BUILT-IN CORROSION PREVENTION SYSTEMS FOR NEW REINFORCED CONCRETE SEAWATER PITS

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ABSTRACT

Cathodic prevention systems are now widely recommended for new reinforced concrete structures that are to be exposed to chloride containing environments. However, there are very little published data or design guidelines for such systems. In two new petrochemical plants, reinforced concrete seawater structures were constructed with built in cathodic prevention systems to prevent corrosion of the steel reinforcement from day one. This paper describes the design, installation and commissioning of these CP systems. The anode system consisted of mixed metal oxide coated mesh anode ribbon and titanium conductor bar. The paper will emphasize particularly on the anode design, anode zone configuration and installation practices. The initial performance of these CP systems will be described and discussed. The discussions will focus on different polarization behavior observed in different parts of the structures, i.e. atmospherically exposed, splash or tidal zone, buried and immersed, during the initial performance assessment.

Keywords: *cathodic prevention, concrete, titanium mesh ribbon, reference electrodes, and protection criteria.*

الملخص

نظام الحماية الكاثودية يوصى به على نحو واسع عند استخدام حديد التسليح في المنشآت الخرسانية الجديدة في المناطق التي تحتوي على كميات من الكلور ، ومع ذلك فإن انتشار المعلومات أو تعليمات التصميم لمثل هذه الأنظمة قليلة . في المنشآت الخرسانية في مصنعين كيميائيين جديدين والتي صممت لتخزين مياه البحر قد تم تنفيذ وإنشاء نظام الحماية الكاثودية لمنع التآكل في حديد التسليح من اليوم الأول .

في هذا البحث وصف للتصميم والإنشاء والصيانة في المراحل التشغيلية الأولى لأنظمة الحماية الكاثودية . وهذا النظام نظام الأنود يحتوي على خليط من أكاسيد المعدن المطلي بأنود شبكي مكون من الريبون "Ribbon " والتيتانيوم "Titanium" .

وسيكون المحور الأساسي في هذه الورقة الفنية عن تصميم نظام الأنود "Anode Design" و شكل المناطق الكاثودية والتدريب على إنشاء هذا النظام ، وسيتم مناقشة الأداء في المراحل الأولى من تشغيل هذا النظام ، وسوف تتركز هذه المناقشة على دراسة الإستقطاب في أجزاء مختلفة من المنشأة الخرسانية مثل المنطقة المكشوفة للبيئة والمتعرضة للرذاذ أو المد والجزر والمناطق المغمورة بمياه البحر أثناء تقييم الأداء المبدئي للنظام .

1. INTRODUCTION

In petrochemical plants, a lot of heat is generated in reactors during the process. Removal of heat is essential to the process. Saudi Basic Industries Corporation (SABIC) operates some 15 very large-scale plants in the industrial cities of Jubail and Yanbu, which use seawater as a cooling system for removal of exothermic heat. Seawater is used because a large quantity of water is needed and fresh water is not available. Each plant has very large-scale reinforced concrete water reservoir structures, i.e., for intake for intake and return supply. About 12 years ago, severe deterioration of concrete was noticed in most of these structures within a few years of operation. Investigations concluded that cause of the deterioration of concrete was due to chloride-induced corrosion of the reinforcing steel. Initially, conventional patch repairs were carried out in damaged areas, which did not last long and also enhanced the corrosion activity in surrounding areas. Subsequently, cathodic protection (CP) systems were installed onto some of the structures, which now have an operating life of between 3 to 10 years [M. Ali et al, 1999]. The monitoring data and periodic inspection of these structures have suggested that CP systems are meeting their design objectives in controlling the corrosion of steel reinforcement and associated concrete deterioration [M.Ali, 1999, Z. Chaudhary, 2001]. No further repairs were ever required on these cathodically protected structures, which showed that corrosion of the reinforcing steel was effectively controlled. This long-term observation is consistent with the statements made by FHWA[US FHWA, 1982] and others [B. Wyatt, 1993], which states that CP is the most appropriate and proven method for controlling corrosion of the reinforcing steel in chloride contaminated structures.

Based on these results, all new seawater reservoir structures in SABIC plants have now been constructed with built in cathodic corrosion control systems that are known as "*Cathodic Prevention Systems*". Cathodic prevention is an electrochemical technique, which components, operation and function are similar to that cathodic protection systems. However, as compared to cathodic protection, cathodic prevention is applied on only new structures containing no or very low levels of chloride ions in the concrete cover. Cathodic polarization is achieved by applying a very low cathodic current density. It is designed and installed to enhance the corrosion resistance of new reinforced concrete structures exposed to chloride rich environments [L. Bertolini, 1996].

This paper describes the design of cathodic prevention system of seawater structures and monitoring results. The performance assessment and protection criteria are also described and discussed.

2. SYSTEM DESIGN & INSTALLATION

2.1. Overall System Philosophy

All concrete sections of the seawater structures are to be cathodically protected throughout the entire structure for a design life of 40 years using embedded inert anode system to be powered

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by distributed small rectifier network system, which can be monitored, controlled and adjusted remotely through a modem line and a PC set up.

2.2. Design Current Density

The information available in national or international standards for designing cathodic prevention systems is very little. The published data in this regard is also very scarce and limited. According to Bertolini et al[5], some 150-200 mV cathodic polarization can be achieved by applying cathodic current densities ranging between 0.4 – 1.7 mA/m^2 of steel in chloride free concrete. The European Standard EN-12696-1 [BS EN 12696, 2000] recommends a range of 0.2 to 2 mA/m^2 of steel for passive steel in non-chloride-contaminated concrete. For reasons of increased safety factor, i.e. considering the prevailing high temperature and humid conditions in the Arabian Gulf environment and the seawater exposure, 2 mA/m^2 of steel was used in this design.

2.3. Anode Design

Mixed metal oxide-coated titanium mesh ribbon anode system was selected to meet the design life of 40 years. As compared to other commercially available materials, mesh ribbon anodes have a good track record and are widely recommended and used in new concrete structures. A good anode design requires sufficient redundancy and uniform current distribution, which are easily achieved with this type of anode.

The designer ensured that the anode system contained sufficient redundancy, such that none of the anode within a given anode zone is made inoperative under any of the following conditions:

- One random break in the power feed
- One random break in any anode ribbon
- One random break in the conductor bar.

According to the design current density requirement, the calculated spacing between the anode ribbons was more than 500 mm. However, for adequately uniform current distribution to the steel reinforcement cage, anode ribbons were positioned on each plane of reinforcement with a maximum spacing of 300 mm between them. This increased the maximum allowable current output per unit area.

The mesh ribbons were mounted directly on the reinforcement cage using the appropriate non-metallic fasteners. These spacers were positioned at every crossing point of anode and reinforcement. The anode ribbon was positioned between and not on the parallel reinforcement bars wherever possible. For anode safety during the concrete pour and compaction, anode ribbons were positioned on the inner side of the slab reinforcement cage.

All ribbons within each independent anode zone were welded to two separate titanium conductor bars, which were placed at right angles to, and at the end of each anode strand. Each conductor bar has its own separate anode feeder cable attached to it. This means that every anode zone has a minimum of two positive connections thus ensuring 100% redundancy in the power circuit. Prior to concrete placement, testing was carried out to ensure the following:

- Electrical continuity of each individual mesh ribbon to the anode feeder cable within each independent zone.
- Anode mesh ribbon and other components of the anode system in two adjacent anode zones are electrically discontinuous.
- Anode mesh ribbon and titanium conductor bar are electrically discontinuous to the steel cage within each zone and throughout the entire structure.

Throughout the concrete pour, testing was continued to ensure that there were no short circuits between the anode and steel reinforcement cage. Where such short circuits were found, concrete pour was temporarily stopped to rectify these faults.

2.4. Anode Zone Configuration

For the effective performance and assessment of CP system, it is normal and recommended practice to divide the structure to be protected into 2 or more zones [J. P. Bromfield, 1997, P.M. Chess, 1998]. A zone is defined as a discrete section of the structure that are powered and controlled separately. Zone design is usually based on; different environments to which steel is exposed, different anode types, chloride contamination, steel density and cover or geometry of the structure etc.

In this design zoning was based on the different environmental exposure regimes associated with the operation conditions of the seawater structure. The seawater structure was split into the following 5 independent zones:

- Zone W Submerged areas of the structure
- Zone S Areas subject to splash and wet conditions
- Zone H Areas above splash zone but subject to moist & humid conditions.
- Zone A Areas exposed to air and dry conditions.
- Zone G Below grade level areas.

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The size of the above zones was between 250 m^2 and 650 m^2 and layout of zones is shown in Figure 1.

2.5. Monitoring System

The CP system is monitored by Ag/AgCl reference electrodes, which are embedded in concrete at representative locations of the structure. About 5-7 reference electrodes were placed in each independent anode zone. The reference electrodes were distributed throughout the entire structure. Their positions were designed to give full range of polarization levels achieved within any anode zone. This ensures that every environmental and structural condition is accurately monitored and not just the areas of greatest corrosion risk.

Each reference electrode has an associated steel connection for monitoring purposes. Prior to their installation in the steel reinforcement cage, all reference electrodes were tested on site and then encapsulated in concrete cylinders of appropriate size. This practice was followed to avoid the development of air pockets that might occur at the measuring interface of reference electrodes during the concrete pour and hardening.

2.6. Negative Circuit

It was ensured that all steel reinforcement and embedded ancillary steelwork within the structure was electrically continuous. In addition, minimum two system negative connections were installed in each individual anode zone, thus ensuring 100% redundancy in the negative circuit. All these negative connections were then bussed together at the junction box to give the absolute maximum contingency in the negative circuit.

2.7. Cabling

All DC power and monitoring cables were appropriately color coded and labeled for their identification. The design calculations ensured that the voltage drop within the system would not exceed 300 mV from the power supply terminals to the farthest point in the circuit. For DC power cables, the specified insulation and minimum cross sectional area was high molecular weight polyethylene (HMWPE) and 4 mm^2 respectively. For monitoring cables, cross-linked polyethylene (XLPE) insulation was specified with a minimum thickness of 0.8 mm and cross-sectional area of 2.5 mm^2.

2.8. Power Supply and Remote Monitoring

All anode zones of the CP system are powered and remotely monitored by the distributed rectifier system [P. Mortensen, 1998]. The main components of this system are local rectifier units (LRUs), a control unit (CU) and a software system. All DC and monitoring cables from the structure are connected into the LRUs, which are linked via two-core cable to the CU.

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Each LRU can be configured to provide 3 output and 7 input channels or all 10 input channels. It can be operated in constant current or constant voltage mode. The CU consists of a portable computer (PC), the interface and the master LRU. The monitoring software is used to communicate between the master LRU, LRU and the PC. At the control unit, DC voltage and current outputs of each individual anode zone can be monitored and adjusted through the PC. Similarly, steel potentials at each embedded reference electrode in all zones can be monitored and recorded remotely.

3. SYSTEM COMMISSIONING AND MONITORING

3.1. Natural Potentials

Prior to energizing of the anode zones, pre-commissioning checks were undertaken to ensure all circuits are in correct order and polarity. Then natural potentials were measured and established at the location of all embedded reference electrodes in all zones. The results are shown in Figure 2.

A clear demarcation and trend was evident from the natural potential results collected from different environmental exposure regimes. The range of potentials in different environmental regimes was as follows:

- Zone W between –554 mV and –948 mV Ag/AgCl
- Zone S between –536 mV and –895 mV Ag/AgCl
- Zone H between –145 mV and –547 mV Ag/AgCl
- Zone A between –145 mV and –418 mV Ag/AgCl
- Zone G between –566 mV and –734 mV Ag/AgCl

As expected steel potentials were more negative in zones W, S and G than in zone A and H, which can be attributed to the low concentration of oxygen.

3.2. Initial Energizing

All anode zones were initially energized in constant current mode at an applied current density of 1 mA/m^2 of steel and left to operate at this current level for seven days. After 7 days, the polarization growth towards more negative potentials in all anode zones was evaluated and generally found to be very small and insufficient. Therefore the applied current was increased and set between 1.75 and 2 mA/m^2 of steel. The system was then allowed to operate at this current level for three weeks.

3.3. System Monitoring

After the initial performance assessment (after 7 days) of the CP system, it has been monitored at 1 month, 3 month and 6 month after the initial energizing of the system. During each monitoring, instant-off steel potentials were recorded at the location of all embedded reference electrodes and then the current was interrupted and current-off potentials were recorded at 1, 4, 24, 48, 72 and 96 hours after the current interruption. The polarization growth (negative potential shift) was determined by calculating the difference between the natural potentials and the instant-off potentials. Similarly, the maximum potential decay was determined by calculating the difference between the instant-off potentials and current-off potentials. The average results of instant-off steel potentials, negative shift and maximum potential decay from all anode zones are illustrated in Figures 3-7.

In Zone W, there was a gradual increase in instant-off potentials, negative potential shift and potential decay. Therefore, the applied current was maintained at 2 mA/m^2. In Zone S, and H, the applied current was increased to a level of 2.4 mA/m^2 to enhance the rate and magnitude of potential growth. In both zones, instant-off potentials were more or less remained unchanged, however, negative shift and potential decay were found to increase in magnitude with time. The magnitude of negative potential shift and potential decay was very small initially in both zones A & G. Therefore the applied current was increased to a level of 3.5 and 4 mA/m^2 of steel respectively. This resulted in increasing the magnitude of shift and decay in both zones.

4. SYSTEM PERFORMANCE ASSESSMENT

4.1. Protection Criteria

Normally, two criteria are used for assessing the effectiveness of the cathodic protection systems of reinforced concrete structures[6].

1. 100 mV potential decay from instant-off in 24 hours after current interruption.
2. An instant-off potential more negative than –720 mV Ag/AgCl.

Since, there are no separate criteria or guidelines available in international literature for cathodic prevention systems, the above two criteria are used for system assessment. The degree of compliance to the above criteria in each zone is shown in Figure 8. The results suggest that the degree of compliance to any one of the above two criteria is greatly affected and related to the conditions that prevail in these zones.

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In submerged areas (Zone W), only –720 mV instant-off criterion was met. Although, the average negative potential shift had reached around 100 mV after six month's operation of CP system, the average potential decay was not more than 50 mV even 72 hours after the current interruption. In zone S, where concrete was fairly wet and sometimes submerged, average instant-off potentials were more negative than –720 mV throughout the monitoring so far. However, the potentials were found to shift towards less negative potentials with time and decay criterion was also met at some locations. In below grade areas (Zone G), average instant-off potentials were always less negative than–720 mV Ag/AgCl but individually at some locations they were more negative –720 mV Ag/AgCl. The decay criterion has also been met at some locations and the decay magnitude is generally found to increase with time. In zones H and A, the instant-off potentials were always significantly less negative than –720 mV Ag/AgCl and on average they ranged between –325 mV and –400 mV Ag/AgCl. In both areas, only decay criterion was met and the decay magnitude has been found to increase with time.

The above results are in good agreement to the past experience, which has suggested that the rate of depolarization is much slower in areas where the oxygen concentration and diffusion is low[Z. Chaudhary, et al, 1997, Concrete Society Technical Report # 36, 1989]. The results have therefore confirmed that for submerged and fairly wet conditions (Zone W & S), –720 mV criterion is more practical than decay. Similarly, for areas exposed to relatively dry conditions and where natural potentials are less negative than –400 mV Ag/AgCl, the 100 mV decay criterion is more practical than –720 mV instant-off. In order to achieve the –720 mV criterion in such areas, a large current would be required to produce this amount of polarization. Firstly, this may not be possible in cathodic prevention systems, as they are designed using very small current densities. Secondly, if large amount of current is available it may as a result exceed the anode current rating damaging the anode. For optimum conditions between the submerged and dry zones, either of these two criteria may be applicable and practical. It is recommended that the CP specialist or analyst should take into account the prevailing conditions, whilst assessing the system performance and apply the more practical criteria.

4.2. Steel Current Density

Although the system was designed using a steel current density of 2 mA/m^2 , it had capacity to deliver much more than that due to the maximum spacing of 300 mm between the anode ribbon (as described above). The results have shown that in all zones, more than 2 mA/m^2 of steel was required to meet one of the above two criteria. For zones W, S and H, the current requirement was between 2 and 2.4 mA/m^2 of steel. However, in zone G and A, it was relatively much higher and ranged between 3.5 and 4 mA/m^2. In spite of higher current levels in these two zones, criteria compliance has been very poor so far. And it appear, more current is required to acquire sufficient protection. Poor compliance in the atmospherically exposed zone is quite unusual, as this area is exposed to dry conditions, where corrosion risk is much lower and depolarization rate is always very high. Therefore, current requirement in this zone should be relatively less. The only explanation, which can be given, is poor current distribution due to dry conditions. However, more time is required to be conclusive. In case of zone G, there may have been some current leakage to adjacent structures (pipelines, sleepers etc.) resulting in higher current demand. In general, the results have shown that much higher current densities are required for sufficient protection in such structures as compared to laboratory scale samples.

5. CONCLUSIONS

Both criteria, i.e.–720mV instant-off and 100 mV decay, can be applied in assessing the performance of cathodic prevention systems. However, for any given area suitability of one of these two criteria is governed by the existing concentration or rate of diffusion of oxygen in that area. For submerged and very wet conditions, –720 mV instant-off criterion is more practical than 100 mV decay. Conversely, for dry and atmospherically exposed areas, 100 mV decay criterion is more practical than –720 mV instant-off. For below grade areas and those subject to splash, both criteria may be applied and practical, however, if they are very deep or wet then –720 mV instant-off criterion is generally more practical than other.

For such large-scale structures, the minimum required steel current density appears to be around 2 mA/m^2 of steel or more. In some cases, it could be as high as 4 mA/m^2 of steel. These values are much higher than the range of 0.4 to 2 mA/m^2 of steel, recommended in the European Standard[6] and in other published work.

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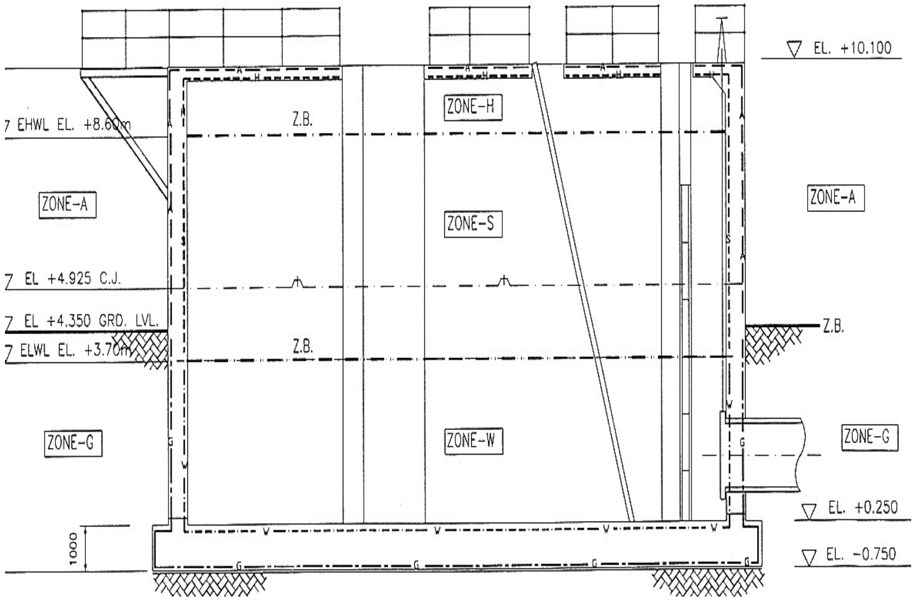

FIGURE 1 – Layout of anode zones.

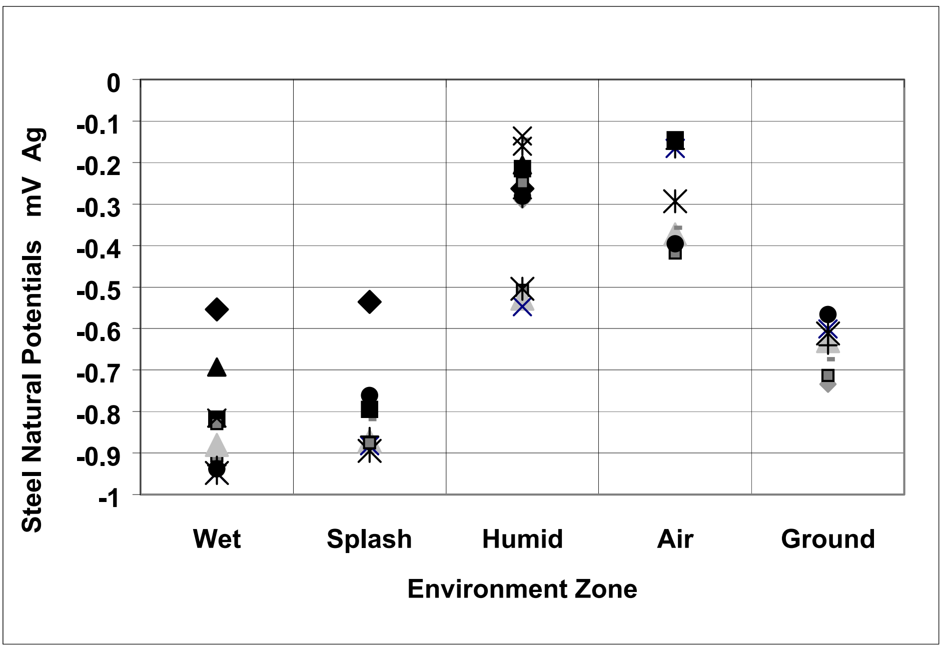

Figure 2- Range of natural steel potentials in different zones

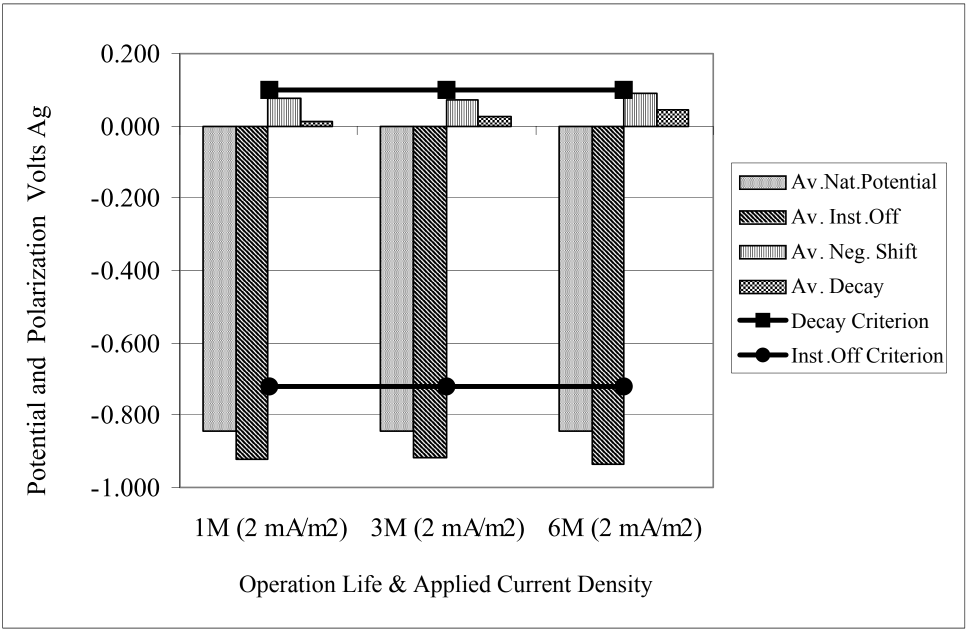

FIGURE 3 – Electrochemical monitoring data collected from Zone W.

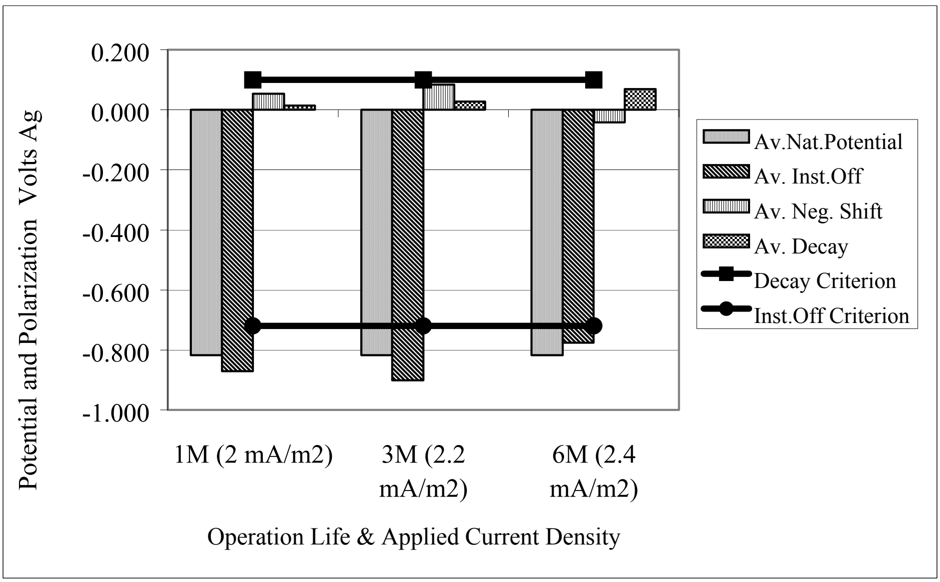

FIGURE 4 – Electrochemical monitoring data collected from Zone S.

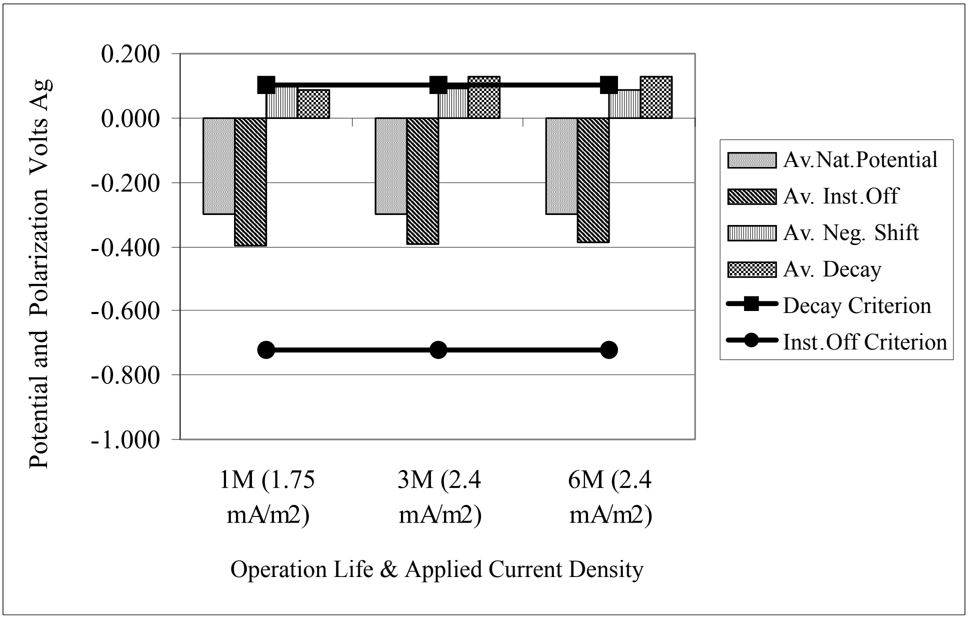

FIGURE 5 – Electrochemical monitoring data collected from Zone H.

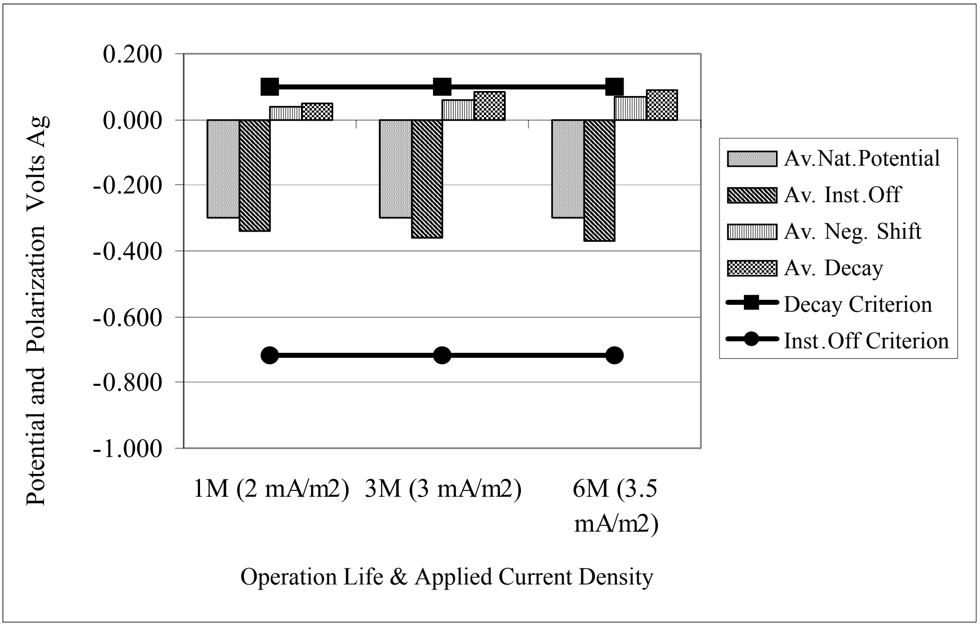

FIGURE 6 – Electrochemical monitoring data collected from Zone A

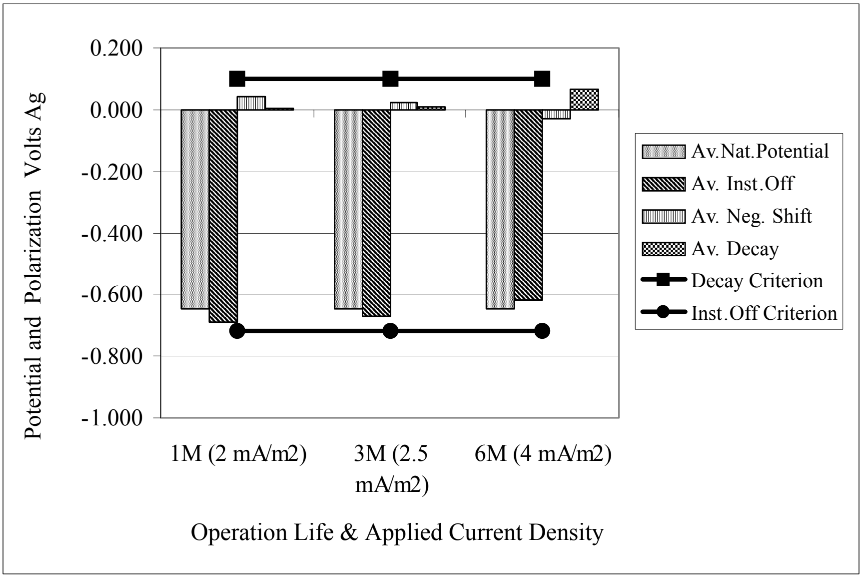

FIGURE 7 – Electrochemical monitoring data collected from Zone G

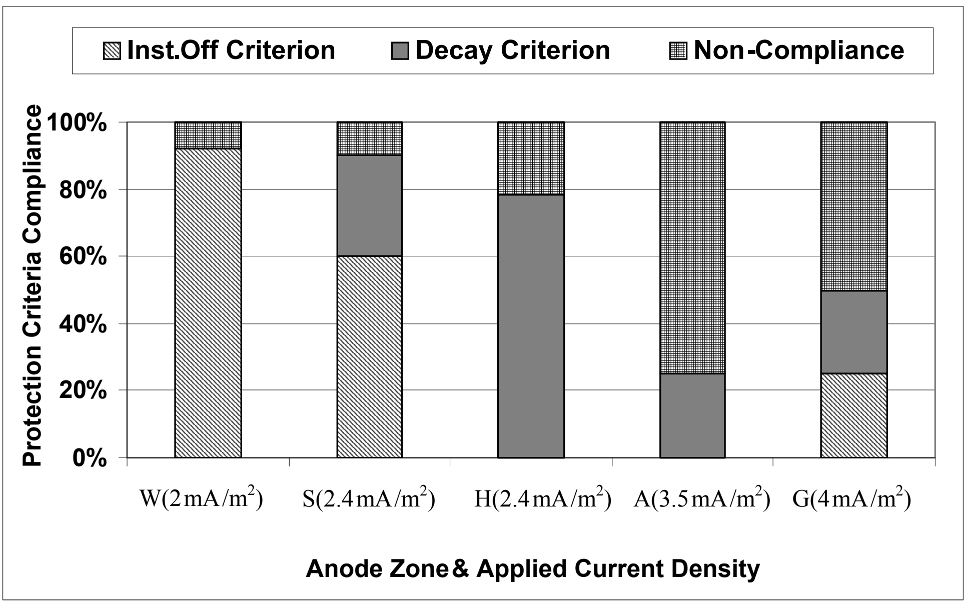

FIGURE 8 – Summary of protection criteria compliance.