WES KNOWLEDGE CAPTURE

REPORT

WP3 – Corrosion & Protection

OYKNOW-REP-0002

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1. PURPOSE

Aquamarine Power has been asked by Wave Energy Scotland (WES) to produce a series of informative knowledge sharing reports. The contract is to facilitate knowledge sharing within the wave energy sector. The aim is to realise cost and time efficiencies by sharing knowledge and lessons learnt from previous experience so that other companies do not have to go through an exercise of learning the same costly lessons all over again.

Aquamarine Power has accumulated a wealth of valuable knowledge and learning through the design, fabrication, installation and operation of the Oyster 1 and Oyster 800 devices. Aquamarine Power recognise that knowledge sharing is a central component for the successful and timely deployment of wave energy projects. As such, Aquamarine Power is keen to share this knowledge for the benefit of the wider wave energy community.

There is a series of 5 reports covering different topics from the experience and knowledge that Aquamarine Power has gained. The topics under contract with WES are:

1. Offshore operational experience;
2. Corrosion & protection in a disturbed water environment;
3. Supply chain (marine components);
4. Tank testing of WECs;
5. Maintainability improvements from Oyster 1 to Oyster 800.

This report covers topic 2 – Corrosion & protection in a disturbed water environment, as listed above.

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2. LESSONS LEARNT SUMMARY

1. A combination of Cathodic Protection (CP), coatings and corrosion allowance can provide a cost effective means of protecting offshore structures from corrosion;

2. Be cautious about using dissimilar metals in close proximity as they may be prone to galvanic corrosion;

3. Corrosion protection design for the splash zone can be feasible by using coatings and corrosion allowances for large structures. Smaller local components can be made of more corrosion resistant alloys (CRA);

4. Do not rely on CP to protect seals and sealing faces. Locally protect these areas with corrosion resistant alloys;

5. Different flange and seal combination will require different materials to ensure a leak resistant joint;

6. Anodes should be installed on discrete parts without having to rely on electrical continuity between components in assemblies;

7. A device called a bathycorrometer which uses a principle of stabbing probe circuit can be reliably used to survey CP systems.

3. KNOWLEDGE AND LESSONS

Aquamarine Power has been developing the Oyster technology for a period of 10 years. Aquamarine Power has performed extensive R&D activity and built, installed and operated two prototype machines (Oyster 1 and Oyster 800) and more recently have conducted two consecutive product improvement campaigns targeting areas for improvement from previous ‘lessons learnt’ activities.

Oxygen, biological activities, pollution, temperature, salinity, suspended sediments and velocity are the known major factors which affect the corrosion behaviour of materials submerged in sea water. In this work package Aquamarine Power documents the lessons experienced in design and from the use of standard off-the-shelf components, materials and material grades and material compatibilities in disturbed water environments. There are many common themes which would benefit the wider wave community. The following topics are covered in this report:

1. Corrosion protection of primary structures;
2. Material compatibility;
3. Splash zone effects;
4. Coatings and clad flanges;
5. Flange and gasket combinations;
6. Use and connection of anodes;
7. Development of a reliable CP inspection technique.

3.1 Corrosion Protection of Primary Structure

Lesson Learnt / Knowledge Captured:

A combination of Cathodic Protection (CP), coatings and corrosion allowance can provide a cost effective means of protecting offshore structures from corrosion.

Identified Problem / Challenge:

How to specify corrosion protection requirements for structures that occupy the complete water column.

Potential Issues:

1. Where is CP effective through the water column;
2. Do paint systems offer reliable protection;
3. How to specify corrosion allowance where CP is not effective.

Knowledge & Candidate Solutions:

APL have had a successful approach to corrosion protection on both Oyster 1 and Oyster 800 devices.

APL have subdivided a structure that pierces the water column into five main areas. This categorisation is a simplification of DNV standard DNV-OS-C101.

1. Submerged zone - The area that is fully submerged in water in the majority of wave or tidal conditions. Generally this has been taken as being the zone below Lowest Astronomical Tide (LAT);
2. Atmospheric zone - The area in free air corrosion, the area immediately above the splash zone where the structure is mostly in air and subject to water spray, precipitation and/or condensation;
3. Splash zone - The area in the splash zone is intermittently exposed to air and exposed to the sea;
4. Dry Internal zones – Tanks or internal surfaces not exposed to water;
5. Wet Internal zones – Tanks or internal surfaces partially or periodically exposed to water.

Cathodic Protection (CP) systems use sacrificial anodes made from electrochemically active metals (usually Aluminium or Zinc alloys) that corrode in preference to the primary structure (usually steel). They rely on the surrounding seawater acting as an electrolyte and therefore are effective on submerged structures but cannot be relied upon for structures in the splash zone. Requirements for CP design are provided in, for example, DNV-RP-B401

For large structures the CP design may be supplemented by coating systems in order to decrease the current demand on the CP system and to make the system more cost effective. Requirements for coatings are provided in standards such as DNV-OS-C101, DNV-OS-C401 and in Norsok M-501.

In general Aquamarine Power used the following coating systems from Norsok M-501:

1. Carbon and stainless steel in the submerged zone – Coating system 7B;
2. Carbon and Stainless steel in the splash zone – Coating system 7A;
3. Carbon and Stainless steel in the atmospheric zone – Coating system 7A;
4. Ballast water or internal seawater filled compartments – Coating system 3B.

In areas where CP is unreliable, a corrosion allowance has been made to the structure. These allowances are based on CH2M Hill (Previously Halcrow group Ltd.) engineering experience, guidelines from EEMUA 194 and on DNV standard DNV-OS-C101 and DNV-OSS-J101. These are for a 20 year design life.

1. Submerged zone – 0mm allowance;

2. Atmospheric zone – 0.3mm/year allowance;
3. Splash zone – This zone has been equally divided into to where the upper half has a 0.2mm/year allowance and the lower half a 0.1mm/year allowance;
4. Dry internal zones – 0mm allowance;
5. Wet internal zones – 2mm allowance.

Pictorially this can be visualised in Figure 1 below:

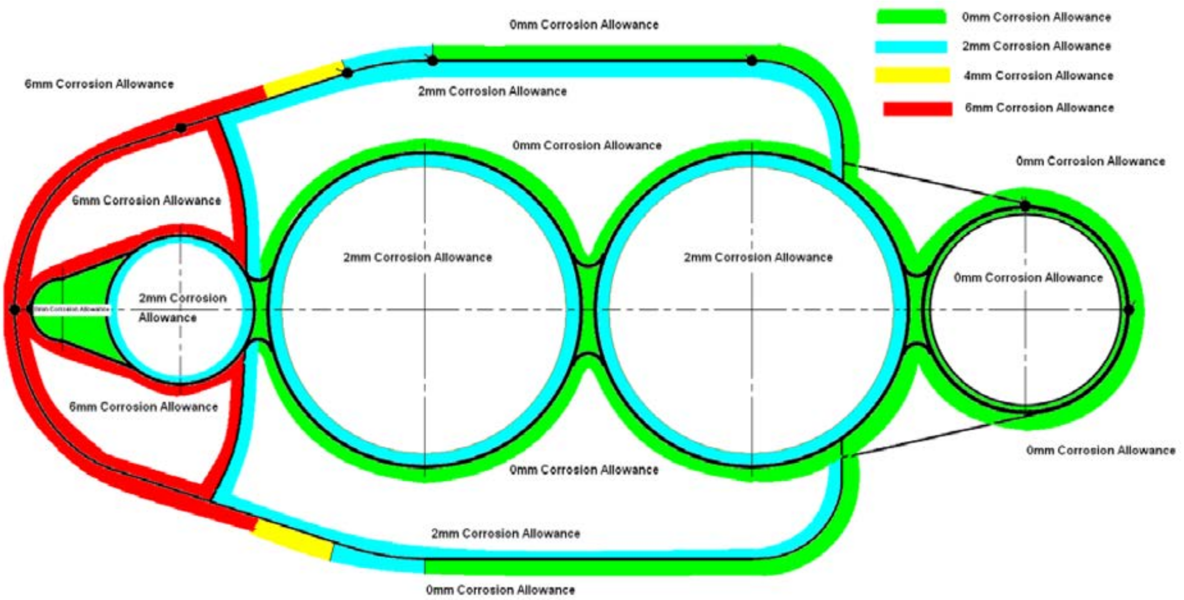

Figure 1 – Diagram of Oyster 800 flap corrosion allowance

There is a risk to the use of high strength steel components due to hydrogen induced stress corrosion (HISC). On a large, complex offshore structure it can be hard to guarantee electrical isolation of a component from the CP system and that this can lead to problems with supply of equipment containing high strength materials. Further notes on the topic can be found in report OYKNOW-REP-0003 – WES Knowledge Capture – WP4 Supply Chain.

3.2 Material Compatibility

Lesson Learnt / Knowledge Captured:

Be cautious about using dissimilar metals in close proximity as they may be prone to galvanic corrosion.

Identified Problem / Challenges:

Corrosion between two different types of metals

Potential Root Causes:

1. Galvanic corrosion between dissimilar metals;
2. Loss of CP between metals.

Knowledge & Candidate Solutions:

Oyster has used a large variety of metals in a range of different applications such as structural elements, hydraulic components, communications cables and connectors, etc. In general where the electro-potential differences are low there is no issue with galvanic corrosion. However there are exceptions.

Galvanic corrosion has been an issue in items where connection to a CP has been lost or not provided. For example on bolted connections where a stainless steel ground anchor or fastener is used to hold a carbon steel component. The carbon steel component preferentially corrodes causing a gap to be created between the component and the fastener. This causes the fastener to lose its pre-load and may lead failure of the bolted joint.

A common place where galvanic corrosion can be evident is on sealing faces. Figure 2 shows a 316ss pressure transducer with severe galvanic corrosion due to a copper seal being used. It is very common to use a softer seal to hydraulically seal a component as some seals require plastic deformation seal. In this instance copper has a potential of -0.3V whereas 316 has a potential of -0.1V.

There are ways of avoiding galvanic corrosion from occurring, these include:

- Avoid the use of dissimilar metals in electrical contact;
- If dissimilar metals are required, select materials with a low electro-potential difference;
- Use insulating material between the metals to avoid an electrical connection;
- When fully submerged, a CP system offers an ideal way of avoiding galvanic corrosion. The sacrificial anodes in the CP system preferentially corrode as they tend to be much more anodic than other metals used.

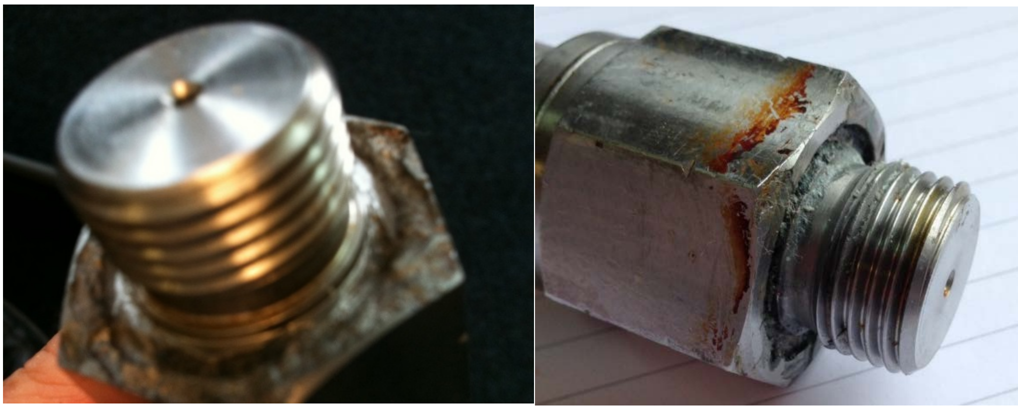

Figure 2 – 316ss pressure transducer showing galvanic corrosion on the sealing face where a copper seal was used.

3.3 Splash Zone Effects

Lesson Learnt / Knowledge Captured:

Corrosion protection design for the splash zone can be feasible by using coatings and corrosion allowances for large structures. Smaller local components can be made of more corrosion resistant alloys.

Identified Problem / Challenges:

How to protect components in the splash zone where CP is not reliable.

Knowledge & Candidate Solutions:

The splash zone is an area defined by the area below mean sea level (MSL) and lowest astronomical tide (LAT). This area is intermittently exposed to air and immersed in the sea. Due to this, it is an area where CP is not reliable. This is also an area with high agitation and oxygenation that may lead to higher levels of free corrosion.

The splash zone makes it difficult to design metallic components sensitive to fatigue due to the higher corrosion exposure in the area. The approach at Aquamarine Power has been to use a SN curve in free corrosion which severely downgrades the strength of the steel (DNVGL-RP-0005). In conjunction, the steel is also coated with a suitable coating and a corrosion allowance is added to allow for free corrosion due to CP not being reliable in this area.

Arguably, when using a suitable coating, it is possible to use an SN curve of a steel in air due to the fact that the metal is protected from the water and sea spray. However, this relies on the coating being robust and maintained.

The use of high strength steels in this area has to be considered with due care. A high strength SN curve may be used for steels with a yield strength larger than 500MPa, however, these steels are susceptible to hydrogen induced stress corrosion (HISC) which is discussed in report OYKNOW-REP-0003 – WES Knowledge Capture – WP4 Supply Chain.

316ss can suffer from pitting and crevice corrosion and is particularly prevalent in stagnant water. In the splash zone, the water is highly agitated and oxygenated and Aquamarine Power have observed 316ss performing better in this environment. If this can be proven, it would provide a cheaper alternative to using more expensive corrosion resistant alloys (CRAs) or “exotics” such as duplex, super duplex and Inconel.

3.4 Coatings and Clad Flanges

Lesson Learnt / Knowledge Captured:

Do not rely on CP to protect seals and sealing faces. Locally protecting these areas with corrosion resistant alloys can be a cost effective solution.

Using carbon steel pipes with a HDPE liner and corrosion resistant alloy end fittings is a cost effective solution for protecting long lengths of pipeline.

Identified Problem / Challenge:

- Leaks in flanges due to corrosion.
- Protection of pipelines from corrosion

Knowledge & Candidate Solutions:

A few pipes and flanges have been recovered from the Oyster 800 project which showed corrosion of the seals and sealing faces on some flanges. The majority of these had been observed in carbon steel pipes with 316 stainless steel seal rings.

The corrosion process observed that was galvanic corrosion due to the difference in potential of the two metals. The pipes had been connected to the CP system, however, due to the geometry around the seals, this creates a nucleus for crevice corrosion where CP is not reliable.

A relatively cheap carbon steel pipe could be protected at these critical areas by using CRA cladding on the sealing faces. Cladding involves cutting away the parent material and overlaying a new weld of material to reform the original geometry. Aquamarine Power have generally adopted the use of Inconel 625 as the CRA material. Figure 3 shows two typical details for CRA cladding on two different types of flanges; hub type flange and a ring joint flange.

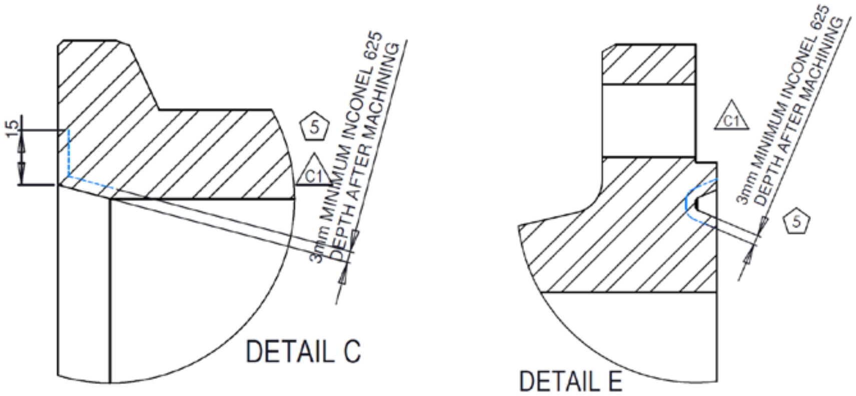

Figure 3 – Cladding details on carbon steel seal flanges. Left: Hub type flange connection. Right: Ring type joint flange connection

The seals have generally been protected by changing to a CRA material. The section below discusses various considerations to be made with different types of sealing faces and parent materials.

Critical pipelines such as the Oyster high pressure return line to shore are permanently installed and maintenance of the pipelines is not possible. In order for the pipeline to survive the full 20 year life, corrosion was considered in the choice of materials. It is possible to fabricate the entire pipeline from CRA material, however this is cost prohibitive. Instead the following approach was taken to address the various design considerations:

- Exterior protection of pipeline to external corrosion - Addressed by using a combination of a 3 layer polypropylene coating in combination with CP.
- External protection of pipeline welds to external corrosion – The pipeline was assembled on land with field welding and pushed through a directionally drilled hole.

To avoid excessive drain on the CP system, the welds where protected by using field coatings based on polypropylene.

- Internal protection to accidental levels of working fluid salinity – Addressed by using a HDPE liner tension pulled into the carbon steel pipe providing an interference fit.
- Protection to welded joints from internal corrosion – The welds between the steel pipes are susceptible to corrosion. Certain joints have been designed to allow the internal liner to be fusion joined and the carbon steel pipe welded in place. A proprietary solution called Swagelining Weldlink has been used at Aquamarine Power (more detail in Figure 5). This involves the two end pieces being machined back and inlayed with a CRA. Castellations are machined into the CRA inlay and a compression ring is added to compress the HDPE liner onto the castellation providing a leak free connection. The pipe is then welded together leaving no corrosion prone surface exposed.
- Internal protection of the end fittings from internal corrosion – The flange end fittings were protected using CRA cladding all along the internal surfaces of the flange as well as the sealing face. A compression ring was then used to mechanically seal the cladding and the HDPE liner from the main pipeline together and then welded similar to the Swagelining Weldlink solution. Details can be seen in Figure 4. This solution is commonly used in the subsea oil and gas industry.

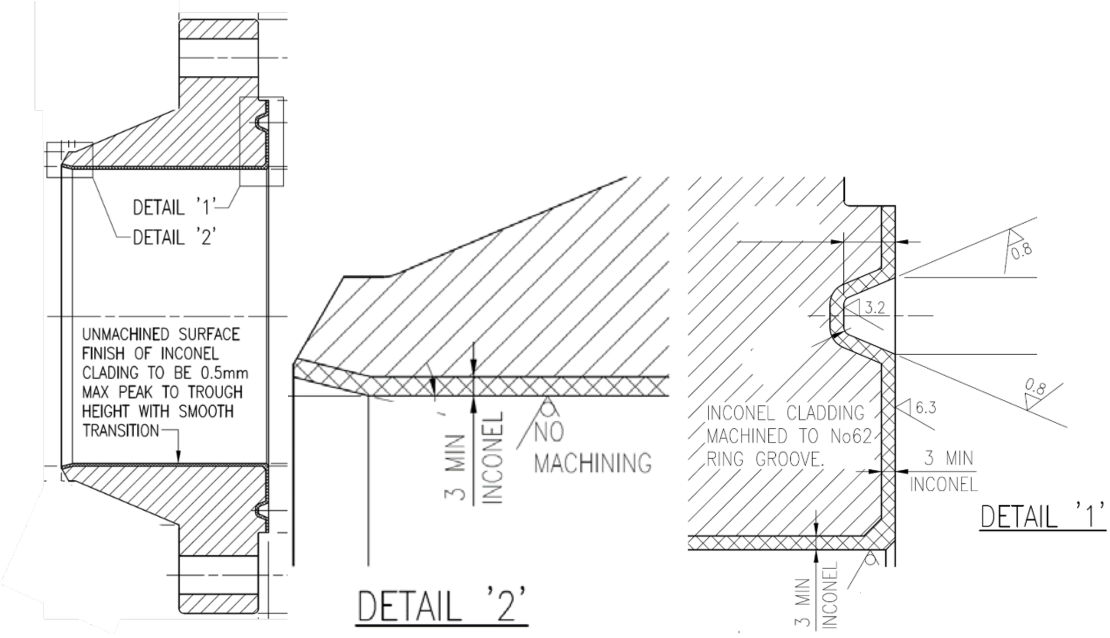

Figure 4 – Details of CRA cladding on Oyster 800 HP pipeline.

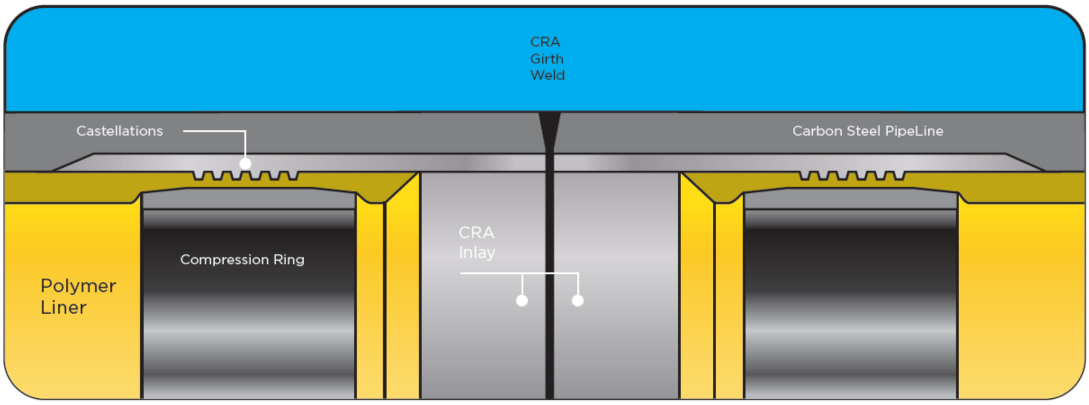

Figure 5 – Swagelining Weldlink proprietary corrosion resistant pipe joining solution

3.5 Flanges and Gasket Combinations

Lesson Learnt / Knowledge Captured:

Different flange and seal combination will require different materials to ensure a leak resistant joint.

Identified Problem / Challenge:

Dissimilar metal combinations at flanges can lead to localised corrosion on the flange sealing face/gasket. Stainless Steel 316 is susceptible to crevice corrosion. Metal gaskets between High Density Polyethylene (HDPE) and Glass reinforced Epoxy (GRE) flanges are electrically isolated.

Knowledge & Candidate Solutions:

There are a wide variety of flanges and materials that may be used in a pipeline system. This section will discuss both metallic flanges (Carbon steel and Duplex) and non-metallic (HDPE and GRE).

Flange types discussed are Flat Face (FF), Raised Face (RF) and Ring Type Joint (RTJ) as seen in Figure 6 below and are typical in water hydraulics applications:

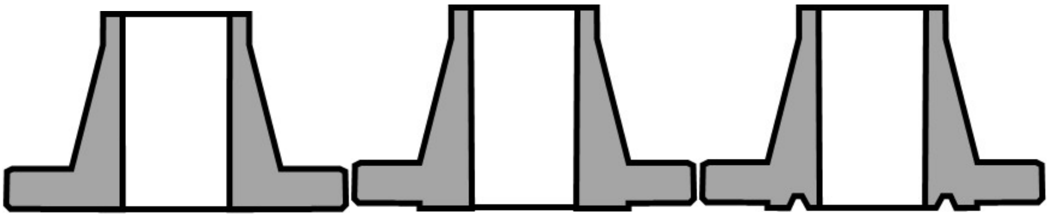

Figure 6 – Flange Types from Left to Right; FF, RF and RTJ

Typically FF and RF flanges are used for low pressure systems. On Oyster 800, these flanges have been used in combination with combination of non-metallic to metallic pipes, as well as non-metallic to non-metallic. The type of gasket used has been Spiral Wound Gaskets (SWG) due to their flat shape and suitability for these flange geometries.

Due to the insulating properties between non-metallic flanges CP is not a reliable protection method for the sealing material. A CRA is required for the SWG gasket. Aquamarine Power have typically chosen to use Duplex S2205 due to its good corrosion resistance, availability as a gasket material and modest price for a CRA. A preferred solution has been to use EPDM profile gaskets as they are much more cost effective and avoids corrosion issues altogether. The EPDM profile gasket contain a steel ring which is covered with rubber, and have a bulbous section around their inner diameter which acts as the sealing face. More common rubber gaskets have proven to be unreliable due to their difficulty in installing correctly, they tend to deform and slip out allowing leaks to develop in the joint.

For higher pressure systems, generally a metallic pipeline is required. For a robust sealing face an RTJ type flange is used. Generally the gasket tends to be of a softer more malleable material than the flange in order for the seal to deform into shape around the groove. This stops the flange face from being damaged and if the joint needs to be opened, only the gasket requires replacing.

The following material combinations have been used on Oyster 800.

- Uncoated carbon steel flanges can be used, providing the gasket material is of a greater electrochemical resistance than the carbon steel. In this case, the cell created with the carbon steel flange surface acts as a large anode to the gasket. Examples of suitable gasket materials are Duplex.
- Stainless Steel 316 pipework has reasonable corrosion resistance, but is not an ideal material for water hydraulic PTO pipework. The flange sealing faces and pipe welds are susceptible to crevice corrosion. Crevice corrosion occurs in stagnant water where

corrosion cells develop and chloride build up can occur, an example can be seen in Figure 7 below.

- Duplex pipework is a lower technical risk, due to it not being as susceptible to crevice corrosion and does not require internal coating. To avoid similarities in material ductility and to maintain the same corrosion resistance properties a 6M0-SS (F44) has been used.

Figure 7 – Crevice corrosion on a 316ss Spacer piece to due to internal seawater in pipeline system.

3.6 Use and Connection of Anodes

Lesson learnt / Knowledge Captured:

Where practicable anodes should be installed on individual parts without having to rely on electrical continuity between components in assemblies.

Identified Problem / Challenge:

Unexpected corrosion of discrete parts or components attached to the main structure

Potential Root Causes:

1. Loss of CP connection due to inadequate connection methods;
2. Unreliable CP due to isolating materials being used.

Knowledge & Candidate Solutions:

Throughout the Oyster 800 device, a number of components or individual parts, attached to the main structure were observed to have corroded. Part of the issue has been inadvertent isolation from the CP system through use of paint under bolts, rubber seals or bearings. In Oyster 800 the main cause has been the failure of continuity cables. The following list highlights some of the causes for cables failure:

- Brittle materials used, in particular soldering/welding of the cable to the connection point;
- Long unsupported spans of cable, which are subject to repeated movement in the wave environment;
- Kelp growth tangling on cables and wave loading imparting larger forces on the cables.

The following design features have been implemented to continuity cables with a larger degree of success (can also be seen in Figure 8):

- Change of solid copper/steel cables to a steel weave. This made the cable much more flexible and less prone to fail at the end connection;
- Use of crimping for end connections rather than soldering into a machined block;
- Minimise cable length by shortening the span between connection points;
- Use bolting techniques to secure the end connections rather than relying on brittle subsea welds.

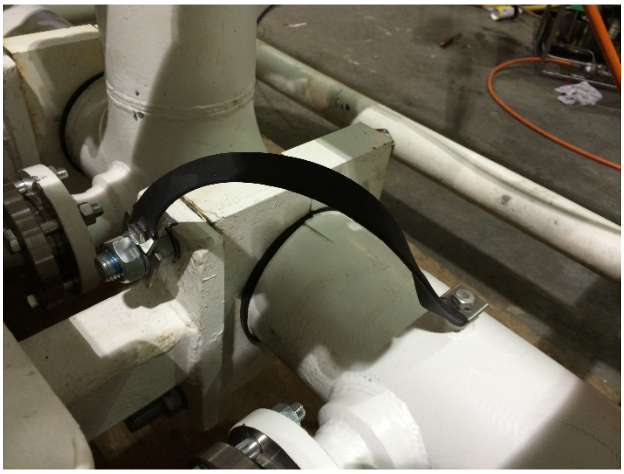

Figure 8 – Example of good continuity cable design. Short span, flexible wire weave, plastic protection around weave, crimped ends bolted to parent components.

Continuity cables have been used to electrically connect components isolated through paints, coatings or dielectric materials (e.g. GRE, HDPE, rubber). This often created a long span between connection points and, with the issues highlighted above, did not provide a reliable CP connection. To mitigate this, any new part being installed or refurbished would have to have an anode on each discrete part, an example is highlighted in Figure 9 below.

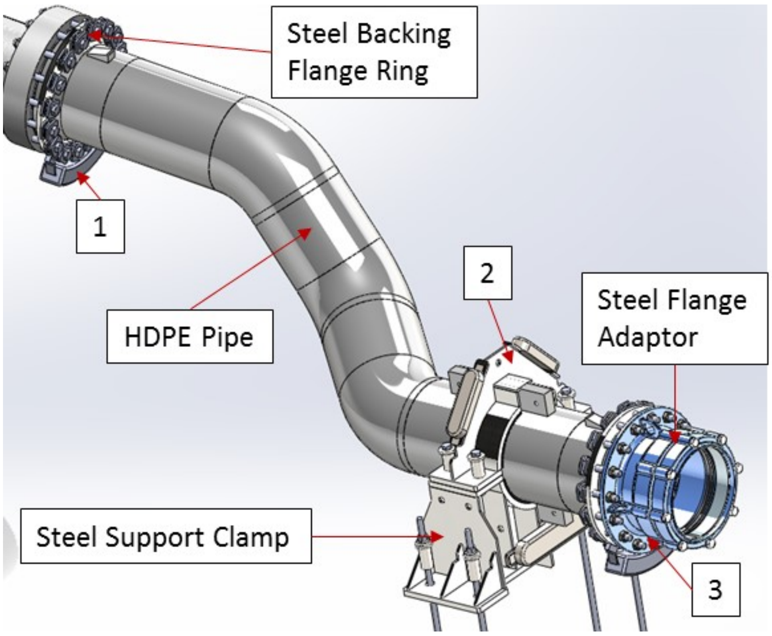

Figure 9 - Example of discrete components with anodes on each part

1. Steel backing ring with anode to avoid using a continuity strap due to long distance away from next anode;

2. Steel top clamp installed subsea with anodes. This is due to the unreliability of ensuring CP continuity through a bolted connection with insulating components in the path such as rubber linings in the clamp and the HDPE pipe itself being clamped;

3. Steel flange adaptor with an anode to avoid directly relying on CP from the steel backing ring due to painted interface at the bolted connection on the adaptor.

3.7 Development of a Reliable CP Inspection Technique

Lesson Learnt / Knowledge Captured:

A device called a bathycorrometer which uses a principle of stabbing probe circuit can be reliably used to survey CP systems.

Identified Problem / Challenge:

How to achieve reliable potential readings to determine the effectiveness of CP systems subsea.

Knowledge & Candidate Solutions:

Aquamarine Power have used two different method to survey cathodic protection (CP) to varying degrees of success. The two methods are:

1. Proximity probe circuit (PPC) – half an electrochemical cell probe connected to a multi-meter and hardwire earth connection to structure being surveyed;
2. Stabbing probe circuit (SPC) – half cell electrochemical cell within a housing connected to a hard tip through a multi-meter.

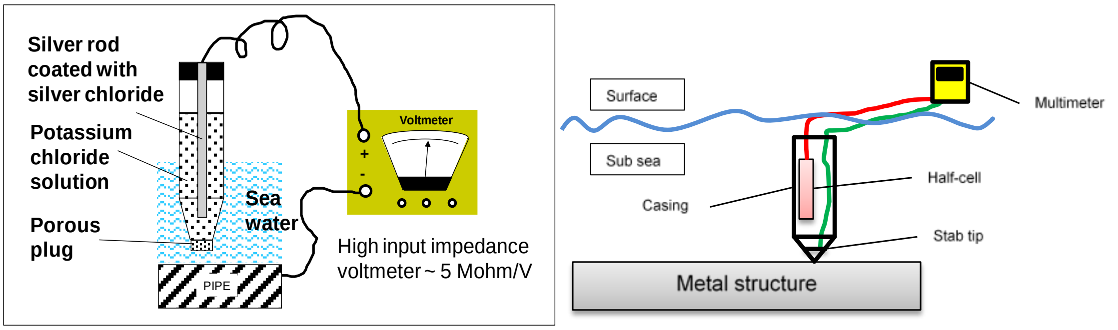

Figure 10 – Left – Proximity probe circuit. Right – Stabbing probe circuit

The use of the PPC in conjunction with divers has been of limited benefit. Although cheap, it requires a lot of dive time to connect the earth back to the surveyed structure and relies on accurate communication of meter readings.

The SPC method has proven to be much more reliable and easy to use, albeit with a slightly higher initial cost required to purchase or hire the necessary equipment. An integrated SPC device is often called a Bathycorrometer (BCM).

Figure 11 – BCM used by Aquamarine Power

A BCM works by measuring the potential difference between its onboard silver/silver chloride reference electrode and a target component or area on the subsea structure. Electrical contact between the on board electrode and the target component is achieved by pressing the BCM tip against the target component through any protective coating. If the potential difference is less than 0.8V then the component is not sufficiently protected. If the value is greater than 1.1V the component is overprotected.

Tips for good use:

1. Press the tip hard against the part to ensure that good electrical contact is achieved;
2. You will know when you have achieved good contact because the value on the BCM will remain very steady (if the contact is poor than the value jumps around). Use a steel brush to remove surface corrosion if the contact is poor and try reading again;
3. The anodes should give a steady value of around 1.03V to 1.05V. Everything connected to the anode should read around about the same but the values will drop the further you move away from the anode;
4. If the value is below 0.8V then the part is not sufficiently protected by the anode. If the value is greater than 1.1V then the protection is excessive (source for limiting values www.buckleys.co.uk).