WES KNOWLEDGE CAPTURE

REPORT

WP4 – Supply Chain

OYKNOW-REP-0003

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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 3 – Supply Chain, as listed above.

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2. LESSONS LEARNT / KNOWLEDGE CAPTURE SUMMARY

1. Supply of components labelled as subsea not to be taken at face value.
2. Metal shelled connectors have proven to be a reliable subsea connector for the near shore environment.
3. Standardisation of communications protocols across the system provides the most options for improved reliability and scalability of the control and instrumentation system.
4. Design and manufacture of cables to be considered for subsea use.
5. Appropriate selection of valve supplier with suitable experience in the nearshore environment. Thorough Factory Acceptance Tests (FAT) required for supplied components.
6. 316 stainless steel is not suitable as a reliable corrosion resistant alloy in seawater without Cathodic Protection (CP). 316 may be used in conjunction with a reliable CP system.
7. General awareness of hydrogen induced stress corrosion (HISC) and ensuring that suppliers are also aware of this issue. Generally advised to have a high and low tolerance when specifying material grades.

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.

Aquamarine Power has suffered from poor component supply. Many of these components have been purchased on the understanding that they are fit for use in subsea marine environments. A number of these components were not bespoke and may be considered by a number of wave developers.

In addition, Aquamarine Power's experience of the supply chain is varied. Often Aquamarine Power has had to choose between expensive 'oil and gas' components that were over specified and overpriced and the other extreme where the costs were more palatable but the product didn't meet Aquamarine Power's overall requirements. This package of work documents real examples of lessons which can be disseminated to the wider wave community. The following topics are covered in this report:

1. Accumulator Supply;
2. Control and instrumentation equipment including connectors;
3. Cables;
4. Isolation (ball) valves;
5. 316 stainless steel components e.g. needle valves;
6. High strength components (Hydrogen induced embrittlement).

3.1 Accumulator Supply

Lesson Learnt / Knowledge Captured

Supply of components labelled as subsea not to be taken at face value.

Identified Problem / Challenges:

Several issues with corrosion on “subsea rated” components.

Potential Root Causes:

1. Inadequate use of material for subsea seawater use;
2. Inadequate means of achieving reliable CP connection;
3. Inadequate material compatibilities leading to galvanic corrosion.

Knowledge & Candidate Solutions:

Aquamarine Power have previously purchased accumulators from a reputable and experience supplier in the understanding that they had been designed for subsea use. Upon a short period of operation on the Oyster 800 device, the majority of the accumulators had leaked their nitrogen gas from the bladders. Detailed inspections founds several critical design flaws which led to the gas escaping mostly stemming from poor corrosion protection design.

The majority of the issues where located on the top of the accumulators where the bladder interfaces onto the bottle. This is a small area where it is challenging to attach a reliable means of cathodic protection (CP) without having to reply on a connection strap (known to fail).

Without reliable CP, the following design flaws took over. The materials used where not subsea rated, 316Ti stainless steel (316 with titanium added). See Section 3.5 for more information on 316 suitability. The material had pitted and crevice corrosion was observed within a few months of deployment, this had a direct path to the nitrogen bladder.

The largest fault was the introduction of an aluminium name plate between a locking nut and the bottle, see figure 1 below. Without any CP to level the corrosion potential, the aluminium name plate acted as an anode to the rest of the bottle and fizzed away entirely. This is due to aluminium being far from the galvanic potential compared to 316. This left a substantial gap between the locking nut and the bottle with a direct path to the system fluid. Details of the connection where not known prior to installation, and as the supplier was a reputable supplier of subsea equipment, this was not checked.

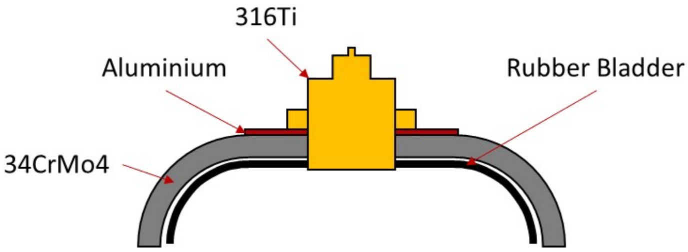


Figure 1 – Detail on top of accumulator bottle supplied leading to galvanic corrosion

The bottle came with a specialised coating system. The coating spec is not within the recommended practices in Norsok M501 and did not offer protection to areas where CP was not accessible or where the throw on the anode was not sufficient.

Aquamarine Power worked with the supplier to improve the accumulator bottle design suitable for the nearshore subsea use. New designs now have an adequate coating system that cover sharp corners with the addition of sealing material to ensure water does not get stagnated in those areas.

A similar issue was apparent in the internal coating. Although the working fluid on Oyster is potable water with additives, the carbon steel on the bottles could still corrode. A nickel plating was added to mitigate this.

3.2 Control and Instrumentation Equipment

3.2.1 Subsea Connectors

Lesson Learnt / Knowledge Captured:

Metal shelled wet mate connectors for instrumentation systems appear to be fit for purpose and resolve various issues associated with a rubber moulded design.

Identified Problem / Challenges:

Aquamarine Power has experienced a number of problems with the rubber moulded wet-mate connectors which were selected for the original installation of the Oyster 800 control and instrumentation (C&I) system. The rubber moulded connectors used on the Oyster 800 failed when wet mated, despite correct instructions for greasing being followed. On Oyster 800, 48% of reported instrumentation failures were caused by rubber moulded connector failures which are marketed and sold by suppliers as subsea mate-able when in fact they are not.

Potential Root Causes:

1. Corroded pins (as seen in Figure 2);
2. Wave loading on cables, leading to sea water ingress where the rubber mouldings was insufficient to maintain a seal;
3. Bent pins – no keyway for alignment;
4. Leaks into Junction Boxes;
5. Brittle Plastic Bodies;
6. Loose Locking Sleeves;
7. Corrosion (304 stainless steel and Brass);
8. Alignment of connector pins;
9. Cable damage / shearing where it joins connector (low integrity neoprene cables).

Knowledge & Candidate Solutions:

Aquamarine Power have identified three different types of subsea connectors available on the market. These are summarised in Table 1.

Oil-filled connectors offer the best solution technically, however, their high cost make them unfeasible for projects involving a large amount of instruments. A compromise solution are the metal shelled connectors which offer a half-way house between the two other designs.

Since 2012, Aquamarine Power has been using metal-shelled connectors with a high degree of success. The following root causes have been addressed:

1. Pin corrosion has not been evident since their introduction to the system in 2012.
2. The coned scooped connection makes bending pins a lot harder, the connectors can be handled rougher by divers. A single pin was noticed to be bent but the connector still works well.
3. The metal shell makes the connector significantly more robust to damage and hence harder for water to leak in the connecting box.
4. Robust metal shelled bodies
5. Able to torque connectors tightly with controlled tightening procedure
6. Connectors come in a variety of corrosion resistant materials such as; Titanium, duplex and Nickel Aluminium Bronze (NAB). NAB was chosen by APL due to lower cost and have since proven to be reliable with CP. Without CP, there can be instances of crevice corrosion due to the geometry on the locking threads.
7. Connectors come with a keyway making it only possible to attach one way. Design is also recessed and scooped so pins do not get damaged when attempting to connect.
8. Only high integrity polyurethane cables are used. An over-moulded rubber end-bell with bend stiffener protects the end from straining.

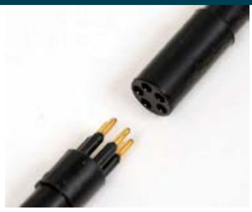
Range of Connector	Rubber-moulded	Metal-shelled	Oil-filled
Image			 
Suppliers (Location)	MacArtney (Denmark) Seacon (UK) Scorpion Oceanics (UK) (These 3 in fact all supply a range of connectors which are compatible (inter-matable) with Subconn's)	Seacon (UK) Scorpion Oceanics (Souriau) (France, UK distributor) Bowtech (same connectors as Seacon) Gisma (Germany) Teledyne (USA) MacArtney (API connectors range, Denmark)	Expro Group (DigiTron connector, have a UK office) Gisma (Germany) Teledyne (USA) Seacon (UK) Souriau (France, UK distributor)
Price range (order of magnitude per single connector half)	£100	£500	£2000
Notes	This is what Aquamarine Power used originally on Oyster 800. Alternative supplier's products unlikely to perform significantly better.	Positive experience of using this grade of connector has been reported from a tidal energy developer. Aquamarine Power has shown positive experience with this type of connector following testing on Oyster 800. This seems to have resolved the pin corrosion issue. This grade of connector tends to come tested to a number of wet-mate cycles (typically 200-500).	Oil bath allows pressure balance, washes the pins as they are assembled, and protects the sliding contact surfaces. This would probably give the best chance of resolving the pin corrosion issues. These connectors tend to be very large for a given number and size of pin. In addition they have large mating forces (circa 500N). These connectors tend to come with a 25-year design life, and tested to a number of mate-de-mate cycles (typically 500)

Table 1 – Summary of subsea connectors available

Figure 2 – Example of pin corrosion on a rubber moulded connector

3.2.2 Input/output (I/O) cards

Lesson Learnt / Knowledge Capture:

Standardisation of communications protocols across the system provides the most options for improved reliability and scalability of the control and instrumentation (C&I) system.

Identified Problem / Challenge:

IO cards for both digital and analogue communications gave reliability and integration issues. Multiple failures occurred across the system.

Potential Root Causes:

The original implementation of the offshore C&I system used bespoke open board PCBs. This was due to the fact that the supplier selected design and manufacture their own bespoke PCBs. The following problems have been observed:

- Don't meet any international standards for shock and vibration;
- Are not IP rated;
- Do not use industry standard communications protocols;
- Have a fixed number of inputs and outputs (are not expandable, a whole new board must be purchased for one more input, for example);
- Are not off-the-shelf components and have a long lead time;
- Are much more expensive than the equivalent off-the-shelf supplier equipment;
- The A-D conversion is only 12 bits.

Knowledge & Candidate Solutions:

All instruments are analog at the point where they take their readings, but at some point the analog signal from the instrument must be converted to a digital signal so that it can be processed or displayed on a computer. In a digital instrument this analog to digital conversion happens inside the instrument itself. Such instruments are called 'smart instruments' to differentiate them from simple digital instruments that are just switches that have an on/off binary digital signal. In many industries and applications, smart instruments are now the norm. Such instruments normally communicate directly to the control system over an industrial standard field bus such as PROFI-BUS, DeviceNet or PROFI-NET.

The Oyster 800 C&I system uses mostly analog instruments. The analog signals are carried on cables back to the junction boxes where the A-D conversion is done on open PCB IO cards. Smart instruments have the following advantages over analog instruments:

1. Smart instruments allow for field buses, which have less cabling than analog signal systems, this is an advantage in terms of time that it takes to wire them up and the number of possible failure locations;

2. Analog signals may attenuate (voltage signals only) or pick up electro-magnetic noise when they are transmitted down a cable, before the A-D conversion. This attenuation or noise will appear as a signal distortion or inaccuracy in the instrument reading, but cannot be identified separately from the instrument reading. Digital signals do not suffer from attenuation and are much less vulnerable to electro-magnetic noise. If, by some unusual circumstance, a digital signal is corrupted by electro-magnetic noise, this corruption can be detected;

3. Smart instruments normally have additional diagnostic (and even configuration) features such that they are able to report their 'health' via a status byte;

4. The A-D conversion on board an instrument normally provides a significantly higher bit-rate to the A-D conversion than can be provided by a common IO board that is converting many signals. This means that signals from smart instruments have a higher resolution and accuracy.

Part of making the offshore C&I more robust has been to move away from bespoke to industry standard (as seen in Figure 3), robust components that have remote diagnostic functions and self-healing type circuit protection. Beckhoff was chosen as the preferred supplier (ABB, Siemens, Allen-Bradley etc. all offer similar hardware) primarily because they have the widest range of IP 67 rated equipment and their software and excellent support services. The EtherCAT protocol, that is native to the Beckhoff hardware, allows a full flexibility of architecture including meshes and daisy chains. Beckhoff hardware is not limited only to EtherCAT communication, but can use any standard industrial protocol e.g. modbus TCP/IP, deviceNet, PROFINET etc.

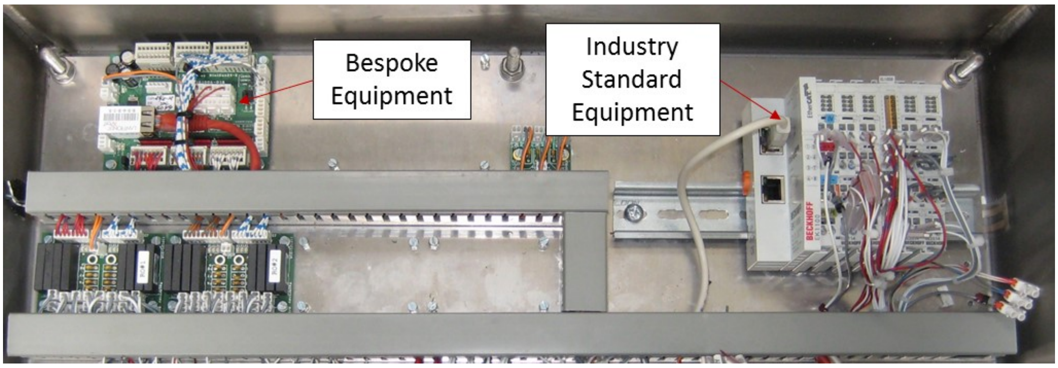


Figure 3 – Picture showing bespoke versus industry standard equipment

3.3 Cables

Lesson Learnt / Knowledge Capture:

Design and manufacture of cables to be considered for subsea use.

Identified Problem / Challenge:

Loss of data due to cables abrading, severing, straining and/or crushed.

Root Causes:

1. Poor selection of materials provided as subsea cables;
2. Inadequate construction;
3. Inadequate design;
4. Inadequate protection.

Knowledge & Candidate Solutions:

APL have worked closely with certain cable manufactures to come up with a suitable design for subsea cables. Different environments require different requirements and hence a standard cable for subsea applications is not available off the shelf, there are various types of cables that may be suitable for certain applications. The following characteristics have been outlined to be considered when selecting or designing cables:

- Polyurethane outer jackets were successful;
- Cables which are to be pulled in should contain an adequate strength member such as Vectran or Kevlar;
- Cables which are expected to see significant impact loads should not be exposed, however exposed sections should incorporate protection within the design. A double jacket with steel wire armour was found to be an adequate way of achieving this;
- Cables with long cable lengths should terminate at wet mate connectors. Fixed connections to junction boxes or instruments (flying leads) are adequate over short lengths (max 10 m);
- Inner and outer jackets should be of different colours so that any damage to the outer jacket is easily identifiable. The inner jacket provides protection from water ingress whilst the outer can serve as a sacrificial abrasive layer;
- Different coloured jackets are an adequate way of providing each cable with a unique feature which can be identified by a subsea diver;
- Cable assemblies with a mixture of fibre optic and copper cores should have the fibre optic bundle located along the centre of the cable. This is to minimise strain on the fragile fibre optics. The fibre optics should be bundled and contained in a sealed metal tube;
- Ensure all junction boxes, cables and instruments are tested independently and together as far as possible and against testing requirements prior to installation;
- Ensure appropriate bend radii for the application;
- Minimise the amount of excess cabling by measuring paths on CAD and verifying during installation. Design in appropriate cable management solutions.

Figure 4 – Example of failed cable

3.4 Isolation Valves

Lesson Learnt / Knowledge Capture:

Appropriate selection of valve supplier with suitable experience in the nearshore environment. Thorough FAT required for supplied components.

Identified Problem / Challenge:

Several of the Oyster 800 subsea isolation valves have been observed with severe quality issues which has caused downtime or unexpected maintenance of the system.

Root Causes:

1. Valve supplier used a third party manufacturer to supply valves;
2. Valve supply from China with severe defects in product;
3. Valves supplied not to specification;
4. Supplier attended FAT but did not catch any of the defects;
5. Valve design not appropriate for subsea use.

Knowledge & Candidate Solutions:

Several issues were identified with the supply of isolation valves for the Oyster 800 project. The primary issues was the naivety of the supplier providing a valve that was “off the shelf” and attempted to marinise it for subsea use. A combination of a lack of experience in the nearshore environment and an attempt to keep away from cost prohibitive oil and gas products led to a design that was unsuitable. Some of the design issues are highlighted below:

- Use of fire safety seals which contain Carbon, these can increase the galvanic corrosion with the parent material and lead to sealing degradation;
- Single seal design instead of the double sealing approach on static seals;
- Use of 316 stainless steel bolts without CP, unsuitable for subsea use.

To mitigate these issues, a supplier with experience in the supply of components for the nearshore environment is desirable. Failing that, closer collaboration is required to get the supplier up to speed with issues.

The second issue originated from the supplier having chosen to use a third party manufacturer based in China. Due to schedule and resource constraints, the supplier attended the factory acceptance test (FAT) of the valves on behalf of Aquamarine Power and did not highlight any major concerns with the valves supplied. With the benefit of hindsight it may have been beneficial if personnel from Aquamarine Power had attended the FAT also as they would have picked up on some of the quality and technical issues which became apparent subsequently. Upon receipt of the valves and through operation a number of issues where recorded and are detailed below:

- Large cracks in the parent material around sealing grooves (as seen in Figure 5);
- Valve actuators were not to the catalogue specification which had been sold to APL, these required additional components to be procured to function with the control system;
- Poor quality welding on low stressed components. Gouges and cracks found in non-destructive testing (NDT) testing post service (as seen in Figure 6);
- Inappropriate bolting used that would have been over stressed;
- Valve indicators assembled, by the manufacturer, with wires crushed between sealing flanges.

Some of the low priority issues where identified on receipt and amended on site (these should have been picked up at FAT) however it was not until operation and recovery that some of the more damaging issues came to light. This is a complex issue to resolve as the most damaging issues where identified through a complete valve dismantling, this is not done during an FAT. One possible mitigation would be to have APL presence at each stage of the assembly, this is resource demanding, expensive and not always possible when the product is manufactured and assembled in China. Within the marine renewable industry there is a reliance on suppliers meeting the Quality Standards they promote in their literature, but experience has shown that this is frequently not the case.

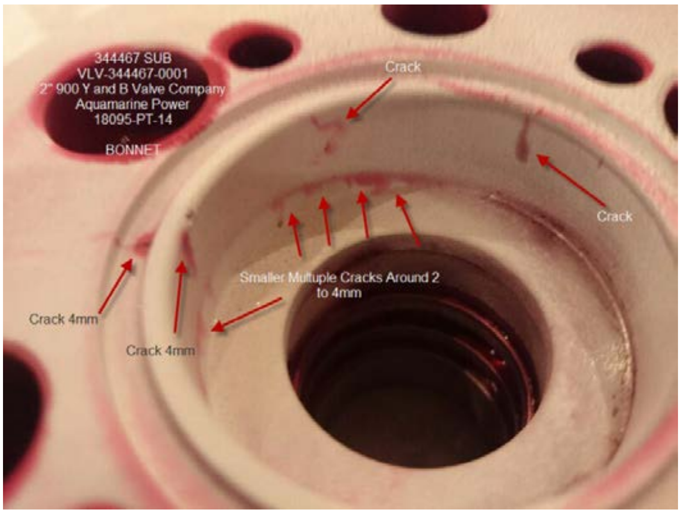


Figure 5 – Cracks found around sealing grooves on a 2" isolation ball valve – For reference: diameter at the centre is 32mm

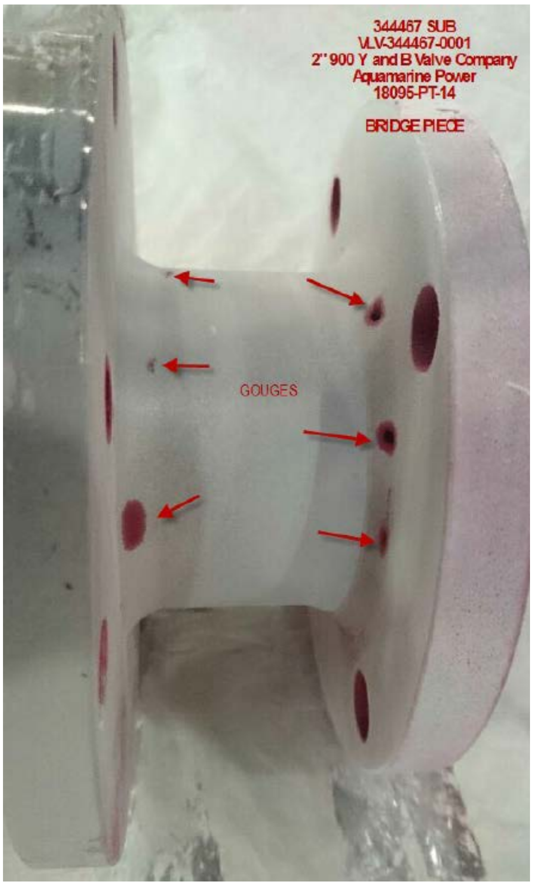


Figure 6 – Gouges found on welding details around a structural bridging spool for a 2" isolation ball valve – For reference: Length between flanges is 44mm

3.5 316 Stainless Steel Components

Lesson Learnt / Knowledge Capture:

316 stainless steel is not suitable as a reliable corrosion resistant alloy in seawater without CP. 316 may be used in conjunction with a reliable CP system.

Identified Problem / Challenge:

Corrosion of 316 stainless steel components in a seawater environment.

Root Causes:

1. Inadequate suitability of 316SS as a corrosion resistance alloy in seawater;
2. Prone to high levels of pitting corrosion;
3. Not suitably connected to CP systems;
4. Low quality 316 stainless steel supply.

Knowledge & Candidate Solutions:

316 stainless steel has been used by suppliers as a corrosion resistance alloy. Whilst 316 is to a certain extent resistant to small levels of corrosion, it is prone to pitting corrosion and in particular in areas with stagnated flow.

This alloy is generally used because it is marketed as a “marine grade” alloy with “good” corrosion resistance. These are subjective terms in comparison to a lower grade of a much more common grade 304 stainless steel. Without an understanding of the chemical and physical properties of the alloy, it is easy to get lured into a false sense of security by the use of comparative of subjective terms in descriptions of material properties.

When looked at a galvanic series chart, 316 is a fairly noble alloy (~ -0.1 to -0.2V). This would make it less prone to general corrosion. However, when the material becomes active (in an area of poor, stagnated, unaerated or shielded flow) 316 tends to have a poor corrosion characteristic, bringing its potential ~ -0.5V.

A measure of a materials resistance to pitting is given by the pitting resistance number (PREN). This is calculated through the composition of Chromium (Cr), Molybdenum (Mo) and Nitrogen (N) as seen in equation 1. For materials in seawater with no cathodic protection (CP) it is recommended that this value is above 34. Due to the differences in the maximum and minimum levels allowed for 316 alloys, 316ss has a (PREN) ranging from 22-30.

$$PREN = 1 \times \%Cr + 3.3 \times \%Mo + 16 \times \%N \qquad \text{Eq.(1)}$$

A way of mitigating this is to ensure adequate CP is available on the parts. The CP will flatten the potential and ensure that the 316 alloy is protected at all times.

The general lesson to learn is that 316 is not an adequate material to use in seawater as an effective corrosion resistant alloy. High quality 316 may become a means of ensuring a component does not corrode badly when CP has been lost (PREN close to acceptable level). However, ensuring the quality of 316 supplied cannot always be done and a poor quality 316 alloy is well below the recommended PREN. Checking this value during FAT would be too late and it is much safer to design with an appropriate material. A much more reliable way of using 316 is to use it in conjunction with an adequate CP system.

Generally it can be more cost effective to use a carbon steel with adequate corrosion protection in the form of; corrosion allowance, coating system and CP. When this is not possible it should be possible to use alternatives such as; Duplex steel alloys, Inconel alloys, Ni-Al-Bronze alloys or Titanium alloys. Considerations should always be given to issues such as (non-extensive); material compatibility, strength required, risk to hydrogen embrittlement, fatigue and cost.

3.6 High Strength Components

Lesson Learnt / Knowledge Capture:

General awareness of Hydrogen Induced Stress Cracking (HISC) and ensuring that suppliers are also aware of this issue. Generally advised to have a high and low tolerance when specifying material grades.

Identified Problem / Challenge:

Premature failure of high strength components.

Root Causes:

1. Supplier not aware of hydrogen induced stress cracking for high strength metals;
2. Applying CP to a component with a metal susceptible to hydrogen induced stress cracking.

Knowledge & Candidate Solutions:

Hydrogen induced stress cracking (HISC) is the interacting of hydrogen atoms (formed through a CP design) with the microstructure of components subject to high stresses. This process initiates the growth of cracks within the material and can cause a premature failure of a component. Guidelines on the materials susceptible to HISC can be found in the DNV recommended practice DNV-RP-B401 – Cathodic Protection Design.

Generally speaking, ferritic structural steels with minimum yield stress higher than 500 MPa may be susceptible to HISC. This includes bolts higher than grade 8.8.

Certain suppliers are unaware of the risks of HISC and have in the past been known to supply higher strength fasteners than the minimum specified. Generally, setscrews, capscrews and countersunk screws are manufactured in grades 10.9 and 12.9 and grades lower are specially made. For a marine environment it is recommended to set bolted designs up to grade 8.8 with a low and high bolt strength specification defined to avoid being supplied with higher strength bolts. If higher strength bolts are required the following options are available, with certain advantages and disadvantages:

- Duplex bolts – Corrosion resistant (may be prone to pitting), higher yield strength achievable, expensive due to non-standard bolting material, must be isolated from CP system due to possible susceptibility to HISC;
- Titanium bolts – High corrosion resistance, higher yield strength achievable, very expensive and rare to find a bolt supplier that works with titanium, must be isolated from CP system and qualification testing may be required;
- Inconel bolts – High corrosion resistant, higher yield strength, expensive material, non-standard bolting material but available as a bolting material and immune to HISC;
- Nickel-Aluminium Bronzes – Corrosion resistant (may be prone to pitting), higher yield strength achievable, non-standard bolting material but available as a bolting material and immune to HISC.

Another area where the use of high strength materials may be required are hydraulic cylinders. Confusion may arise either from the complexity of the product or due to product intentionally being designed to be isolated from CP. The designer must be aware of any high strength materials used in a design and mitigate accordingly.