ICorr Aberdeen Branch Welcomes Aberdeen Foundries
ABERDEEN FOUNDRIES
SACRIFICIAL ANODES AND NON FERROUS CASTINGS
SCOTLAND -> THE WORLD
NIGEL OWEN
ABERDEEN FOUNDRIES
Dr. Nigel Owen. B.Sc., D.I.C, Ph.D, MIMMM.


After completing Degrees worked in the Aluminium Industry for over 35 years: RTZ Australia & USA - R & D of Cast and Rolled Aluminium products and Smelter waste recycling in New Zealand.

Worked as a Materials Consultant and in the Galvanising industry before joining Aberdeen Foundries as Sales, Technical and Plant Manager.

At the Aberdeen Foundry he is in charge of manufacturing, testing and technical specification of Subsea and marine sacrificial anode systems.
CORROSION MITIGATION BY CATHODIC PROTECTION
Corrosion Awareness Day 2017

Nigel Owen, Aberdeen Foundries. Mitigation of Corrosion by Cathodic Protection
Scope

**CORROSION MITIGATION BY CATHODIC PROTECTION**

- Galvanic System
- Materials for Sacrificial Anode Systems
- Manufacture and Testing of sacrificial anodes
- Designing of a CP system to protect a structure
- Applications of Sacrificial Anodes
- The selection of the CP system: pros and cons of sacrificial and Impressed current
- Impressed current applications
To Mitigate Corrosion by Cathodic Protection

• Means by imposing a current on the item of interest which will halt or reduce the corrosion level to one which is insignificant

• How?

• Either by:
  • utilising the galvanic properties of 2 dis-similar metals when joined together in a conductive medium (Anode/Cathode) or
  • Imposing a current using an electrical system (Impressed Current) to achieve similar
Sacrificial Anode System

Sacrificial Anode Cathodic Protection

Protected Structure in Seawater

Aluminium Alloy Anode

O$_2$ + 2H$_2$O $\rightarrow$ 4OH$^-$

Ar$^{3+}$

Ar$^{3+}$

3e$^-$
Primary Requirements for Sacrificial Anode - Reasons for Selection

What makes the best anode material?

• Potential sufficiently electronegative – Galvanic Table vs you coupled material (driving potential)
• Temperature and Conductivity (salinity)
• High current output per Kg consumed
• Low Metal Cost (Amps per Kg)
Sacrificial Anode Material Types

- **Magnesium**
  - High Potential, low life, Fresh water (5-150 ohm. m), High cost/Kg

- **Zinc**
  - Low capacity/ Kg (800), Limited Temp (50 °C), water to 30 ohm. m

- **Aluminium**
  - High Capacity/Kg (2500), High Temp (80-100 °C), water to 10 ohm. m
### Primary Requirements for Sacrificial Anode - Reasons for Selection

<table>
<thead>
<tr>
<th>Al-Zn-In Anode Alloy</th>
<th>Galvallum III</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Element</td>
<td>Al</td>
</tr>
<tr>
<td>Wt%</td>
<td>Min</td>
<td>Bal</td>
</tr>
<tr>
<td>Wt%</td>
<td>Max</td>
<td>Bal</td>
</tr>
<tr>
<td>Wt%</td>
<td>Nom</td>
<td>Bal</td>
</tr>
</tbody>
</table>

**Typical Performance:**
- Nominal closed circuit anode potential: -1050 (mV relative to Ag/AgCl/seawater)
- Short term test Capacity: Ampere hours <2500 Amp. Hr/ Kg
- Density: Nominally 2750kg/m³
• Al-Zn-In Alloying - Base metals

• Al (99.85% min)
  • Fe, Cu, Ga, Sn
  • Ingot Spec PO610

• Zn (99.99%)
  • Fe, Cu, Pb, Sn
  • Ingot SHG

• Indium
  • 99.99%

• Si (Al-Si) - hardener
Manufacturing

• Heat melt – Alloy constituents
• Prepare and manufacture steel insert
• Select & Assemble mould
• Test melt and approve*
• Cast into mould and top up
• Fettle /tidy
• Mark identification on anode

*Melt sample Test piece OES
Melting, Pouring & Finishing

- Melt Base Metal
- Zinc Additions
- Indium Additions
- Add balance of Silicon
- Heat to Molten, stir, prepare
- Sample and Test
  - Spectrometry OES
- Pour
Testing of Anodes

- Composition
- Dimensions (body/insert)
- Cracks / sinks/ finish
- Integrity (porosity/Holes)*
- Insert position
- Shape (straightness/Fit)
- Electrical Continuity
- Electrochemical test
Electrochemical Testing

Secondary test
DNV
- 1 test per 15 Tonnes production importance?

Comparative Test
Set temp
Accelerated (x 20 current density) cannot be used as test of field condition performance

Reliability
Subject to debate – sampling
Multiple test methods

Redundant
Totally Composition dependant
Unrealistic sampling and accelerated parameters
Example of a project to Design install a Sacrificial CP system

• Harbour wall CP protection system
System Parameters

• Design Life: Years or months
• Areas of the materials
  • Bare, Painted & immersed in mud
  • Type of materials.
  • All those conductive and have continuity to the main unit
• Design Current Densities
  • Initial mean and final (for bare surfaces)
    affected by Geographic region and depth
  • Coating Breakdown factors (discounts for coating integrity)
• Resistivity of Medium in which they are immersed: Seawater, Estuarine/River waters soils & muds/ sediment
Design Solution

• Select sacrificial anode material (Al, Zn or Mg base)
  Material has properties of Amp Hr/Kg and Potential

• Multiply areas of materials and Current density required with coating factors –
  Calculate mean current Demand
  Then calculate the Mean mass requirement for system design life

7.7 Anode Mass Calculations

7.7.1 The total net anode mass, $M_a$ (kg), required to maintain cathodic protection throughout the design life, $t_f$ (yrs), is to be calculated from $I_{cm}$ (A) for each unit of the protection object (including any current drain):

$$M_a = \frac{I_{cm} \cdot t_f \cdot 8760}{u \cdot \varepsilon} \quad (2)$$

In (2), 8760 refers to hours per year, $u$ and $\varepsilon$ (Ah/kg) are to be selected based on (6.8) and (6.5), respectively.
### Anode Material Design Properties

<table>
<thead>
<tr>
<th>Anode type</th>
<th>Anode surface temperature (a)</th>
<th>Immersed in seawater</th>
<th>Buried in seawater sediments (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Potential (\text{Ag/AgCl/ seawater})</td>
<td>Electrochemical capacity (\varepsilon)</td>
<td>Potential (\text{Ag/AgCl/ seawater})</td>
</tr>
<tr>
<td></td>
<td>°C</td>
<td>mV</td>
<td>A-h/kg</td>
</tr>
<tr>
<td>Aluminium</td>
<td>&lt; 30</td>
<td>-1050</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>-1050</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>80 (b)</td>
<td>-1000</td>
<td>900</td>
</tr>
<tr>
<td>Zinc</td>
<td>&lt; 30</td>
<td>-1030</td>
<td>780</td>
</tr>
<tr>
<td></td>
<td>&gt; 30 to 50 (c)</td>
<td>-980</td>
<td>580</td>
</tr>
</tbody>
</table>

Electrochemical capacity for a given alloy is a function of temperature and anode current density. Reference is made to Annex A for guidance on CP design for variations in anode current densities.

For non-buried pipelines, the anode surface temperature should be taken as the external pipeline temperature and not the internal fluid temperature. For buried pipelines, the anode surface temperature shall be taken as the internal fluid temperature.

\(a\) For anode surface temperatures between the limits stated, the electrochemical capacity shall be interpolated.

\(b\) For aluminium anodes, the anode surface temperature shall not exceed 80 °C unless the performance has been demonstrated in tests and has been documented.

\(c\) For zinc anodes, the anode surface temperature shall not exceed 50 °C unless satisfactory performance has been demonstrated in tests and has been documented.

\(d\) Pipelines which are rock-dumped shall be considered as buried in seawater sediments.
Anode Type solution

• Decide Type of anodes that can be fitted or will be most practical to fit (Flush fit, Standoff Type, Long or Short, Bracelet?)
• Estimate number, distribution of anodes (spacing/coverage) and anode mount type (position/utilisation factor)
• Proceed with Design

• Calculate anode resistance from shape & mount type
• Check the initial and final current output of the anode types meets the given required current for polarisation and final life
Design Parameters – Anode Resistance for Shape Utilisation Factor

Table 10-7 Recommended Anode Resistance Formulae for CP Design Calculations.

<table>
<thead>
<tr>
<th>Anode Type</th>
<th>Resistance Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long slender stand-off (1, 2) L ≥ 4r</td>
<td>$R_a = \frac{\rho}{2 \cdot \pi \cdot L} (\ln \frac{4 \cdot L}{r} - 1)$</td>
</tr>
<tr>
<td>Short slender stand-off (1, 2) L &lt; 4r</td>
<td>$R_a = \frac{\rho}{2 \cdot \pi \cdot L} \left[ \ln \frac{2r}{L} \left( 1 + \sqrt{1 + \left( \frac{r}{2L} \right)^2} \right) - \frac{r}{2L} - \sqrt{1 + \left( \frac{r}{2L} \right)^2} \right]$</td>
</tr>
<tr>
<td>Long flush mounted (3) L ≥ 4 width and</td>
<td>$R_a = \frac{\rho}{2 \cdot S}$</td>
</tr>
<tr>
<td>L ≥ 4 thickness</td>
<td></td>
</tr>
<tr>
<td>Short flush-mounted, bracelet and other types</td>
<td>$R_a = 0.315 \cdot \rho \cdot \sqrt{A}$</td>
</tr>
</tbody>
</table>

1) The equation is valid for anodes with minimum distance 0.30 m from protection object. For anode-to-object distance less than 0.30 m but minimum 0.15 m the same equation may be applied with a correction factor of 1.3.
2) For non-cylindrical anodes: $r = c/2$ m where $c$ is the anode cross sectional perimeter.

Table 10-8 Recommended Anode Utilisation Factors for CP Design Calculations.

<table>
<thead>
<tr>
<th>Anode Type</th>
<th>Anode Utilisation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long slender stand-off L ≥ 4r</td>
<td>0.90</td>
</tr>
<tr>
<td>Short slender stand-off L &lt; 4r</td>
<td>0.85</td>
</tr>
<tr>
<td>Long flush mounted L ≥ 4 width and</td>
<td>0.85</td>
</tr>
<tr>
<td>L ≥ 4 thickness</td>
<td></td>
</tr>
<tr>
<td>Short flush-mounted, bracelet and other types</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Design Parameters – Anode Resistance for given Shape & Utilisation

- Flush Fit
  - Hull Long flush (UT=0.85)
  - curved segments, Bracelets Short Flush (UT=0.8)

- Standoff
  - Long & Slender (UT=0.9)
  - Massive
Design of Cathodic Protection system

The aim of the CP design is to polarise the structure (period A) as quickly as possible and maintain the protection (period B) for the design life.

When depolarisation (period C) starts the CP system has reached its design life and leads to under protection (period D).
Long stand-off anodes for Harbour wall installation
Corrosion Awareness Day 2017

• Design & Install Anodes

Nigel Owen, Aberdeen Foundries . Mitigation of Corrosion by Cathodic Protection
Corrosion Awareness Day 2017

Jetty Anodes installed
Sacrificial Anode Applications
Corrosion Awareness Day 2017

Sacrificial anodes in Zinc for flush fit (Hulls & steelwork)
Slender Anodes for Subsea Manifold Frame
Manifold Anodes
Corrosion Awareness Day 2017

Nigel Owen, Aberdeen Foundries . Mitigation of Corrosion by Cathodic Protection
Bracelet Anodes for Pipelines & Spools
Retrofit Anodes
Corrosion Awareness Day 2017

Anode Skids for Remote Retrofit of Manifold
Design Parameters may limit the use of Sacrificial Anodes or make them impractical.

- Conductivity / Resistivity of the environment
- Size of the areas to be protected by the system
- Location and water depth
- Availability of Power sources or personnel (operation & monitoring)
- Ability to install
- Design Life of the system   short term submersion or 60 year lifespan

- Impressed Current Cathodic protection can be utilised to cover most other fields of protection.
Sacrificial Protection vs Impressed Current

Sacrificial Anode
- Simple
- Short term (Days to 30 years)
- Low/no maintenance
- Welded, secure installation
- Conductive environments (seawater)
- Restricted by anode material
- No adverse effects on structures, coatings etc
- Doesn’t overprotect

Impressed Current
- Anodes are not consumed (inert)
- Use for long term systems (20-50 yr’s)
- Requires regular maintenance
- Remote anodes & wiring
- Complex - has to be accurately set up
- Works in Low conductivity water areas (& onshore buried pipelines & Concrete)
- Can cause:
  - Coating de-bonding
  - Hydrogen embrittlement of steel piles
  - Cathodic corrosion of Al (hulls etc)
  - Stray current corrosion
Cathodic Protection - Impressed Current Systems

- Steel pipe
- Positive current from anode to pipeline through earth or water
- Anode (usually remote from pipe)
- Ground or water level
- Electrons
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

- MAIN DIFFERENCES BETWEEN SACRIFICIAL (IP) AND IMPRESSED CURRENT (SAC) SYSTEMS
- COMMON APPLICATIONS OF IP SYSTEMS
- COMMON DESIGN FAILINGS OF IP SYSTEMS
- COMMON OPERATIONAL FAILINGS OF IP SYSTEMS
- RECENT INNOVATIONS IN MONITORING IP SYSTEMS
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

CATHODIC PROTECTION – POLARIZATION PRINCIPLE

- 950mV (if Bacteria)
- 500mV

According to Coating Type / Condition

T/R Interrupter’s installed to Measure.

Removes IR Error

Typical Natural value before CP Applied.
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

Mesh for RC concrete and linear anodes for jackets and pipelines.
CATHODIC PROTECTION OVERVIEW
/ IMPRESSED CURRENT SYSTEMS

COMMON APPLICATIONS OF IP SYSTEMS

• LARGE SHIPS, CRUDE OIL TANKERS.
• LONG-DISTANCE PIPELINES.
• HIGHWAYS / BRIDGE FOUNDATIONS.
• LOADING JETTIES.
• BASES OF STORAGE TANKS.
• PROTECTION OF REINFORCED CONCRETE
Corrosion Awareness Day 2017

Typical System components

- Rudder Stock Bonding
- Shaft Earthing Device
- Linear Stripe Anode
- P.S.U. (Power Supply Unit)
- Circular Anode
- R.M.P. (Remote Monitoring Panel)
- Reference Cell
CATHODIC PROTECTION OVERVIEW
/ IMPRESSED CURRENT SYSTEMS

WHITECART VIADUCT GLASGOW
AIRPORT AND TAY ROAD BRIDGE
DUNDEE BOTH HAVE CP –
FOUNDATIONS AND RC
CONCRETE SUPPORTS,
AS DO M9 BRIDGES
Protection of reinforced Concrete
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

TANKS, JETTIES, TANKERS, LARGE SHIPS AND PIPELINES.
COMMON DESIGN FAILINGS OF IP SYSTEMS

• **OVER ESTIMATION OF CP CURRENT REQUIREMENTS.**
• **OVER-SIZING OF POWER SOURCES AND CONTROL UNITS.**
• **LACK OF CONSIDERATION FOR NEIGHBOURING CP SCHEMES.**
• **CP INTERACTION ISSUES.**
• **OVER-PROTECTION OF CRA’S / NON CARBON STEEL ITEMS.**
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

COMMON DESIGN FAILINGS OF IP SYSTEMS

• **Over Estimation of CP Current Requirements.**
• **Lack of Understanding of Modern Coating Performance,** e.g. **Multi-Layer Polypropylene and FBE – Fusion Bonded Epoxy’s.**
• **Current Requirement May be 1 Amp Max.**
• **Design House Then Doubles for Contingency.**
• **Later Client Rep, Doubles Further Amends Spec.**
• **End Result - Transformer Unit is too Powerful and CP Output cannot be Finely Tuned / Controlled To Actual CP Requirement at Site.**
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

SGP / SVT – CP PLANT AND PIPELINES OVERVIEW

LACK OF CONSIDERATION FOR NEIGHBOURING CP SCHEMES AT DESIGN STAGE.
LAYING MODERN PIPELINES FOR CATHODIC PROTECTION

5 x Pipelines
Corrosion Awareness Day 2017

**Sacrificial Anode CP Method**

Sacrificial Anode

\[ \text{Mg} \rightarrow \text{Mg}^{2+} + 2\text{e}^- \]

\[ \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{OH}^- \]

Protected Aluminum structure

\[ E^\circ_{\text{CP}, \text{Mg}} = -1.55 \text{ V vs. SCE} \] (in 0.1 wt% NaCl solution)

\[ E^\circ_{\text{CP}, \text{AA2024}} = -0.5 \text{ V vs. SCE} \] (in 0.1 wt% NaCl solution)

**Impressed Current CP Method**

Negative Return Cable (Structure Connection)

\[ 2\text{e}^- \]

DC Power Source

Insulated Anode Cable

Impressed Current Permanent Anode

\[ \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{OH}^- \]

Protected Aluminum Structure

Current

Nigel Owen, Aberdeen Foundries. Mitigation of Corrosion by Cathodic Protection
OLDER PIPELINES – COATING DIS-BONDMENT ISSUES

A

What can go wrong

External corrosion at dis-bonded coating at Field Joint on buried gas transmission pipeline in bog soil of Germany. Trench with coated carbon steel gas pipeline in waterlogged, anoxic soil. CP cannot not get to areas under Dis-bonded Coatings.

B

Welding site with corrosion pits, (No’s indicate pit depth in mm)

C

Higher magnification of corrosion Pits.
COMMON OPERATIONAL FAILINGS OF IP SYSTEMS

• LOSS OF CP ISOLATION AT PIPELINE ENDS / E.G. GAS TERMINALS.
• ISOLATION FLANGES BONDED OVER BY CLADDING.
• LIGHTENING STRIKES.
• FUSE FAILURES.
• STAFF SWITCHING OFF CP SYSTEM (INTERFERES WITH TELEVISION!).
• CABLE DAMAGE / CABLE THEFT.
• CONTRACTORS DIGGING NEAR PIPELINES.
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

CP INTERFERENCE / DAMAGE – LIGHTENING AND TV.
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

ENSURE ISOLATION JOINTS ARE NOT BRIDGED / SHORTED BY INSULATION CLADDING, OR WILL GET LOSS OF CP
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

RECENT INNOVATIONS IN MONITORING IP SYSTEMS

- **REMOTE DATA COLLECTION (OPERATING CHARACTERISTICS AND PERFORMANCE).**
- **MORE ADVANCED / MORE DURABLE ANODE MATERIALS.**
- **WIDER RANGE OF ANODE TYPES TO SUIT MANY APPLICATIONS.**
- **USE OF DRONES AND HELICOPTERS TO ASSIST CP MONITORING (ESP. OF PIPELINES).**
Cathodic Protection Overview / Impressed Current Systems

Use of Drones for Equipment Monitoring – Transformer Rectifiers Etc.
THE END

More Anodes Please!
THANK YOU FOR YOUR ATTENTION ANY QUESTIONS?
CATHODIC PROTECTION OVERVIEW / IMPRESSED CURRENT SYSTEMS

TEST COUPONS ON PIPELINES TO MEASURE CP VALUES

- Typical cast concrete foundation of site construction and procurement. Actual orientation, layout and size to be finalized on site with respect to local soil conditions and equipment layout.
- 2" NB PVC TUBE
- EMPTY TUBE
- PVC tube
- COUPON CABLE TAIL
- 6 MP2 XLPE/PEWA/PVC 16W LONG TO TEST POST
- CABLE TIPS USED TO RESTRAIN CABLE AT EVERY NOMINAL 500MM INTERVALS
- MILD STEEL COUPON
- EXPOSED SURFACE UNDERNEATH ONLY (OTHER SURFACES OF COUPON TO BE EPoxy COATED)
- STONE FREE NATURAL SOIL
- PIPE INVERT LEVEL
- REQUIRED CP MONITORING FACILITIES AT PIPE INVERT LEVEL TO RECORD IR ERROR FREE CP VALUES.
- CONCRETE POLYMER COATED
- CONNECTION
- PVC SIZE APPROX 50 MM
- SIDE AND ABOVE COUPON SURFACES COATED
- UNDERNEATH COUPON SURFACE SIZE ONLY (APPROX 10 CM).
LAYING MODERN PIPELINES FOR CATHODIC PROTECTION
Corrosion Awareness Day 2017

Nigel Owen, Aberdeen Foundries. Mitigation of Corrosion by Cathodic Protection

Diagram showing cathodic protection of a pipeline. The diagram includes:
- A sacrificial anode (Mg) with the reaction: \( \text{Mg(s) \rightarrow Mg}^{2+}(aq) + 2e^- \)
- A pipeline cathode (Fe) with the reaction: \( O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l) \)

The diagram also shows the flow of electrons and ions in the moist soil.
Corrosion Awareness Day 2017

• **THE END**

• More Anodes Please!
Corrosion Awareness Day 2017

Nigel Owen, Aberdeen Foundries - Mitigation of Corrosion by Cathodic Protection