking
- All causes considered individually
- All causes considered combined
- External metal loss corrosion only
- Internal metal loss corrosion only
- Mechanical damage only
- Natural Hazard Damage
- Environmentally induced cracks (SCC) only
- Mechanically induced cracks (fatigue) only
- Other causes only
Optimization of Metal Loss Corrosion Maintenance

- Objectives
  - Develop models to
    » Calculate probability of failure due to corrosion
    » Quantify impact of maintenance on failure probability
  - Incorporate models into PIRAMID to make corrosion maintenance optimization decisions
Review of Basic Influence Diagram

- Integrity Maintenance Action
- Pipeline Perform. (Failure?)
- Consequences
- Value

Individual projects expand different nodes
Example

- Company X inspected a 50-km segment using a high resolution in-line tool
- Inspection revealed 63 external corrosion defects
- For each defect inspection provided
  - maximum axial length
  - Maximum depth
Required

• Should a more accurate inspection be carried out?
• Which defects should be repaired?
• How long to the next inspection?
Step 1 - Statistical Characterization of Defect Population

- **Average defect frequency**
  - Number of defects / segment length = 1.37 defects / km

- **Probability distribution of defect depth**
  - Lognormal
    » mean = 15% wt
    » standard deviation = 5% wt

- **Probability distribution of defect length**
  - Lognormal
    » mean = 27 mm
    » standard deviation = 17 mm
Step 2 - Calculate Safety Factor for Each Defect

\[ R = 2.3C \frac{TS}{D} \left[ \frac{1 - H / T}{1 - H / MT} \right] \]

R = Resistance
C = Mean model error factor
T = Wall thickness
S = Yield strength
H = Average defect depth
M = Folias factor (function of D,T,L)
L = Maximum defect length
Step 3 - Run PIRAMID

• Input
  – Line attributes
  – Defect characteristics
  – Defect growth rates

• Output
  – Another inspection? (Yes / No)
  – Repair criterion --> 1.64 safety factor
  – Time to next maintenance --> 16 years
Step 4 - Implement Plan

- Repair defects with safety factor < 1.64
- Re-analyze the line in 16 years
Project Outcomes

- PIRAMID Corrosion (Beta)
  - Separate module for corrosion maintenance optimization
- Updated User Guide
Original Development Plan

- Risk-based Decision Analysis
  - Consequence Evaluation
    - Corrosion
    - Mechanical Damage
      - Punctures
    - Cracking
    - Dents
  - Probability Evaluation & Maintenance Optimization
    - Ground Movement
Optimization of Mechanical Damage Prevention
Project Objectives

- Develop a model for estimating probability of line failure due to mechanical interference
  - Model to be line specific (reflect line attributes)
  - Model to account for the effects of preventative maintenance activities on failure probability

- Integrate probability estimation model within the existing decision analysis framework

Note: model addresses immediate failures due to line puncture only, delayed failure of dents and gouges to be addressed elsewhere
Decision Analysis Framework

Conceptual Influence Diagram

- Integrity Maintenance Action
- Pipe Performance
- Value
- Consequences
Mechanical Damage Influence Diagram

Effect of action on probability of failure due to mech. interference

Preventative Maintenance Action

Pipe Performance

Consequences

Value

Effect of action on line operating cost
Mechanical Damage Influence Diagram

New Node Groups

Outside Force

Conditions at Failure

Spill Characteristics

Release & Damage Costs

Release Character - istics

Hazard Type

Total Cost

Repair & Interrupt Cost

Number of Fatalities

Pipe Performance

Mech. Properties

Damage Potential

Choices

Value

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Choices

- Preventative maintenance actions considered:
  - Enhance: ROW condition / generic markers
    Explicit pipeline signage
    Notification system
  - Modify: Response to notification
    ROW patrol frequency
    ROW patrol method
  - Introduce: permanent alignment markers
    mechanical protection
  - Increase: cover / burial depth
Damage Potential

• Estimate frequency of third party activity resulting in line impact

• Approach based on Fault Trees
  – deductive analysis identifying logical combinations of basic events that lead to top event (line impact)
  – basic event probabilities estimated from:
    » line attributes
    » preventative maintenance choices
  – defaults based on:
    » historical data (where available)
    » analytical models (where applicable)
    » subjective judgement (where necessary)
Damage Potential

• Line attributes affecting damage potential
  » Land use type
  » Crossings / Special terrain
  » Notification system / System response
  » ROW condition / Generic markers
  » Explicit Pipeline signage
  » ROW patrol frequency / patrol method
  » Permanent above-ground alignment markers
  » Buried alignment markers
  » Mechanical protection
  » Cover / burial depth
Fault tree for mechanical interference
Outside Force

- Characterize magnitude and uncertainty associated with line impact force

- Approach involves specification of PDFs of impact force for different land use types

- Default model assumes that maximum impact force is proportional to equipment weight
  - PDF of impact force developed from PDF of North American excavator equipment weights
Mechanical Properties

- Characterize the magnitude and uncertainty of
  - pipe body yield strength (affects puncture resistance)
  - pipe body notch toughness (affects leak vs. rupture)

- Approach involves specification of PDFs of $F_Y$ and $C_V$ for different steel grades

- Defaults based on specified material properties with historical data used to establish
  - probability distribution type
  - mean-to-specified ratio
  - coefficient of variation

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Pipe Performance

- Estimate the probability of line failure, $P_F$

\[ P_F = P_{F|I} P_I \]

where $P_{F|I}$ = probability of failure given impact

$P_I = \text{probability of line impact (per yr)}$

and

\[ P_I = R_I L_{Seg} \]

where $R_I = \text{rate of line impact (per km yr)}$

$L_{Seg} = \text{segment length (km)}$
Probability of Failure Given Impact

- Estimate probability of line leak and rupture

  Structural Reliability Model

  Leak vs. Rupture Model

  yes
  
  no
  
  Failure Mode
  
  Failure

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Structural Reliability Model

- Failure given line impact


Yield strength distribution

Outside Force

Impact force distribution

Reliability estimate

Deterministic resistance model

Resistance probability distribution

Geometric Properties
Deterministic Resistance Model

- **Pipe puncture resistance** (Spiekhout et al. 1987)

\[ R_P = 2.3F_Y t^2 \left[ 0.4D \sqrt{\frac{D}{2t}} + L \right] \frac{1}{(D - 0.7w)} \]

where

- \( D \) = line diameter
- \( t \) = wall thickness
- \( F_Y \) = yield strength
- \( L \) = indentor length
- \( w \) = indentor width

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Leak vs. Rupture Model

- **Through-wall defect model** (Kiefner et al. 1973)

Rupture if 

$$C_v < \frac{2 A_c}{3 \pi E} c \sigma_F^2 \ln \sec \left( \frac{\pi M_T}{2} \frac{PR}{\sigma_F} \frac{1}{t} \right)$$

where 

- $C_v =$ **Charpy plateau energy** (for shear area = $A_c$)
- $c =$ **flaw length** (related to assumed indentor size)
- $\sigma_F =$ **flow stress** = $F_y + 70$ MPa
- $M_T =$ **Folias factor** = $f(R, t, and c)$
- $P =$ **operating pressure**
- $R =$ **pipe radius**
- $t =$ **pipe wall thickness**
Choice Evaluation - Utility Theory

![Utility Outcome Diagram]

Choice 1: 0.999815  
Choice 2: 0.999813  
Choice 3: 0.999755

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Choice Evaluation - Cost Optimization
<table>
<thead>
<tr>
<th>Project</th>
<th>Budget $1000</th>
<th>Spent (%)</th>
<th>Comp. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIRAMID Updating</td>
<td>85</td>
<td>82</td>
<td>95</td>
</tr>
<tr>
<td>Offshore Prioritization</td>
<td>60</td>
<td>56</td>
<td>90</td>
</tr>
<tr>
<td>Mechanical Damage</td>
<td>170</td>
<td>62</td>
<td>50</td>
</tr>
<tr>
<td>Corrosion (Phase II)</td>
<td>85</td>
<td>107</td>
<td>85</td>
</tr>
<tr>
<td>Management &amp; Marketing</td>
<td>45</td>
<td>51</td>
<td>90</td>
</tr>
<tr>
<td>Contingency</td>
<td>36</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>481</strong></td>
<td><strong>363</strong></td>
<td><strong>72%</strong></td>
</tr>
</tbody>
</table>