ICorr Aberdeen Branch Welcomes

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With inputs from
Dr Ed Whyte
PLANT INTEGRITY MANAGEMENT LTD

PIM was established in 2011 to provide consultancy and strategic management support for their clients - helping them manage the function and integrity of their critical plant and equipment.

WHAT WE DO: STRATEGIC MANAGEMENT OF INTEGRITY AND THE PROVISION OF OPERATIONAL SUPPORT

WHERE WE ARE: UK, KSA, MALAYSIA
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2010 – 2014 CAN OFFSHORE / ENGTEQ
2014 – 2017 LR SENERGY / LR
2017 – TO DATE PLANT INTEGRITY MANAGEMENT

CEng FIMMM, MICorr, MIEP
CORROSION RATE MODELLING AND MONITORING

INTRODUCTION

CO₂ MODELLING SOFTWARE

HOW TO USE CALCULATED CORROSION RATE

ONLINE MONITORING

WHAT TO EXPECT OUT OF MONITORING DATA

HOW TO USE MONITORING DATA
Introduction

PART 1 - Corrosion Modelling - complete life cycle of the plant

• **Design of new facilities**
  - Materials Selection (C-steel vs CRA)
  - Corrosion barrier (Inhibition, coating, CP etc.) requirements

• **Integrity Management**
  - React to change in process conditions
  - New facility tie-in

PART 2 - Monitoring (*Indirect estimate of corrosion through inserted probes/coupons*) observe if predicted corrosion rates are valid.
This presentation covers

• Carbon steel - *not* Corrosion Resistant Alloys
• Linear corrosion mechanism (general corrosion) – *not* cracking

Objective is to:

• Provide an overview of corrosion modelling and monitoring
• Avoid black box approach – “Computer says…..”
• Use engineering judgment with numbers (modelling/monitoring)
• Understand limitation of modelling / monitoring
PART 1 - CORROSION RATE MODELLING
Corrosion Modelling for Oil and Gas

- **CO₂ Corrosion**
- **O₂ Corrosion**
- **H₂S Corrosion**

- **Anodic Reaction**
  \[ \text{Fe} \leftrightarrow \text{Fe}^{2+} + 2\text{e}^- \]

- **Cathodic Reaction(s)**
  \[ \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 + 2\text{e}^- \leftrightarrow \text{H}_2 + \text{CO}_3^{2-} \text{ (CO}_2 \text{ Corrosion)} \]
  \[ \text{O}_2 + 4\text{H}^+ + 4\text{e}^- \leftrightarrow 2\text{H}_2\text{O} \text{ (O}_2 \text{ corrosion – Not covered here)} \]
  \[ \text{H}_2\text{S} \leftrightarrow 2\text{H}^+ + \text{S}^{2-} \text{ (H}_2\text{S Corrosion – Not covered here)} \]
CO$_2$ Corrosion

General Corrosion

Raindrop attack - gas condensate

Mesa-type corrosion
Types of Predictive Models

- **Mechanistic**
  - Formulated from quantitative knowledge of reaction *thermodynamic* and *kinetics*

- **Empirical**
  - Formulated from array of *experimental measurements*

- **Semi-empirical**
  - *Mix of Above*
De Waard and Milliams (Carbonic Acid Corrosion of Steel, 1975)

\[ \log V_{corr} = 5.8 - \left( \frac{1710}{(273 + T)} \right) + 0.67 \log (P_{CO_2}) \]

where

- \( V_{corr} \) is corrosion rate
- \( T \) is Temperature, and
- \( P_{CO_2} \) is partial pressure of CO\(_2\)

(cathode reaction: \( H_2CO_3 \) reduction)
Partial pressure of a gas

- Partial pressure quantifies gas dissolved in water at equilibrium
  - Total pressure * Mole fraction in gas

For example:
For 0.1% CO$_2$ in gas at pressure of 10 bara

\[ P_{CO_2} = 10 \times 0.1 = 1 \text{ bara} \]

- Ideal gas – Henry’s law
- Fugacity correction
Effect of acid gases on pH

- pH is function of
  - Partial pressure of acid gases
  - Temperature
  - Organic acid (Acetates)
  - Formation water chemistry
    - Formation water >~ 4.5
    - Condensed water >= 3.5
• About 60 - 70°C carbonate scale start forming on carbon steel surface

\[ Fe + H_2O + CO_2 \leftrightarrow FeCO_3 \text{ (Siderite)} + H_2 \]
De Waard & Milliams Nomogram

Example:
0.2 bar CO₂ at 120 °C
gives 10 × 0.7 = 7 mm/y

\[ CR_{scale} = CR_{free} \times SF \]
Development of Predictive Model Software

- pH
- Scale
- Steel composition
- Glycol %
- Inhibition
- CP
- Organic acids

- de Waard et al (Shell)
- NORSOK model (Statoil, Saga, Hydro)
- HYDROCOR (Shell)
- Cassandra (BP)
- CORMED (Elf)
- LIPUCOR (Total)
- CORPLUS (Total)
- KSC Model (IFE)
- ECE model (Intetech)
- SweetCor (Shell)
- OLI model (OLI Systems)
- PREDICT (InterCorr)
- Tulsa model (University of Tulsa)
- Jepson model (University of Ohio)
- MULTICORP (University of Ohio)
- Corpos (CorrOcean)
- ULL model (University of Louisiana at Lafayette)
- DREAM (Oklahoma State University)
NORSOK M-506 (2005)

• Input

• Limitations

The model is valid for temperature 5 - 150 °C, pH 3.5 - 6.5, CO₂ partial pressure 0.1 - 10 bar and shear stress 1 - 150 Pa. The model is not applicable when the H₂S partial pressure is higher than 0.5 bar, or when the ratio between the partial pressure of CO₂ and H₂S is less than 20. The model can lead to underprediction of the corrosion rate when the total content of organic acids exceeds 100 ppm and the CO₂ partial pressure is less than 0.5 bar.

• Output

Pressure = 10 bar, Shear stress = 10 Pa, CO₂ = 5 mole%
Corrosion allowance (mm)

- Calculated corrosion rate \( \times \) design life

  \textit{If corrosion allowance is more than 10 mm for carbon steel – consider using corrosion resistant alloys (NORSOK M-001)}

- Complete life cycle cost analysis with carbon steel + inhibition

- Be aware of different corrosion rates (outputs) from different models
Comparison of Predictive models

- $f$ Temperature
- $f$ pH
- $f$ Pressure
### Example:

**Corrosion Rates for Carbon Steel**

**pH Model BP**

**Water Composition** Western Isles

**Corrosion Inhibitor 95%**

**Pipe OD 219.1 mm**

**Inhibited Rate mm/yr**

**Required corrosion allowance**

<table>
<thead>
<tr>
<th>Corrosion Inhibitor</th>
<th>95%</th>
<th>Design Life</th>
<th>15 years</th>
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<tbody>
<tr>
<td><strong>8&quot; Production</strong></td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Average Mol% CO₂</th>
<th>Mol% H₂S</th>
<th>Oil Flowrate</th>
<th>Water Flowrate</th>
<th>Gas Flowrate</th>
<th>pH</th>
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**Example: Corrosion Allowance Calculation**

- **Inhibited Rate mm/yr**
- **Basic Flow-sensitive**
- **Uninhibited**
- **Uninhibited**
- **Inhibited**

**Inhibited Rate mm/yr**

### Required corrosion allowance
Flow regimes in horizontal pipe

Example of steady-state flow regime map for a horizontal pipe. Superficial liquid velocity $V_L$ vs superficial gas velocity $V_G$. 

- **Dispersed-bubble or bubble flow**
- **Intermittent: Elongated bubble, slug, and churn flow**
- **Stratified-smooth flow**
- **Stratified-wavy flow**
- **Annular flow**
- **Annular flow with droplets**
- **Annular flow**
- **Churn flow**
- **Slug flow**
- **Dispersed bubble flow**
# Exploiting Output – Inhibition categorisation

<table>
<thead>
<tr>
<th>Category</th>
<th>Maximum Required Availability</th>
<th>Maximum Expected Uninhibited Corrosion Rate (mm/yr)</th>
<th>Comment</th>
<th>Possible Category Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0%</td>
<td>0.4</td>
<td>Benign fluids where corrosion inhibitor usage is not anticipated (dry gas, stabilised oil). Predicted metal loss can be accommodated by corrosion allowance alone.</td>
<td>Benign</td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
<td>0.7</td>
<td>Corrosion inhibitor will probably be required but at the expected corrosion rates there will be time to review the need for inhibition based on inspection data.</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>90%</td>
<td>3</td>
<td>Corrosion inhibitor will be required for the majority of the field life but the facilities need not be available from day 1.</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>6</td>
<td>Inhibition is relied on heavily and will be required for the lifetime of the operation. Inhibitor must be available from day 1 to ensure success of the inhibition programme.</td>
<td>High</td>
</tr>
<tr>
<td>5</td>
<td>&gt;95%</td>
<td>&gt;6</td>
<td>Carbon steel and inhibition is unlikely to provide integrity for the full field life. Select corrosion resistant materials or plan for repairs &amp; replacements.</td>
<td>Unacceptable</td>
</tr>
</tbody>
</table>

PART 2 - CORROSION MONITORING
Online Corrosion monitoring

- Corrosion Coupons
- Electrical Resistance
- Linear Polarisation Resistance
- Galvanic Current
- Electrochemical Noise
- Hydrogen Permeation
- Field Signature Method
- Ring Pair Corrosion Monitoring
- Iron Counts/Chemical Analysis models
Why Monitoring

- Identify rate and type of corrosion at given location (e.g. general corrosion, localized corrosion)

- Provide assurance of chemical performance (e.g. injection rates)

- Provides an early indication of potential threat allowing proactive resolution and reduce risk of hydrocarbon release.

- Used as input into RBI assessment (IoW)

- Increase confidence in plant integrity.
Corrosion Coupon and Corrosion Probe (Typical Assembly)
Corrosion Coupons

- Weight loss - average corrosion rate
  \[
  \frac{\text{Initial weight} - \text{Final weight}}{\text{Area} \times \text{Density} \times \text{Exposure period}} \times \text{Unit factor}
  \]

- Visual Inspection – Localised corrosion

- Microbial Sampling (Swab)
• Electrically isolated to avoid galvanic interaction
• Strip coupons usually mounted in pairs from top / side / bottom of pipe
• Flush Disc normally mounted in top/bottom of pipe
Mounting/Location Examples

- Strip Coupon Top of Line
- Strip Coupon Top and Bottom Monitoring
- Flush Disc
- Projecting Disc
- Multiple Disc
- Strip Coupon 3 Phase Monitoring
Methodology - Coupons

- Select appropriate material / dimensions / surface finish
- Weigh coupon
- Insert into equipment
- Retrieve after a period (e.g. 6 months) - Swab for microbial analyses
- Clean/reweight
- Calc. CR
**Corrosion Coupons – Pros-Cons**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple and cheap</td>
<td>In very low corrosion rate conditions - insensitive - long exposure periods are required</td>
</tr>
<tr>
<td>Can be used in any environment</td>
<td>Can provide relatively long term data</td>
</tr>
<tr>
<td>Provide a visual indication of corrosion type as well as rate</td>
<td>Require laboratory stage (cleaning and weighing) before data are available</td>
</tr>
<tr>
<td>Can provide pitting rate data</td>
<td>Time averaging – will not tell you about corrosion rates at any specific time</td>
</tr>
</tbody>
</table>
Electrical Resistance (ER) Probe

- Corrosion cause reduction in cross section
  \[
  \Delta(x\text{-sectional area}) \rightarrow \Delta ER \text{ is measured} \rightarrow \propto \text{ corrosion rate}
  \]
- Reference element eliminates temperature effects
## ER probe – Pros-Cons

<table>
<thead>
<tr>
<th>ER probes</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can be used in any environment (conducting and non-conducting)</td>
<td>Will not give reliable data in pitting or localised corrosion conditions</td>
<td></td>
</tr>
<tr>
<td>Different types of probe elements available to cover different requirements, i.e. high sensitivity, long life, flush or protruding shapes</td>
<td>Probes can be either sensitive with a short life, or insensitive with a long life, but not both</td>
<td></td>
</tr>
<tr>
<td>Can give data “on-line” either:</td>
<td>Response time for reliable result dependent on corrosion rate:</td>
<td></td>
</tr>
<tr>
<td>Intermittently (single readings taken daily/weekly/monthly)</td>
<td>1 - 10 hrs at 5 mm/yr</td>
<td></td>
</tr>
<tr>
<td>Continuously (readings taken at regular intervals, typically 1 hourly)</td>
<td>10 - 100 hrs at 0.5 mm/yr</td>
<td></td>
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<tr>
<td>Sensitivity down to several nm possible with latest technology</td>
<td>100 - 1,000 hrs at 0.05 mm/yr</td>
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<tr>
<td></td>
<td>Average rates only between data sampling intervals</td>
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</table>
Typical ER probe data

- 0.2 mm/y
- 0.7 mm/y
- 0.84 mm/y
Reporting Monitoring Data
• Based on standard LPR technique

• Corrosion rate is $\propto 1/R_{\text{electrode}}$

• *Instantaneous* corrosion rate (~ 1 min for a measurement)
LPR Probe Measurement

![Graph showing Inhibitor Addition and Corrosion Rate over Time]

- **Corrosion Rate [mm/yr]**
  - 0.1
  - 0.2
  - 0.3
  - 0.4
  - 0.5
  - 0.6
  - 0.7
- **Time [hours]**
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
  - 70
  - 80
  - 90

- **Inhibitor Addition**
- **Dosaged**
- **Stopped**
## LPR Probe – Pros-Cons

<table>
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<td><strong>Advantages</strong></td>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>Gives relatively instantaneous corrosion rate</td>
<td>Can only be used in conductive media (mainly aqueous)</td>
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<tr>
<td></td>
<td>If electrodes become fouled - can give erroneous results</td>
</tr>
<tr>
<td></td>
<td>Generally gives little information on localised corrosion</td>
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Various Corrosion prediction models and monitoring options are available

• Use corrosion prediction model with care and engineering judgment should always be applied.

• Always challenge and sense check the output - Don’t always believe what “Computer says…………”.

• Understand the limitation of predictive models.

• Correlate predictive and monitored rates with in-service inspection data for integrity management decisions.

• Corrosion monitoring is ‘part of’ not the whole story.
THANK YOU FOR YOUR ATTENTION ANY QUESTIONS?