**Internal Cathodic Protection of Offshore Sea Water Pump Caissons**

Brian Wyatt  
Corrosion Control Associates Ltd (CCAL)

Robin Jacob  
The CP Consultancy Ltd

John MW Baynham, Tim Froome  
CM BEASY Ltd, Ashurst Lodge, Southampton SO40 7AA, England

**ABSTRACT**

This paper describes application of simulation to a specific case in which significant corrosion (in the form of perforations – aligned with uncoated welds) had been detected in a lined CS seawater lift pump (SWLP) caisson. The coated CRA pump column and SDSS pump bowls were fitted with galvanic anodes. The holes had then subsequently been trepanned and covered with SS plates with sealing gasket. However, the holes had continued to grow. Fatigue assessment indicated the need to restrict hole size to less than 350mm. During withdrawal of the SWLP column for maintenance, very poor coating condition was found.

Modelling was used to inform the retrofit CP design, and to determine the limiting size of perforation of the caisson. It was selected to assist understanding of the behaviour of different materials (under high flow rate condition); restrictions to current flow in the narrow annular gap between pump and caisson; a combination of discrete and uniform coating damage areas; complex structural geometries, and used survey measurements to capture the effects of the external CP system (fitted to the associated jacket). The models demonstrated that the edges of the holes could be protected and holes would reach a maximum size that was less than the structurally critical level. The model was used to establish the likely corrosion rate on the exposed steel area at the welds, and the effectiveness of alternative CP designs (and coating re-conditioning strategies).

Key words: Cathodic Protection System, pump caisson, CRA, Super Duplex stainless steel, BEM
INTRODUCTION

Seawater and firewater offshore lift pumps are, from necessity, constructed from more corrosion resistant materials than the carbon steel of the caissons in which they are installed. This introduces the probability of galvanic corrosion of the caissons caused by electrical continuity with the pump columns, which are often the same material as the pumps. The galvanic corrosion rate, being dependent on the rate of oxygen diffusion to the caisson surface, is significantly increased when the pumps are operating, particularly in the vicinity of the pump inlet strainers.

Lining the internal surfaces of the caisson is often carried out, but this will seriously exacerbate and localise corrosion rates at any areas of damage. Coating of the pump column will markedly reduce galvanic corrosion, but has rarely been practiced, due to the view often held by pump manufacturers that there is no need to apply coating to a corrosion resistant material.

Cathodic protection by galvanic (sacrificial) anodes is often used in offshore sea water pump installations, but the designs have on many occasions proved inadequate, both mechanically and in respect of the use of inappropriate design current densities.

Even competent cathodic protection designs appear to have been incompetently applied/fitted due to a lack of understanding and rigour by those parties responsible for these activities. There are extensive reports of serious corrosion to caissons on the North Sea oil and gas assets. Some operators appear to consider that such corrosion damage is unavoidable and should simply be remedied by repairs or replacement of caissons.

This paper presents the experience of one operator who applied rigour to the investigation of the problem and its appropriate remedy.

PUMP CAISSON CORROSION - MATERIALS

Background
Early pump and pump column material of choice was Ni-Resist cast iron. The galvanic couple between Ni-Resist pump columns and carbon steel caissons is limited, with lives of usually uncoated caissons often exceeding 20 years. However, Ni-resist is an inherently brittle material and has suffered significantly from vibration induced cracking and mechanical failure.

The development of materials more resistant both to mechanical failure and corrosion in flowing seawater has, more recently, led to the use of super-duplex stainless steels [SDSS], both in new and replacement pumps and columns.

This has increased the intensity of galvanic attack of the carbon steel caissons, especially as the corrosion resistance of SDSS has persuaded designers that coating of these components is not needed.

The offshore supply chain has relied upon the expertise of pump suppliers in the delivery of coated or uncoated pump column assemblies, with or without galvanic anode systems applied to control the corrosion of the carbon steel caissons for which the pump supplier is not responsible.

The CP design and supply is generally subcontracted by the pump supplier and may not be rigorously assessed or its implementation checked.
Case study
An offshore platform was fitted with SDSS SWLP and Ni-Resist fire water lift pump (FWLP) in the mid-1990s. The pumps and their lift columns were installed in polyurethane lined carbon steel caissons. A coating of uncertain competence was applied to the SDSS SWLP columns.

The pump columns were originally fitted with a galvanic anode system, supplied by the pump manufacturer, consisting of 4 bracelet assemblies on the SWLP columns and 4 on the pump and motor assembly. On the FWLP columns, which only pump intermittently, 4 bracelets were fitted only to the columns. It is believed that these systems may have been ineffective from the start; there is evidence that indicates the FWLP anodes were never connected.

The work for the Client was initiated by reported corrosion of the SWLP caissons. Corrosion, in the form of perforations in the caissons, was observed about 9 years after installation of the SWLPs and their caissons. The points of perforation were determined to be at the level of uncoated welds between the caisson and pump retaining bars.

Study of the construction records also disclosed the presence of an unlined construction weld in all of the caissons (SWLP and FWLP) in the immersed zones, close to the SDSS strainers. These welds had been competently coated externally, where the external CP would easily have prevented corrosion. They were not repaired internally.

Anodes on column sections 1, 3, 5 & 7 uniformly distributed from just below LAT to just above the pump. Anodes also on pump and motor below pump and strainer

Corrosion in caisson at ca.-17 m and perforations at ca.-28m

Figure 1: Corrosion case study: SWLP
Prior to the work, the following activities were undertaken to ensure the structural integrity of the caissons:

- The holes were trepanned (to limit cracking) out to 150mm diameter and covered with stainless steel plates with neoprene sealing gaskets
- In a further 4 years, the trepanned holes were observed to have grown in diameter to ca. 220mm diameter
- Fatigue assessment indicated that if the hole sizes developed to ca. 350mm, the defects became structurally significant
- Concepts were developed for a retrofit clamp arrangement to strengthen the caisson if the corrosion were to continue
- A SWLP pump column was withdrawn for maintenance including the installation of a galvanic anode CP system by the pump maintenance company
- An internal video survey indicated significant corrosion of the uncoated field weld at -17m
- The original column coating was found to be very poor. Recoating of the column was not carried before fitting the new anodes and re-installation of the column. No CP specialist was involved to inspect/check the installation.

A desk study of the SWLP information was carried out to evaluate the data and to recommend remedial measures. The conclusions of that evaluation were:

- The originally installed internal CP system was inadequate and had failed
- The coating on the pump column was ineffective
- Corrosion of the caisson at the, originally uncoated, field weld and retaining bar welds, was being exacerbated by the galvanic effect of a large area of SDSS on the small area of exposed carbon steel
- Enlargement of the holes in the caisson had occurred, at least in part, due to the covers shielding the edges from the external CP system, thus exposing them to galvanic corrosion as above.
- It was clear that mitigation of further corrosion of the caissons required the provision of an effective CP system, in conjunction with a competent coating on as many of the SDSS components of the SWLP as was feasible.

**Corrosion Mitigation**

CP is effective in mitigating corrosion, including marine galvanic corrosion, of carbon steels. It is well established and defined in Standards and design codes. None of these Standards or codes are intended for or include in their scope sea water pump caisson internals, but some attempt to use DNV RP B401.
There are specific issues:

- High seawater flow rates and aeration increase the current demand for protection
- The restricted locations available for installing anodes can adversely affect distribution of the protection current to all the of the internal caisson surfaces.
- Vendor designs apparently do not attempt to protect the full internal surface of the immersed caisson
- The narrow annular gap between pump and caisson restricts current flow from anodes on the column to caisson surfaces below the pump
- It also restricts the size (= Current output) and weight (= Life) of the galvanic anodes that can be installed
- The galvanic couple between the SDSS and the CS needs to be addressed by polarising the SDSS

All the effects listed above are much reduced by competently coating as many of the pump column components as possible.

**Boundary Element Modelling study**

Modelling (using BEASY software (1)) was chosen as the means to inform the most appropriate galvanic anode CP design and to determine any limiting size of perforation of a caisson IF the internal CP remained incompetent. The following objectives were set:

- Determine the ability of the external CP system to prevent further increase in the size of the existing holes, and to limit the size of new perforations, in the absence of internal cathodic protection and with the SS cover plates removed
- Assess the effectiveness of the recently installed galvanic anode system in providing protection to the caisson with an uncoated [as installed] SDSS column, assuming competent installation of the CP system.
- Assess the effectiveness of the existing galvanic anode system design with a competently coated, SDSS column [for planned future SWLP refurbishments]
- Assess the effectiveness of a proposed alternative galvanic anode system design in providing protection to the full caisson with a competently coated SWLP

**Parallel Work on FWLP**

The CP systems being fitted to the FWLPs which were having Ni-Resist columns replaced with SDSS were also assessed:

- Based on the initial SWLP study a decision had been taken to coat the future FWLP columns and pump bowls
- A galvanic anode design/supply via the pump refurbishment co, similar to that previously installed on the (uncoated) SWLP, was commissioned
- The anodes were cast onto SDSS cores and SDSS bracelet fabrications were made
- A monitoring system to measure the internal CP system performance was made

The refurbished FWLPs with their new SDSS columns were subject to final trial fit up and testing at the pump refurbishment company premises. The Client encouraged all parties to jointly attend and inspect:

- It was argued (based on competent metallurgical advice from another party) that SDSS anode cores would likely fail due to excessive nitrides and sigma phase formation during the anode casting process at ca 780C and slow cooling. Anodes were scrapped (awaiting investigation to prove excessive nitrides/sigma)
- It was argued that the extensive use of cable bonds between anodes and the column was a reliability issue

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(1) www.beasy.com
- It was possible to measure electrical resistance values for all the components of the FWLP system and the CP system connected to it and to use these data to inform the SWLP BEMM work.
- The inspections disclosed many issues between otherwise very competent pump and CP experts which would not have been detected in the normal supply chain management and inspections by non CP specialists. These are considered certain to have resulted in poor or non-performance of the CP system.
- It is considered likely that these issues would have affected the previously installed SWLP CP system (to the uncoated SDSS column) and likely MANY other pump caisson systems.

![Figure 3: Anodes mounted on pump bowl. Pump bowls coated and yellow spaces appropriately larger OD](image1)

![Figure 4: Anode bracelet mounted on column. Note cable bond to column. Cores and bracelet were SDSS.](image2)
Figure 5: Cable bond details

Figure 6: Resistance measurements

Figure 7: Subsequent revised anode design by CP vendor, no cable bonds, no SDSS anode cores. Note anodes now on lower pump bowl, bare SDSS strainer, no cables.
Figure 8: Anodes and reference electrodes at pump inlet. SDSS strainer not fitted.

Figure 9: Anodes and reference electrodes on pump column. Strapping for trial purposes only

Figure 10: Ca 15 year old anodes from bare Ni-Resist FWLP columns: Suspected not connected to column, likely only protecting anode bracelet steel
Figure 11: BEM model geometry of the SWLP caisson, pump column, pump and inlet strainer, including perforations at the observed locations on the caisson.

Figure 12: BEM model polarisation curves for CS were those proven in past projects as accurate for bare steel areas on coated components, allowing for the formation of calcareous deposits. The effects of seawater flow rate were also included.
Figure 13: BEM model polarisation curves for SDSS. Less data available, but those presented in a paper by Neville et al \(^1\) were used.

<table>
<thead>
<tr>
<th>Material</th>
<th>Where</th>
<th>Bf</th>
<th>Bf change per year</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zeron 100</td>
<td>Bare metal</td>
<td>1.0</td>
<td>n/a</td>
<td>Applied to bolts, strainer and motor housing at all times.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Applied to all other lift column surfaces <strong>before</strong> refurbishment.</td>
</tr>
<tr>
<td>Zeron 100</td>
<td>Coated [Norsok system 7B]</td>
<td>0.04</td>
<td>0.024</td>
<td>Applied to pipes, adaptor pipe, and pump bowl <strong>after</strong> refurbishment.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Change from 0.04 to 0.4 over 15 years.</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>100 mm wide weld inside caisson</td>
<td>1.0</td>
<td>n/a</td>
<td>Bare from start</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>50 mm narrow weld inside caisson</td>
<td>0.2</td>
<td>0.02</td>
<td>Change from 0.2 to 0.5 over 15 years.</td>
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<tr>
<td>Carbon steel</td>
<td>Damaged external coating</td>
<td>0.3</td>
<td>0.012</td>
<td>Applied to damaged outer coating around the holes. Change from 0.3 to 0.48 over 15 years.</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>Caisson exterior</td>
<td>0.2</td>
<td>0.012</td>
<td>Applied to outer caisson CTE coated surface. Change from 0.2 to 0.38 over 15 years.</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>Caisson interior</td>
<td>0.02</td>
<td>0.002</td>
<td>Applied to inner caisson lined surface. Change from 0.02 to 0.05 over 15 years.</td>
</tr>
</tbody>
</table>

Figure 14: BEM model coating breakdown. Particular attention was paid to the selection of assumed coating breakdown factors for each of the components.
Protection at caisson perforations

Initial model runs were completed for caisson perforations in the range seen to the size where they became structurally significant [220, 250, 300 and 350mm]. The edges of the hole were assumed to be bare steel, with the inside of the caisson lined and the outside coated.

For all hole sizes modelled, and for both flow and no-flow conditions, the edges of the holes are fully protected by the external CP system even when there is no effective CP inside the caisson. The external CP system (galvanic anodes to well coated jacket and caissons) is particularly competent with protection levels at ca -1020mV Ag/AgCl/sea water.

The least negative protection potential on the bare steel surface forming the edge of the holes was on the inside of the edge. The potential at this location became 40 mV more negative with increasing hole size from 220mm [-860mV] to 350mm [-900mV].

In all cases the potential shift between flow and no-flow was minimal [ca. 2mV]. Potentials on the outer edge were consistently ca. 30mV more negative than the inside values.

In order to determine if smaller holes could be protected, once formed, from the external CP system, an additional theoretical hole, 40mm in diameter, was introduced into the model geometry at the level of the strainer. The results indicated that the majority of the edge of this hole was unprotected, with only the extreme outer edge at protected potentials.
Extension, by continued galvanic corrosion, of the original [120mm] holes detected in the caissons was exacerbated by the installation of [stainless steel] cover plates which shielded the hole edges from the external CP system.

Following removal of the cover plates, the resultant ca. 220mm diameter holes will be protected from further extension by the external CP system, even before the installation of an effective internal CP system.

As indicated by modelling a 40mm hole, in the absence of an internal CP system new holes forming in the caisson would be protected from growing by the external CP system; they will not reach a structurally significant size.

The size at which growth ceases has not been directly determined, but lies between 120mm [known to have occurred before cover plates were installed] and 220mm [indicated as fully protected by the model].
**Corrosion of internal exposed caisson steel**

The model was used to determine the likely corrosion rate on exposed steel at the welds if the internal CP system was not fitted, or did not function, with the SDSS pump components not coated.

The model indicates a protection current flow of ca. 5.9A flowing from the external CP system through the existing holes, the majority of which flows to the SDSS components of the SWLP.

The model indicates that the internal caisson steel to about 1m above the holes is receiving only limited protection, and above that elevation corrosion rates will be higher than normally experienced in seawater. Below the holes, i.e. below the pump, protection is being provided from the external CP system, with 2.6A flowing through the orifice plate at the lower end of the caisson.

Assuming Faradaic dissolution of the steel, the current density data for the exposed bare steel of the welds inside the caisson indicates that the corrosion rate at the uncoated field weld could be as high as 0.85mm/y.

Given an initial caisson wall thickness of 15mm, this indicates a time to perforation of 17.5 years. Since the lift pump has been in service for 18 years, and the initially installed internal CP system probably failed relatively early in that time, the risk of significant corrosion at this weld must be considered as being high (subsequent inspection indicated corrosion was present but not yet structurally significant).

The model further indicates that the corrosion rate of any steel exposed by lining damage on the longitudinal and circumferential welds close to the strainer and pump housing could be as high as 3.5mm/y.

Since, to date, no perforation of these welds has been seen indicates that the lining in these areas has remained in excellent condition.

However, the time to initial perforation at the hole locations, which was less than 9 years, is consistent with the model current density data, particularly as the holes were already ca 120mm in diameter when first observed.

**Assessment of recently installed CP System**

Following the evaluation of internal corrosion in the absence of internal CP, the anode arrangement recently fitted to the (uncoated) pump column was incorporated into the model.

![Figure 18: Anode arrangement in the model](image)
The model was initially run for an uncoated [as installed] GACP system.

The potential distribution immediately after installation [year 0] showed that CP was incapable, even at an early stage, of providing full protection to exposed caisson steel under operational [pumping] conditions.

Additionally the model was used to derive anode lives, for comparison with a target operating CP life of 15 years.
The data indicate that anodes lives would range from 3 – 12 years depending on location, with the shortest lives for anodes on the pump column.

Assessment of Vendor Designed CP system with coated SDSS
Following observation of the inadequacy of the recent CP system for an uncoated lift pump, the model was re-run assuming application of a competent coating to most of the SDSS (not strainer).

This showed that, at year 0, full protection was achieved on the caisson.
The model with pump column coating was used to derive anode lives, again for comparison with a target operating CP life of 15 years.

The data indicate that, with the column coated, anode lives would improve to 11 – 20 years, but the anodes on the pump motor and strainer would still not reach the design life.

**Revised CP system design**
The outputs for the Vendor designed CP system prompted design of a revised system, with a modified anode distribution and increased anode weights.
The model of the revised design was time stepped through to the end of the 15 year design life to determine if the required anode lives could be achieved. At 15 years, the remaining lives indicated were 2-10 years.

The potential distribution at year 15 indicates that, due to increased current demand caused by coating breakdown on the SDSS, potentials on the caisson steel at pump level are only -744mV Ag/AgCl/sea water.
While less negative than design code criteria, protection current is still reaching the steel, and the corrosion rate is estimated to be only ca. 1% of the free corrosion value in seawater.

This design is being applied for a 7-8 year design (before removal of the pump string for maintenance) with a factor of safety of 2. In this regime protection is anticipated to be complete for the full life.

**Model predictions of CP performance**
The recently installed Vendor designed CP system, on a non-recoated lift column, will not provide full protection to the caisson steel even at year 0. By year 3 some of the anodes on the column sections will have been consumed and protection of the caisson above about - 18m will have been lost, with additional galvanic corrosion on any bare steel. Anodes around the strainer will be consumed after around 7-12 years, with consequent resumed galvanic attack at this level on the caisson.

It is uncertain that the anodes (with cable connections) were adequately connected to the pump and column; if they were not, the performance above would not be delivered.

The Vendor designed CP system would provide initially good protection to bare steel of the caissons with the SDSS columns coated. However, levels of protection would decrease with time, with some anodes consumed and protection lost in some areas after about 10 years.

An alternative CP system design was prepared, with heavier anodes distributed differently on the coated SWLP and column would ensure anode lives in excess of 15 years.

However, due to predicted increased current demand on the SDSS components, as their coatings deteriorate, accepted protection criteria may not be fully achieved to year 15. Despite this, the model indicates that galvanic corrosion will be fully suppressed and the ‘background’ corrosion rate of the carbon steel reduced by >90%.

A detailed design informed by this work is underway.

**CONCLUSIONS**
The programme of modelling assumed, critically, that any coating used on the SDSS would have been applied competently. This has been independently assessed for these projects.

It also assumed that the galvanic anodes, and in particular, their attachments would be properly engineered for their full life, and that they would be correctly installed. This has been ensured for the latest of these projects.

There is evidence from investigations related to these projects that early failure of such installations is common.

It is known that many offshore pump caissons are suffering corrosion damage.

All the parties in the reported projects were technically competent and well intentioned; there was not a deficient party involved.

Despite this, the installed SWLP CP system is unlikely to be fully functional and the system that was first inspected at the trial fit for the FWLP is assessed as being most unlikely to function.

The key issues leading to these failures of CP systems and resultant, possibly endemic, corrosion of offshore caissons are considered to be:
• Inadequate supply chain relationships leading to poor (or no) understanding of CP by the contractor responsible for buying it and fitting it
• Inadequate liaison between Offshore Asset operator, the pump supplier / service co and the CP system vendor. The result may be general levels of ignorance, no / inadequate coating of SDSS, inadequate assessment of the impact of the external CP system on internal corrosion of the caisson and inadequate supervision of the CP system installation
• These issues are made worse by the competitive purchasing regime of systems not understood by the buying team
• The result is CP systems that are likely to be incompetent and which will allow corrosion of caissons

Possible solutions are:
• Greater intervention by the Operators
• The generation of a Standard (EN or ISO) for pump caisson CP that requires actions and design minima to avoid these problems (but timescales would be lengthy)
• Better education by the CP Vendors of the pump Vendors and refurbishment companies IF they are able and prepared to deliver higher cost reliable CP systems to the Operators via the complex supply chain
• An acceptance that even rigorous CP designs are improved by modelling
• Greater use of reliable (simple) monitoring systems to monitor/prove CP system performance and provide design verification

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• Our Client who was uncommonly rigorous and proactive
• The Vendors (CP and pump) who were open and cooperative throughout; they might have responded otherwise and this would have made this project very difficult to complete successfully

REFERENCES