ICorr Aberdeen Branch Welcomes Mott MacDonal
The Mott MacDonald Group is a multidisciplinary consultancy with headquarters in the United Kingdom. It provides engineering, management and development services internationally, with 16,000 staff in 150 countries. Mott MacDonald is one of the largest employee-owned companies in the world.

Mott MacDonald was established in 1989 by the merger of Mott, Hay and Anderson with Sir M MacDonald & Partners. It has won more than 500 industry awards in the last five years and is among the top ranked firms in the annual league tables published by Engineering News Record and New Civil Engineer. Projects completed include the Hong Kong International Airport, Wembley Stadium and the Channel Tunnel.
Paul Lambert is Head Of Materials And Corrosion Technology For Mott Macdonald, Based In Altrincham Near Manchester, United Kingdom. He Has Over 30 Years’ Experience In The Investigation Of Structural Durability And Degradation And In The Development Of Novel Remedial Techniques For Many Types Of Structures.

Paul Is Visiting Professor At The Centre For Infrastructure Management At Sheffield Hallam University Where He Carries Out Research Into Novel Materials, Protective Coatings And Repair Technologies. He Is A Fellow Of The Institute Of Materials, Minerals And Mining, A Fellow And Past President Of The Institute Of Corrosion, A Chartered Materials Engineer, A Chartered Corrosion Scientist And A NACE Certificated Corrosion Specialist.
AN INTRODUCTION TO CORROSION

MECHANISMS

EXAMPLES

COSTS
Steel

- Availability and relatively low cost
- Strong and tough
- Ability to be formed into the required sections
- Ability to be joined by welding
  - upper limit of around 0.25% carbon
Steel

- Relatively simple alloys of iron and carbon with various other alloying elements, principally manganese
- Manganese is added to:
  - reduce embrittling effects of iron sulphide during secondary steelmaking processes
  - give low-temperature toughness
Steel for Construction
Steel for Reinforced Concrete

- Takes the tensile load of the concrete beams or slabs
- Carries a proportion of the compressive stress
- Withstands tensile stresses that may arise due to eccentric load, as in columns
- Withstands sheer stresses in beams near to supports
Steel for Reinforced Concrete

- Prevents propagation of cracks initiated in the concrete
- When used near the surface in mass concrete, reduces cracking by drying shrinkage
- In some cases, is used to prevent spalling of concrete surfaces due to fire
Steel for Reinforced Concrete

- Bond between steel and concrete is important to allow load transfer
- Bond depends upon a number of factors:
  - area of contact
  - strength of concrete
  - condition of the steel surface
  - thin layer of adherent rust improves bond
  - so does use of ribbed bars
Corrosion Awareness Day 2017
Corrosion Awareness Day 2017

Ynys-y-Gwas Bridge, 1985
Corrosion Awareness Day 2017
So Why Use Steel?

• Steels are the backbone of the built environment
• A range of relatively simple iron-carbon alloys
• They offer an excellent combination of properties
  – Relatively inexpensive
  – Easily formed and joined
  – Range of mechanical properties
  – Recyclable
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Metals Usage - World Wide

- Iron & Steel
- Other Metals
Steel Usage - Alloy & Non Alloy

- Non-Alloy
- Alloy
Alloy Steels

- General Engineering
- Stainless
- Tool Steel
- High Speed Steels
Anode

Cathode

Electrons

Electrolyte

RUST

Fe^{2+} + 2OH^- → Fe^{2+} + H_2 + 2OH^-

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Why does steel corrode? (1)

- Differences in electrical potential on the surface form ANODIC and CATHODIC sites

- At anodic sites the metal oxidises:

\[ \text{Fe (metal)} \Leftrightarrow \text{Fe}^{2+} + 2e^- \]
Why does steel corrode? (2)

- Simultaneously, reduction occurs at cathodic sites, typically:
  
  - \( \frac{1}{2}O_2 + H_2O + 2e^- \text{(metal)} \Leftrightarrow 2OH^- \text{(aq.)} \) or
  
  - \( 2H^+ \text{(aq.)} + 2e^- \text{(metal)} \Leftrightarrow H_2 \text{(gas)} \)

- Electrons are conducted through metal while ions travel through electrolyte
Anodes & Cathodes
General Corrosion

• Uniform attack of the metal surface
• Low rate of penetration
• Potentially greater degree of contamination
• ‘Typical’ rates are available for most metal/environment combinations
• Difficult to design against
• May require protection - e.g. coatings
General Corrosion
Pitting Corrosion

- Highly localised, high rate corrosion
- Rapid perforation of sections
- Several causes, including chloride ions
- Once initiated, pits can be self perpetuating
- Often associated with stagnant conditions
- Coatings can provide barrier but any defects can become active anodic sites
Pitting Corrosion
Crevice Corrosion

- Typically occurs in gaps between two surfaces
- Only one surface needs to be metal
- Surface deposits can also produce crevices
- Corrosion cell caused by differential oxidation
- The smaller the crevice, the more intense the corrosion
- Must be designed-out or filled-in
Crevice Corrosion
Bimetallic Corrosion

- Five conditions must be satisfied:
  - an environment in which the ‘anode’ can corrode
  - an electrolytic path
  - an electronic path
  - a large potential difference
  - no restriction of the reactions at the ‘cathode’

- Control involves preventing or interfering with one of these requirements
Bimetallic Corrosion

STAINLESS STEEL

COATED CARBON STEEL
Galvanic Series for Seawater

Source: NPL
Stress Corrosion Cracking

- Requires both tensile stress and a specific corrosive medium
- Highly specific to alloy, environment and exposure conditions
- Stresses may be due to fabrication or service
- Coatings can exclude the environment
Stress Corrosion Cracking

CRACK

CREVICE
Corrosion Fatigue

- Caused by a combination of cyclic stress and a corrosive environment
- Hard to distinguish from plain fatigue
- Coatings can exclude the environment
- Techniques that improve plain fatigue resistance can also help with corrosion fatigue - e.g. carburising, nitriding, shot peening
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Corrosion Fatigue
Other Forms of Corrosion

- EROSION-CORROSION
  - synergy of erosive and corrosive decay
- CAVITATION
  - collapsing air bubbles erode surface
- GRAPHITIC CORROSION
  - preferential attack in grey cast iron
- GALLING
  - local cold welding and tearing (stainless steels)
- FRETTING
  - small movements generating fine debris
Reinforcement Corrosion
Reinforcement Corrosion
Reinforcement Corrosion
## Cost of Corrosion - Studies

<table>
<thead>
<tr>
<th>Year</th>
<th>Study</th>
<th>Cost of GDP</th>
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</thead>
<tbody>
<tr>
<td>1950</td>
<td>H.H. Uhlig, US</td>
<td>2.1%</td>
</tr>
<tr>
<td>1970</td>
<td>T.P. Hoar, UK</td>
<td>3.5%</td>
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<tr>
<td>1974</td>
<td>Japan Study</td>
<td>1.2%</td>
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<tr>
<td>1975</td>
<td>Battelle/NBS, US</td>
<td>4.5%</td>
</tr>
<tr>
<td>2003</td>
<td>NACE, Global</td>
<td>3.4%</td>
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</table>
## Cost of Corrosion – World-Wide

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>2.0</td>
<td>303.2</td>
<td>146.0</td>
<td>451.3</td>
<td>16,720</td>
<td>2.7%</td>
</tr>
<tr>
<td>India</td>
<td>17.7</td>
<td>20.3</td>
<td>32.3</td>
<td>70.3</td>
<td>1,670</td>
<td>4.2%</td>
</tr>
<tr>
<td>European Region</td>
<td>3.5</td>
<td>401</td>
<td>297</td>
<td>701.5</td>
<td>18,331</td>
<td>3.8%</td>
</tr>
<tr>
<td>Arab World</td>
<td>13.3</td>
<td>34.2</td>
<td>92.6</td>
<td>140.1</td>
<td>2,789</td>
<td>5.0%</td>
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<tr>
<td>China</td>
<td>56.2</td>
<td>192.5</td>
<td>146.2</td>
<td>394.9</td>
<td>9,330</td>
<td>4.2%</td>
</tr>
<tr>
<td>Russia</td>
<td>5.4</td>
<td>37.2</td>
<td>41.9</td>
<td>84.5</td>
<td>2,113</td>
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<tr>
<td>Japan</td>
<td>0.6</td>
<td>45.9</td>
<td>5.1</td>
<td>51.6</td>
<td>5,002</td>
<td>1.0%</td>
</tr>
<tr>
<td>Four Asian Tigers + Macau</td>
<td>1.5</td>
<td>29.9</td>
<td>27.3</td>
<td>58.6</td>
<td>2,302</td>
<td>2.5%</td>
</tr>
<tr>
<td>Rest of the World</td>
<td>52.4</td>
<td>382.5</td>
<td>117.6</td>
<td>552.5</td>
<td>16,057</td>
<td>3.4%</td>
</tr>
<tr>
<td><strong>Global</strong></td>
<td><strong>152.7</strong></td>
<td><strong>1446.7</strong></td>
<td><strong>906.0</strong></td>
<td><strong>2505.4</strong></td>
<td><strong>74,314</strong></td>
<td><strong>3.4%</strong></td>
</tr>
</tbody>
</table>

Source: NACE
Cost of Corrosion – USA

- Transportation and Utilities, 34.9%
  - $96.2 Billion
- Manufacturing, 31.5%
  - $86.8 Billion
- Construction, 18.1%
  - $50.0 Billion
- Federal Government, 7.3%
  - $20.1 Billion
- Services, 5.2%
  - $14.3 Billion
- State and Local Government, 3.0%
  - $8.3 Billion

Source: NACE
The State of the Nation (ICE) Assessment of Condition of UK Infrastructure

<table>
<thead>
<tr>
<th>Category</th>
<th>Condition Grade</th>
<th>Change</th>
<th>Sustainability Grade</th>
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</thead>
<tbody>
<tr>
<td>Overall</td>
<td>C-</td>
<td>↑</td>
<td>C</td>
</tr>
<tr>
<td>Energy</td>
<td>D+</td>
<td>↑</td>
<td>D</td>
</tr>
<tr>
<td>Waste Management</td>
<td>C-</td>
<td>↑</td>
<td>D+</td>
</tr>
<tr>
<td>Water &amp; Wastewater</td>
<td>B</td>
<td>↓</td>
<td>C+</td>
</tr>
<tr>
<td>Flood Risk Management</td>
<td>C</td>
<td>↓</td>
<td>B</td>
</tr>
<tr>
<td>Rail</td>
<td>C</td>
<td>_</td>
<td>D+</td>
</tr>
<tr>
<td>National Roads</td>
<td>C+</td>
<td>_</td>
<td>D</td>
</tr>
<tr>
<td>Local Transport</td>
<td>C</td>
<td>_</td>
<td>C-</td>
</tr>
<tr>
<td>Seaports</td>
<td>B-</td>
<td>_</td>
<td>C+</td>
</tr>
<tr>
<td>Airports</td>
<td>C+</td>
<td>_</td>
<td>D+</td>
</tr>
</tbody>
</table>

A = Good,  B = Fair,  C = Average,  D = Poor,  E = Bad
## American Infrastructure Report Card by American Society of Civil Engineers

<table>
<thead>
<tr>
<th>Category</th>
<th>Condition Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads</td>
<td>D</td>
</tr>
<tr>
<td>Bridges</td>
<td>C</td>
</tr>
<tr>
<td>Transit</td>
<td>D+</td>
</tr>
<tr>
<td>Rail</td>
<td>C-</td>
</tr>
<tr>
<td>Aviation</td>
<td>D+</td>
</tr>
<tr>
<td>Power Grid</td>
<td>D</td>
</tr>
<tr>
<td>Drinking Water</td>
<td>D-</td>
</tr>
<tr>
<td>Waste Water</td>
<td>D-</td>
</tr>
<tr>
<td>Dams</td>
<td>D</td>
</tr>
</tbody>
</table>

A = Exceptional,  B = Good,  C = Mediocre,  D = Poor,  E = Failing
Corrosion Awareness Day 2017

Paul Lambert – Mott MacDonald – An Introduction to Corrosion
To Conclude

• Corrosion is a costly business in terms of:
  – Money
  – Resources
  – Energy
  – Lives
To Conclude

• Corrosion is a costly business in terms of:
  – Money
  – Resources
  – Energy
  – Lives
• While it cannot be totally avoided, it can be controlled
• Corrosion control is a major industry worldwide
  – and not a bad way to make a living
THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?