CATHODIC PROTECTION OF STAINLESS STEEL 316L ROTATING SCREENS ON SEAWATER INTAKE STRUCTURES

Rod Callon
Corrosion Technology Services

ABSTRACT

Reinforced concrete seawater intake structures are a critical component to enable continuous operation of power stations, desalination plants, petrochemical plants and other heavy industries located near to the coast. The primary objective of these structures is to supply a reliable quantity of clean seawater, which can be used as per plant or refinery requirements. For continuous operation, seawater intake structures require protective screens to prevent debris and marine life entering and damaging the pumps. These screens are made from a variety of material but even when 316L Stainless Steel (SS), (UNS S31603), is used it is often considered insufficient to provide long term corrosion resistance by itself. Cathodic Protection (CP) systems are therefore utilized to protect the submerged sections of these screens with the aim of extending the life of the stainless steel equipment.

This paper will focus on the various design parameters required for CP of SS screens with particular attention on design and operational current density values and suitable protection criteria. The detrimental effects of overprotection will also be discussed.

A suitable case study is used to highlight the available anode systems, methods of monitoring and how maintenance worries can be overcome by state of the art remote monitoring and control systems, capable of controlling large scale CP systems from a single location using a standard internet web browser

INTRODUCTION

Due to the high temperature, humidity and salinity of the seawater, the coastal environment within the Middle East offers one of the harshest environments for stainless steel screens immersed in seawater. The Middle East has a history of corrosion problems related to such equipment and many structure owners adopt CP as a prevention technique to mitigate corrosion of submerged equipment.

For this particular project, the main contractor evaluated the use of Duplex Stainless Steel as an alternate to Stainless Steel 316L (SS), in conjunction with CP. However the additional cost associated with a more corrosion resistant grade of Stainless Steel resulted in SS and CP as the most cost effective solution.

The main contractor appointed a Specialist CP Company two years into the construction phase of the intake structure and at this point the reinforced concrete base slab and walls were complete with the roof slab under construction. Provisions for the CP system had been implemented during construction and were based on adopting a similar CP system to Phase I intake structure; located next door. These provisions were recesses in the concrete walls below the low tide level and conduits embedded between the recess and the deck slab. The purpose was to allow for anode locations and anode cables to be routed to the deck slab.

Prior to designing the CP system the Specialist CP Company met with the owners in order to discuss various anode systems. The client was insistent on using a similar anode system and monitoring electrodes installed at Phase I as this system had proven reliable.

A more modern power supply system was permitted as the type installed on Phase I was based on 10 year old technology.

The new system was to be equipped to allow for full remote monitoring and control and to interface with the plant Supervisory Control and Data Acquisition System (SCADA). This would allow the Plant Operators to monitor CP readings and alarms transmitted from the CP Master Control Unit to their SCADA system.

DESIGN OF THE SUBMERGED CP SYSTEM

The CP system is based on the use of mixed metal oxide coated titanium strip anodes positioned at strategic locations below with waterline to protect the rotating screens and stop log guides.

Negative connections are made directly to the screens and guides at deck level. Individual metallic parts of each component are electrically continuous with each other for both static and rotating parts. The challenge of electrical continuity between the various parts of the rotating screens is addressed later on in the paper.

Permanent submerged zinc reference electrodes housed inside uPVC conduits are used to monitor the submerged equipment. The conduits are fixed to the concrete walls using non-metallic brackets and fixings.

The system is powered by a state of the art power and monitoring system. All monitoring and adjustment of the CP system are from a single source located next to the Power Supply Units. To assist the Operators with monitoring the CP system, the Main Control Unit is interfaced with the plant SCADA via Ethernet.

STRUCTURES HIGHLIGHTED FOR PROTECTION

The intake structure consists of an Inlet Bay, 11 Screen Chambers and 5 Distribution Chambers. Each screen chamber contains a Continuous Chain Raked Bar Screen and a Band Screen Assembly. These assemblies are used to filter out physical debris, jelly fish and other marine life which can damage the pumps. The pumps, when installed will be housed at the back of the Distribution Chambers.

The design of the CP system does not allow for CP to the pumps as they are not supplied by the Owner of the Intake Structure. The pumps are supplied at a later date by the Consumer once a contract is in place to distribute water from the intake structure to their plant or refinery.

The following components were targeted for CP, refer to Table 1. All submerged equipment is uncoated. The Table highlights two types of Stop Log Guides. The differences are only dimensional and are a result of small geometrical differences in the openings at the Inlet bay and Distribution Bay. The net effect on the CP design is small differences in current requirements. This range is presented in Table 3.

Table 1
Submerged Equipment Targeted for CP

Metallic Component	No. of Units	Material
Band Screen Assembly	11	SS 316L
Continuous Chain Raked Bar Screen	11	SS 316L
Stop Log Guides at Inlet Channel	11	SS 316L
Stop Log Guides at Inlet Bay (Type 1)	11	SS 316L
Stop Log Guides at Distribution Bay (Type 2)	8	SS 316L

ZONING

The CP system is zoned taking into consideration future maintenance where various sections of the intake structure may be drained. Separate compartments, such as the Inlet bay, Screens and Distribution Bays are therefore independently powered and controlled by separate anodes. This zoning arrangement is similar to the CP system at Phase I. The zoning arrangement is summarized below and illustrated in Figure 1.

- Inlet Bay: Zones 1-3
- Screen Chambers: Zones 4-14
- Distribution Chambers: Zones 15-19

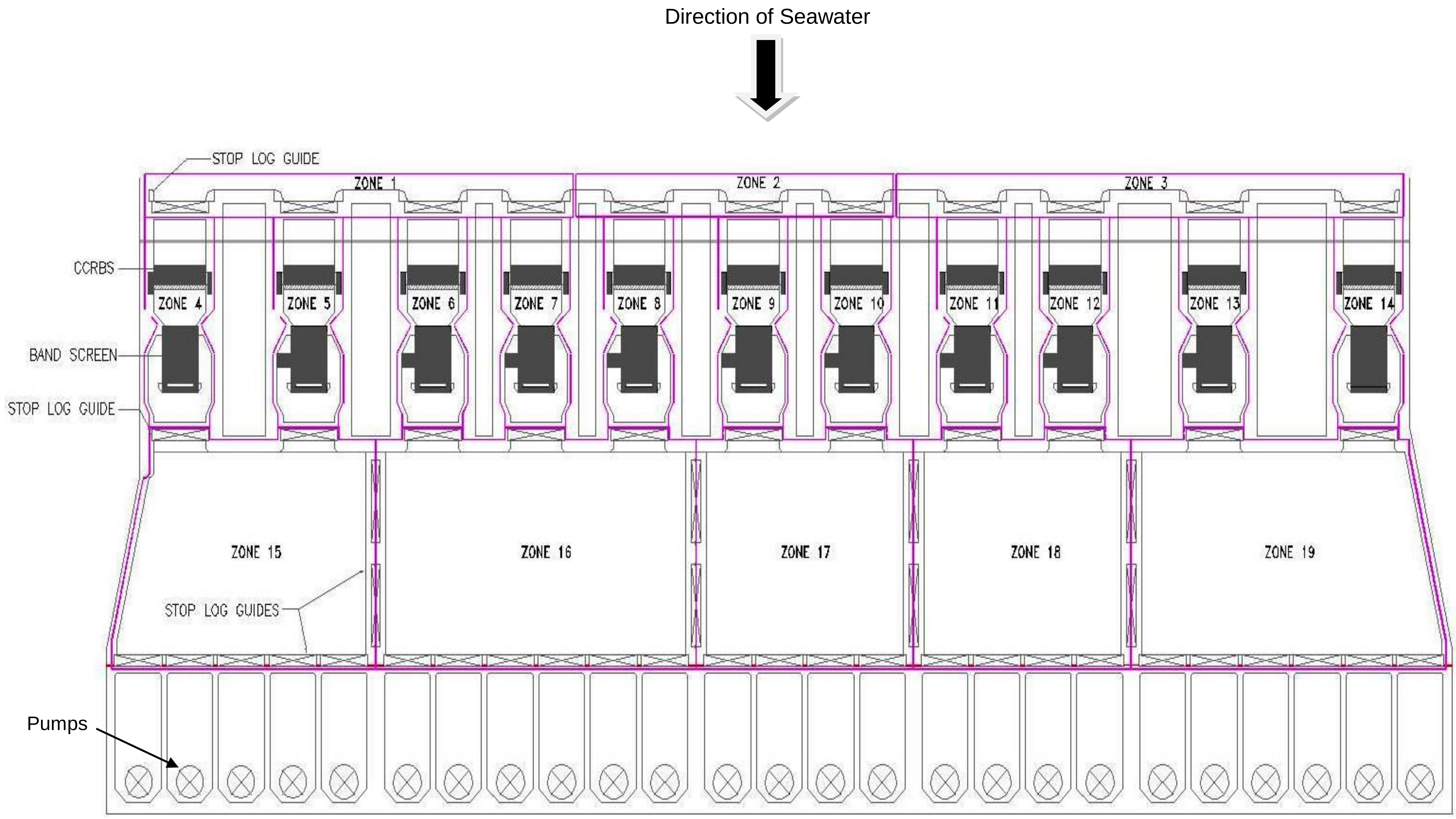

Figure 1: Zoning arrangement of the CP system

PROTECTION CRITERIA

Prevailing International standards highlight protection potentials for various grades of Stainless Steels. Many Austenitic stainless steels can be protected using a polarised potential of +450mV wrt zinc[4] (-600mV wrt Ag/AgCl). For more corrosion resistant stainless steels it is considered that a potential of +750mV wrt Zinc (-300mV wrt Ag/AgCl) is adequate[3].

There are references to susceptibility of cracking from Duplex or high strength steels when overpolarised[3,4], which is why a limit of -300mV wrt AgAgCl is often placed on its protection potential. On this project since SS316L was used, the protection potential of -300mV was not applied.

As a limit on overprotection, for stainless steel 316L, -900mV is often cited[1]. However in view of the wide range of austenitic stainless steels available potentials upto -900mV should only be applied if documented by service performance or appropriate laboratory tests[3].

Protection potentials and limits were discussed with the plant operators. According to them, the operating potentials for Phase I were originally set between +50mV to +100mV wrt Zinc (-1000mV to -950mV wrt Ag/AgCl. At these potentials problems were encountered with the link pins on the rotating screens. Although not discussed in detail in this paper, analysis of the pins highlighted the failure mechanism to be hydrogen embrittlement. Once the failed pins were replaced the CP system was set to operate at a less negative potential, a range of +250mV to +350mV wrt Zn (-800mV to -700mV wrt Ag/AgCl). To date the previous problems have not been observed.

For Phase II it was decided to use the same upper limit as on Phase I, +250mV wrt Zn (-800mV Ag/AgCl) and a lower limit of +450mV wrt to zinc (-600mV wrt Ag/AgCl). The objective was to apply sufficient polarisation to address the exposed stainless steel frame and to address areas such as crevices, which can be present on such complicated screen assemblies due to the arrangement of the fixings and rotating parts.

Applied protection criteria to assess the performance of the CP system:

- Zinc RE: On potential +450mV to +250mV
- Ag/AgCl Seawater: On potential -600mV to -800mV

CURRENT DENSITY

The current densities used to calculate current demand was at the CP Specialists discretion. A number of prevailing local and international specifications exist which document various current densities based on tidal flow, depth, aeration and temperature at both initial, final and mean values. Table 2 below summarizes the values referenced in prevailing international standards. In all cases the specifications refer to bare steel and do not specifically highlight any difference in current density requirements between c-steel and various grades of stainless steel.

After review of the various standards, the current density values were selected from ISO13174:2012 CP for Harbour Installations[2], refer to Table 2 below, values highlighted in bold underline. These values were selected based on low flow rate, well aerated seawater as this best reflects the conditions the screens and guides are expected to operate within a breakwater environment.

Table 2
Typical Design Current Densities for Protecting Bare Steel in Seawater

Standard	**Tidal Flow**	**Aeration**	**Initial**	**Mean**	**Average**
BS 7361:1991[6]	-	-	100	70-30	70-30
ISO 13174:2012[2]	**<0.5m/s**	**Well Aerated**	**150-120**	**80-65**	**100-80**
		Poorly Aerated	100-80	65-50	80-60
ISO 13174:2012[2]	>0.5m/s	Well Aerated	200-170	100-80	130-100
		Poorly Aerated	120-150	80-60	100-80
DNV-RP-B401: 2010[5]	-	-	150	100	70
SABIC Standard[7]	-	-	75	75	75

The initial current density was applied to size the power supply units as this allows for the initial high current demand in order to polarise the steel and is the maximum current requirement expected throughout the CP systems life. The anodes are rated on the mean or operating current density as this is the current output they are expected to operate at throughout the majority of the systems life. Current requirements per zone using the above current densities and calculated exposed surface area are presented in Tables 3 & 4.

Table 3
Current Requirements per Component

Metallic Component	**Initial Current (A)**	**Mean Current (A)**
Band Screen Assembly	23	12.5
Continuous Chain Raked Bar Screen	13	8
Stop Log Guides (Various Sizes)	3 – 7	1.6 - 3.8

Table 4
Current Requirements per Zone

Zoning Arrangement	**Initial Current per Zone (A)**	**Mean or Operating Current per Zone (A)**
Inlet Bay (Zones 1-3)	4	2
Screens (Zones 4-14)	36	20.5
Distribution Bays (Zones 15-19)	14	8

ANODE TYPE

The anode system was designed around the use of strip anodes fixed onto the front of a non-metallic mounting board. (Refer to Figures 2 & 3). The mounting was set into a concrete recess adjacent to the equipment it is designed to protect. During construction conduits were encapsulated within the concrete wall, to allow for anode cables to be routed to deck level.

All fixings are non-metallic to avoid any corrosion related problems throughout the design life of the CP system. The anode system was designed in a similar manner to Phase I.

Figure 2: Installed Strip Anode

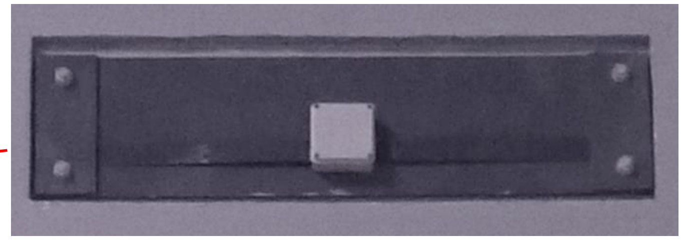

Figure 3: Strip Anode

The main drawback with the above anode system is the anodes are non-retractable. If any maintenance issues are encountered in the future, either the chamber will need to be drained or divers will be required to replace the anodes. This drawback was communicated to the owner of the intake structure and alternate anode systems, such as tubular anodes installed in PVC conduit and fixed to the wall of the intake such as those illustrated below were recommended, (Figure 4). The owners however declined this option due to the track record of the anode system at Phase I.

Figure 4: Alternate Anode Arrangement

Sacrificial anodes were not considered for the screens and stop log guides as the high current demand would result in excessive anode weights for a 10 year maintenance free period.

Aluminium anodes were installed onto the coated carbon steel stop log gates as the current requirements for these components are an order of magnitude lower than the stainless steel equipment. This is a standard type of anode system for such equipment as the gates are only installed periodically during a shutdown. The sacrificial anode systems were designed as an isolated CP system to the ICCP.

REFERENCE ELECTRODE TYPE (Ag/AgCl vs Zn), PERMANENT & PORTABLE MONITORING

To assess for compliance with the protection criteria permanent submerged zinc reference electrodes were installed within perforated uPVC pipes, (Figure 5). This RE type was selected to match with the REs installed on Phase I, to aid with the Plant Operators maintenance and monitoring program for both Phase I & II systems. Test connections were made directly to the stainless steel bosses, which were welded to the equipment at deck level, (Figure 6).

From past experience many systems are designed around the use of Ag/AgCl seawater reference electrodes. Many designers or Consultants specifying a reference electrode type in a project specification prefer this type of electrode as they are more familiar with the potential ranges for protecting carbon steel which is around -800mV wrt AgAgCl. The only major drawback with Ag/AgCl REs is they are more expensive than zinc electrodes for the same mass of material. As a result the Ag/AgCl element is supplied significantly smaller and is therefore more susceptible to malfunction due to the formation of marine growth on the monitoring element with time. On the other hand zinc REs are often sold as a large block of zinc metal with a much larger interface area.

It is also possible to monitor the CP system with the use a portable reference electrode. There are adequate openings around the equipment to suspend a RE below the seawater. This test could be conducted as part of the future operation & maintenance of the CP system to verify the accuracy of the permanent submerged REs.

Figure 5: Reference Electrode Monitoring

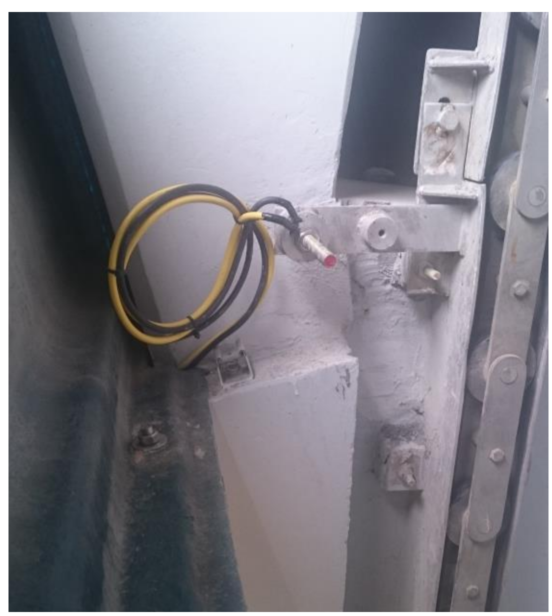

Figure 6: Cable Connections onto the Equipment

ELECTRICAL CONTINUITY OF SUB-COMPONENTS

One of the major challenges associated with this type of CP system was to ensure the electrical continuity of the rotating equipment, (Figures 7 & 8). The suppliers of the screens, were required to address this issue in their mechanical design. All rotating parts were made electrically continuous through the sprocket and by allowing several of the rollers to be metallic. The screens were assembled in-situ. Once completed, resistance checks were conducted for all static and rotating parts to ensure continuity was present.

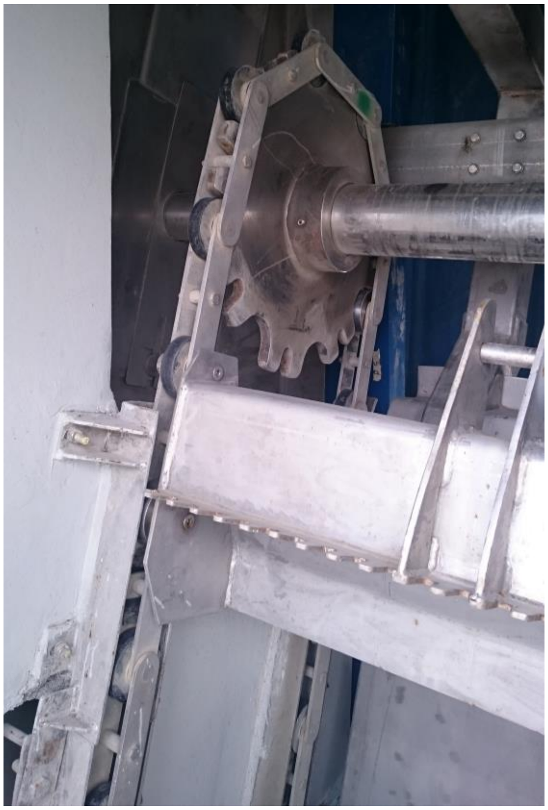

Figure 7: Continuous Chain Raked Bar Screen

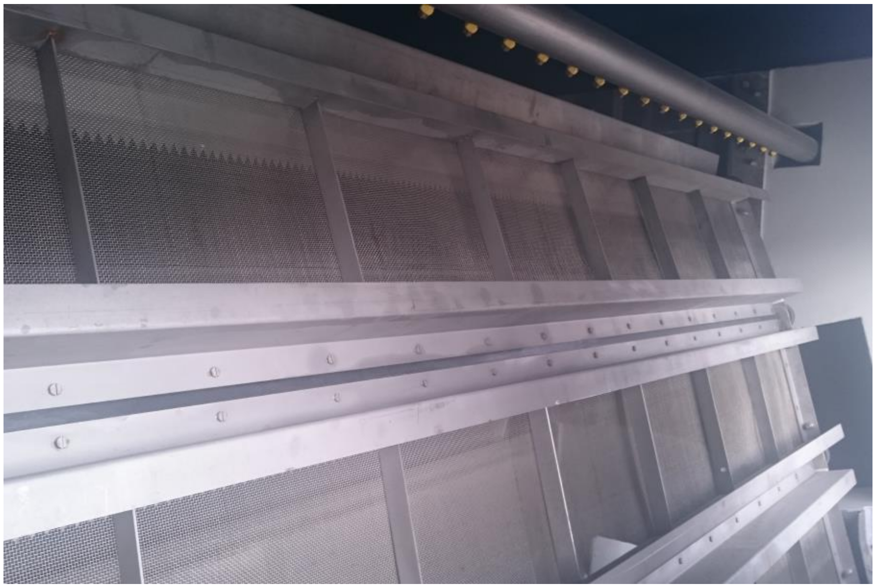

Figure 8: Band Screen

In order to eliminate current drain to the steel reinforcement, the screens and stop log guides were not bonded to the steel reinforcement. Stray current corrosion onto the rebar was not considered a risk due to the location of the rebar with respect to the anodes and screens/guides, (ie/. the rebar is encapsulated within 50mm of concrete cover with the concrete surface coated with a heavy duty polyurethane coating).

POWER SUPPLY SYSTEM

All power and monitoring field cables were terminated into coated SS316L junction boxes located at deck level. For ease of cable terminations, a single junction box was designed for each zone. The anode system was designed without the need for current balancing resistors as these components would interfere with the systems objective, which is full remote monitoring and control.

To protect the electrical equipment from the extreme temperatures during the summer season, the power supply units were located inside the plant sub-station, adjacent to the intake structure, (Figure 9).

The power supply system comprises of modular, switch mode units with varying output capacities depending on the current requirements of each zone, refer to Table 5 below.

Due to the high current demand of the screens, the Inlet Bay and Distribution Bay units are populated in an 8 channel cabinet and the screens are populated in 3 cabinets consisting of either 3 or 4 channels. The system was designed around the use of 4 cabinets. Aswell as the remote monitoring and control feature, each zone can be controlled and monitored locally using the keypad, (Figure 10).

Table 5
PSU Capacities per Zone

Zone No.	Location	PSU Current (A)	PSU Voltage (V)
1-3	Inlet Bay	8	14
4-14	Screens	40	14
15-19	Distribution Bay	16	14

Figure 9: Switch Mode Power Supply

Figure 10:
Local Access with Keypad

REMOTE MONITORING AND CONTROL

Remote monitoring and control was used for this system to simplify its operation. The Power Supply system is networked together to allow full access and control from a single point (the Master Control Unit) (MCU) at the Sub-station. By networking the MCU, the system has provisions to be operated from anywhere on the LAN or via the internet by anyone with the correct log in credentials.

Presently the remote monitoring system is interfaced with the plant SCADA. All monitoring is conducted from the SCADA system and any alarms such as AC or DC failure or reference electrodes which are out of range are generated by the MCU and transmitted to the SCADA as a specific alarm. On receipt of the alarm the operator can troubleshoot the fault. A schematic representation is presented below, (Figure 11).

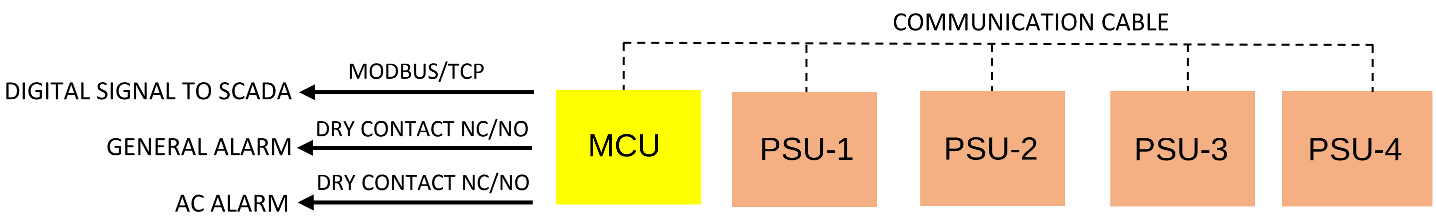

Figure 11: Remote Monitoring and Control Architecture

COMMISSIONING

Prior to energizing the CP system free corrosion potentials were recorded at all reference electrode locations. For the Screens and Distribution Chambers the natural potentials ranged between +780mV to +500mV wrt zinc or -500mV to -600mV wrt Ag/AgCl seawater electrodes. Refer to Table 6 for the equipment free corrosion potentials at all RE locations.

In the case of the Inlet Bay Guides (Zones 1-3) the potentials were significantly more negative. This was attributed to the stop log gates being installed at all Inlet Bay Areas. These remained installed throughout the commissioning period due to the possibility of maintenance works within the intake structure prior to handover. As the stop log gates have sacrificial anodes welded onto the front face, continuity between the guides and the gates resulted in CP being afforded to both the gates and guides at the Inlet Area. Hence the potentials for Zones 1-3 are in fact ‘on’ potentials. It is also possible that a small degree of polarisation has occurred on the equipment within the intake structure but to a much lesser degree. It would only be possible to measure true natural potentials on all equipment if the stop log gates were removed.

Table 6
Natural Potentials of Stainless Steel Equipment

		Free Corrosion Potentials (mV)	
Zone ID	**Area**	**RE-1**	**RE-2**
Zone 1	Inlet Bay	131*	147*
Zone 2	Inlet Bay	80*	157*
Zone 3	Inlet Bay	140*	102*
Zone 4	Screens	669	664
Zone 5	Screens	627	677
Zone 6	Screens	670	643
Zone 7	Screens	645	608
Zone 8	Screens	776	715
Zone 9	Screens	675	663
Zone 10	Screens	626	609
Zone 11	Screens	730	730
Zone 12	Screens	597	750
Zone 13	Screens	697	709
Zone 14	Screens	716	722
Zone 15	Distribution Bay	700	713
Zone 16	Distribution Bay	538	475
Zone 17	Distribution Bay	524	546
Zone 18	Distribution Bay	677	665
Zone 19	Distribution Bay	677	677

The CP system was commissioned in constant current mode to assess how the stainless steel polarised with time. The graphs below were created by the remote monitoring system. All results from the commissioning are not repeated in this paper, the examples below are typical of the results achieved at each similar type of zone.

INLET BAY (Figure 12):

Zones 1-3 were energized at less than 5% current output (7.5mA/m^2) as the sacrificial system from the stop log gates was providing adequate protection. The purpose of the 'trickle current' from the ICCP system was to produce a small amount of chlorine (a product of the anode reaction when in seawater), aimed at preventing marine growth from building up on the anode surface which may affect anode operation in the future.

Presently the stop log gates are operating above the selected upper limit. However this is a short term set up and once the gates are removed Zones 1-3 will be optimized using the ICCP system.

Once the stop log gates are removed the current output for Zones 1-3 will require optimizing to ensure protection is maintained along the entire Inlet Bay area.

Figure 12: Potential vs Time curve for Zone 3, Inlet Bay

SCREENS (Figure 13):

Polarisation of the stainless steel screens was faster than expected and the potentials recorded were more negative than expected with the applied current density. Full polarisation was achieved within 48 hours using only 20% of the initial current density, ie/. 30mA/m^2 out of the available 150mA/m^2. The current output was reduced to 20mA/m^2 within a week of energisation in order to shift the operating potential between +450mV to +250mV.

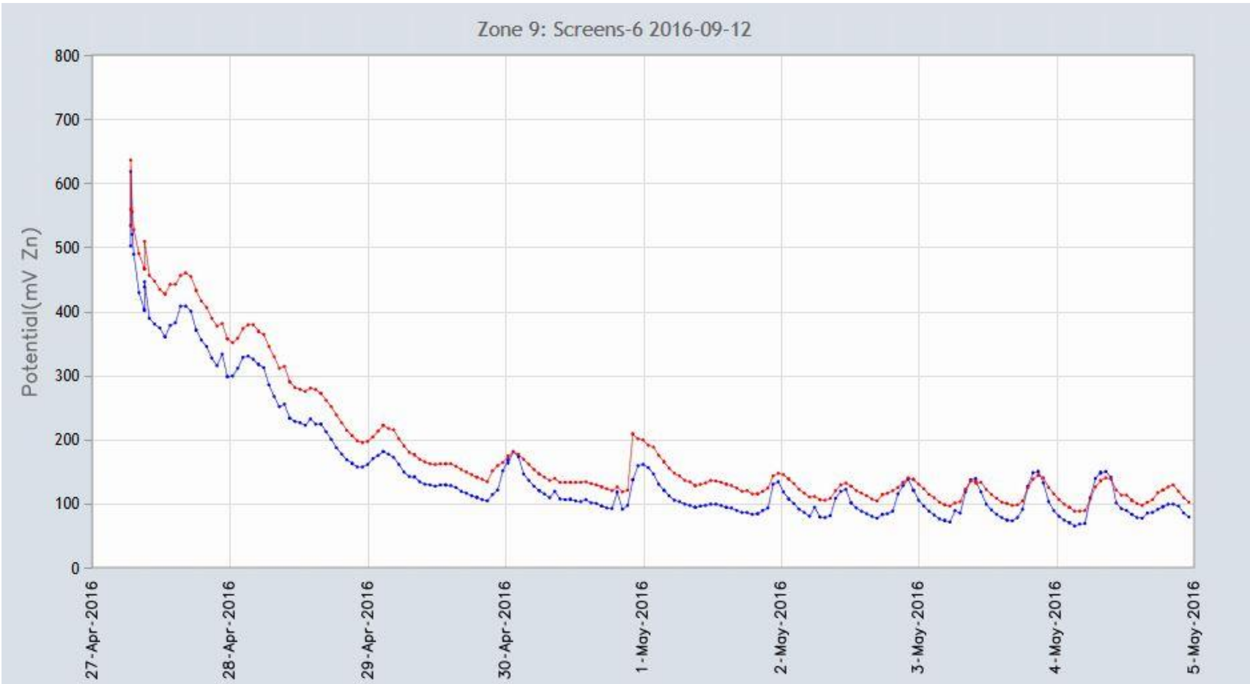

Figure 13: Potential vs Time curve for Zone 6, Screens

DISTRIBUTION BAYS (Figure 14):

Polarisation of the stainless steel guides at the Distribution Bays were similar in speed to the Screens. Full polarisation was achieved within 48 hours using only 20% of the initial current density, ie/. 30mA/m^2 out of the available 150mA/m^2. The current output was reduced further to 20mA/m^2 within a week of energisation in order to shift the operating potential between +450mV to +250mV.

Figure 14: Potential vs Time curve for Zone 18, Distribution Bay

In all zones the current distribution between the anodes was uniform demonstrating that balancing resistors are not required, (Table 7).

Table 7
Anode and PSU Current Output Values

Zone	Current (A)						
	A1	A2	A3	A4	A5	Header Cable	PSU Current
Zone 3 – Forebay 3	0.2	0.2	0.2	0.2	-	**0.8**	**0.9**
Zone 9 – Screen 6	2.5	2.7	2.1	-	-	**7.3**	**7.1**
Zone 19 – Distribution Bay 5	0.6	0.7	0.7	0.7	-	**2.6**	**2.6**

For the Screens and Distribution Bay Zones, the daily fluctuations in potential were a result of tidal action. This occurred even with the stop log gates installed as the gates were partially open to prevent water height differentials between high/low tides either side of the gates.

The CP system for the Screens and Distribution Bays were commissioned at 20% design current, (30mA/m^2). This demonstrates that a high initial current density value as specified by BS EN 13174: 2012 was not required. Based on the commissioning data we also expect the CP system to operate at a significantly lower operating current density than the value specified in the same standard.

Presently the intake structure has only 5 out of 25 pumps installed and all Stop Log Gates are installed at the Inlet Bay Area. The pumps are not yet operational and the screens are only rotated for 2 hours per day. The intake structure is not yet fully operational and this may explain the low current demand required to protect the equipment. Once the stop log gates are removed and the pumps and screens are operational, the rate of water flow through each chamber is expected to be significantly more turbulent. At this point a higher current demand is expected to maintain an adequate level of polarisation on the stainless steel. The effect this has on the demand of the CP system is subject to a separate paper.

The remote monitoring and control system has proved useful in recording the output current and operating potentials over the early stages of commissioning. The system has removed the need to have a full time Engineer based at site throughout the commissioning stage, which is a more cost effective set up. By interfacing the CP system with the Plant SCADA the Operator is able to monitor the system as and when required, without visiting the intake structure. Any system malfunction, such as loss of AC power to the power supply units or loss of DC power to a particular zone is relayed to the SCADA system and displayed as an alarm. This also applies to any potentials which fall out of range.

CONCLUSIONS

1. CP can be applied to submerged stainless steel screens and guides in order to extend its lifetime.
2. Middle East track record shows CP is now the technique of choice for structures exposed to chloride where long term durability is required, both technically and commercially.
3. Care needs to be exercised with respect to operating potentials to avoid overpolarising the steel as there is a risk of premature failure on components which are subject to dynamic stresses.
4. Current densities for protecting submerged equipment differ between prevailing local and international standards. It is up to the CP Specialist to select current densities from these standards that best represent the environment the equipment is exposed to.
5. The results indicate the system is operating satisfactory and that adequate protection is being achieved at current densities much lower than called for in many specifications. Additional adjustments are envisaged over the next 3 months but no problems are expected at maintaining the criteria at all reference electrodes.
6. Maintenance and Monitoring need not be a burden with the availability of modern computer controlled systems.

REFERENCES

1. NACE Corrosion 2012: Cathodic Protection of Stainless Steels and other Corrosion Resistant Alloys. Page 3
2. BS EN 13174: 2012: Cathodic Protection for Harbour Installations. Annex A. Page 22
3. EN 12473:2000: General Principles of Cathodic Protection in Seawater. Page 24
4. EN 12954:2001: Cathodic Protection of immersed or buried metallic structures. Page 16
5. DNV RP-B401 2010: Cathodic Protection Design. Annex A, Page 30
6. BS7361: Cathodic Protection Part 1: Code and Practice for Land and Marine Applications. Page 73.
7. SABIC Standard, KSA. Page 7