Advanced Cathodic Protection Modeling Associated with Coating Degradation Conditions

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There are two effective methods in use to protect ship ballast tank against corrosion. One is paint coating and the other cathodic protection(CP). The conventional cathodic protection design has mainly relied on the expert's experience. During the last two decades computer modeling has been significantly developed as an advanced design technology for cathoidic protection systems not only for ships, but also for offshore structures. However the present computer modeling of cathodic protection systems have some limitations simulating corrosion in the ballast tank with a deteriorated coating. In this study, "coating breakdown factor" considering coating degradation states with time has been attempted to improve the cathodic protection modeling using the data from literatures.

Keywords *: cathodic protection(CP), boundary element method, computer modeling, CP required current density, paint coating break down*

1. Introduction

Cathodic Protection (CP) is widely accepted in ships, offshore structures, as well as buried pipelines for corrosion prevention.[1] CP systems have been utilized as a compensation technique for the loss of physical protection due to the degradation of paint coatings over time.

In a traditional CP design, the distribution of potential and current on the surface of protected structures has always relied on the judgment and experiences of the operator or designer. The traditional design has been carried out by simple arithmetic rules based on CP data, including the structure area to be protected, the current demand to be supplied, and the anode resistance associated with anode shape.[2] Therefore, in the case of complicated structures the uniform and optimized distribution of CP potential and current could not be achieved because of the simple experience-base arithmetic methods, instead of a science-based systematic way. Using the traditional method, the required current density, one of the most important factors for CP design, is significantly different from that of real structures, since the estimation has not properly considered the coating condition and related degraded areas on the surface of protected structures.[3]

Computer modeling has been used to attempt to solve the un-distribution problem and to achieve an optimized CP design. Boundary element method (BEM) has become one of the successful techniques which has been adapted in the CP design field and presently it is an acceptable practice in many corrosion-related studies as well as supplemental works.[4] The numerical analyses have been conducted by the BEASY software which was commercially developed and presently well recognized as a useful tool in the field of cathodic protection design.

The purpose of this paper is not only to confirm the BEM analysis for better potential/current distribution, but also to attempt to model the degraded coating to achieve a more accurate in CP design. A ship ballast tank filled with seawater was chosen as a simulation for a sacrificial anode cathodic protection (SACP) design. The study computes and analyzes the best position of Aluminum sacrificial anodes in ballast tank for even CP potential/current in association with various coating degradation conditions.

2. Experimental procedures

2.1 Governing equation and boundary conditions

The current density distribution is produced from a re-

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sult of solution resistance and potential difference between anode and cathode metals. The potentials of the anode and cathode in the same electrolyte are different due to the current flow through the electrolyte where the two metals contact.

The equation governing the current flow and the potential distribution in an electrolyte can be derived from first principles.[1)] The continuity equation (charge conservation) requires that the current per unit volume, I, is related to the charge q as :

$$-\nabla I = \frac{\partial q}{\partial t} \quad (1)$$

For a system in steady state, $\partial q/\partial t = 0$. Taking into account the relationship of electric field intensity, E [V/m],

$$E = -\nabla \phi \quad (2)$$

and Ohms law

$$I = KE \quad (3)$$

where K is the conductivity of electrolyte. The continuity equation transforms to

$$\nabla(K\nabla \phi) = 0 \quad (4)$$

For an electrolyte with uniform, isotropic conductivity, K is a constant, so that,

$$\nabla^2 \phi = 0 \quad (5)$$

Therefore, for a uniform, isotropic electrolyte, the potential obeys equation (5) which is the Laplace equation. The current density, at any point inside the electrolyte can be evaluated by :

$$I_n = -K\frac{\partial \phi}{\partial n} \quad (6)$$

where I_n is the current density in the n direction Φ [N · m/C] = [V] is the potential.

In a galvanic corrosion or cathodic protection problem, the potential field through the electrolyte volume is determined by solving the Laplace equation. Three computational domains were used in this study. The finite domain interior to water ballast tank/seawater interface was used to simulate the galvanic corrosion problem in a closed volume of sea. The structure/seawater interface consists of two areas: anode (e.g. aluminum-alloy anode), cathode (e.g. painted water ballast tank inside). The boundary conditions for these two areas are as follows:

$$\text{Anode} \qquad \frac{\partial \phi}{\partial n} = f_A(\phi) \quad (7)$$

$$\text{Cathode} \qquad \frac{\partial \phi}{\partial n} = f_C(\phi) \quad (8)$$

The boundary conditions of both anode and cathode are the linear functions obtained from traditional design factors with coating degradation conditions. In this study, the coating degradation of the structure of the water ballast tanks inside are assumed to be uniform through the whole structure.

2.2 Anode output current

The type of sacrificial anode used in this study is the Al-anode as shown in Fig. 1. For BEM analyses, the func-

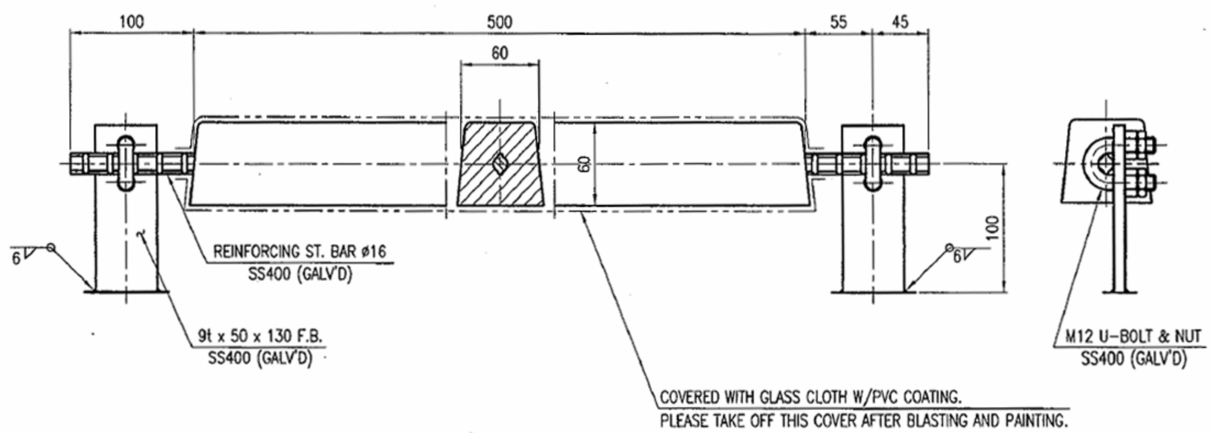


Fig. 1. The dimensions of selected Al-anode.

tion between potential and current density is required for anodic material behavior in seawater. The performance results of Al-anode submitted by manufacturer are applied as anode boundary conditions.

An estimation of anode output current can be derived from ohm's law as follows;

$$I = \frac{\Delta V}{R} \tag{9}$$

ΔV = Driving voltage (=Potential difference)
R = Anode resistance, ohms (L≥10r)

$$R = \frac{\rho}{2\pi L}(\log_e \frac{2L}{r} - 1.0) \tag{10}$$

ρ = Assumed resistivity of sea water, ohm-cm
L = Length of anode, cm
r = Mean effective radius of anode, cm

$$r = \sqrt{\frac{A}{\pi} \times \%} \tag{11}$$

A = Cross section area of anode, cm^2

2.3 Coating breakdown rate and anode current density

As a vessel ages, anode mass is reduced. The reduction of anode mass means that the cross sectional area of the anode (A in Eq. 11) becomes smaller. The time based coating breakdown rate has been adapted to estimate the coated steel condition of structures. Required current density with time in coating breakdown rate (12) is affected by the calcareous deposit formations reducing the current density on current density on bare steel and paint degradations increasing the current density on coated steel. The series of equations below show how to derive the anode current density at the boundary condition for the CP design obtained from the required current density of coated steel. The mass loss of anodes with time can be assumed through this series of equations until under-protection areas are appeared.

1) Required current density of protected metal (cathode) (Amp/m^2) :

$$Coating\ breakdown\ rate = \frac{Current\ density\ on\ coated\ steel}{Current\ density\ on\ bare\ steel} \times 100 \tag{12}$$

2) Required current of protected metal (Cathode) (Amp) :

$$Current\ density\ on\ coated\ steel \times Cathode\ area \tag{13}$$

3) Anode consumption (kg) :

$$\frac{Lifetime\,(yr) \times 8760\,(hr/yr) \times required\ current\,(A) \times Ballast\ Ratio\,(\%)}{Anode\ Material\ Current\ Capacity\ (A.hr/kg) \times Utilization\ Factor} \tag{14}$$

4) Anode consumption rate (%) :

$$Anode\ consumption\ rate = \frac{Accumulated\ anode\ consumption\ (kg)}{Total\ anode\ net\ weight\ (kg)} \tag{15}$$

5) Effective radius (cm) : refer to Equation (11)
6) Anode resistance (ohm) : refer to Equation (10)
7) Anode current (A/pc) : refer to Equation (9)
8) Anode current density (Amp/m^2) :

$$\frac{I(anode\ current)}{A(anode\ area)} \tag{16}$$

3. Results and discussions

3.1 Anode consumption

The consumption rate and the volume reduction for aluminum sacrificial anodes calculated by the traditional sequence in section 2.3 with time for the water ballast separated by three sections, i.e. side, hopper and bottom, respectively, as shown in Fig. 2. Figs. 3-5 is the viewgraphs of calculated results up to 9 years of life time, and the reduction of anode mass for each 5 years is indicated in each figure. Even the actual paint deterioration rate is different from the constant design value used in this calculation, the anode mass was predicted to reduce about 45~57% from original in 5 years.

When the reduction of anode mass reaches around 50% of original, the anode radius remains about 70% of the initial size. This means that the size of used anode may not be apparently different from the original one. This is why the renewal time of anodes can be practically miss-estimated by many investigators.

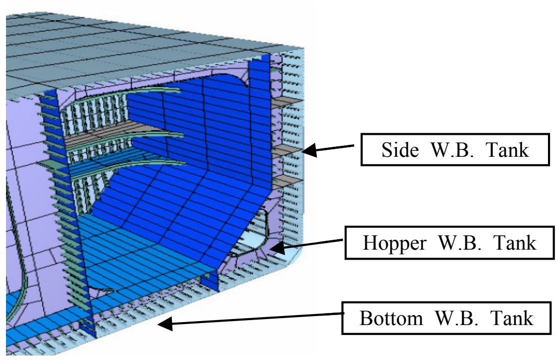
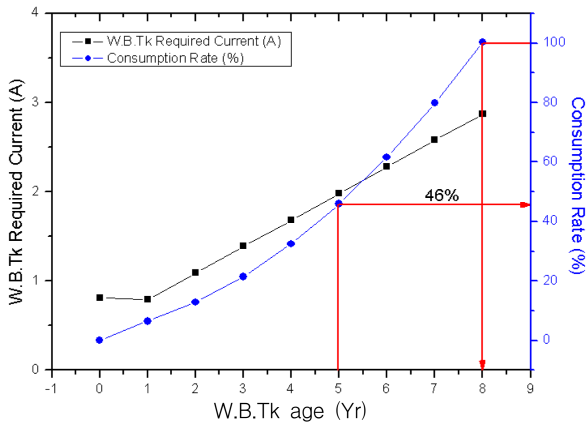
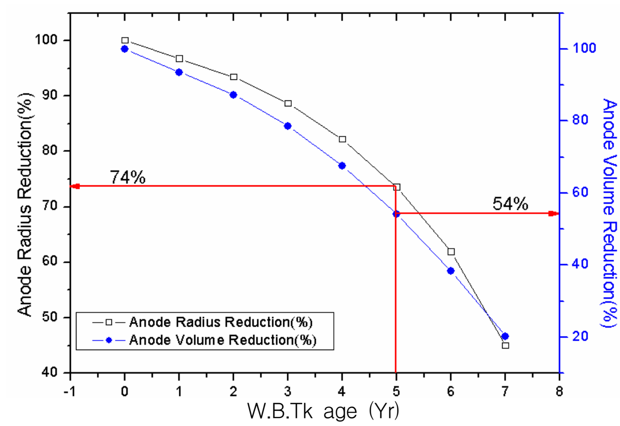


Fig. 2. Typical water ballast tanks of a crude oil tanker.

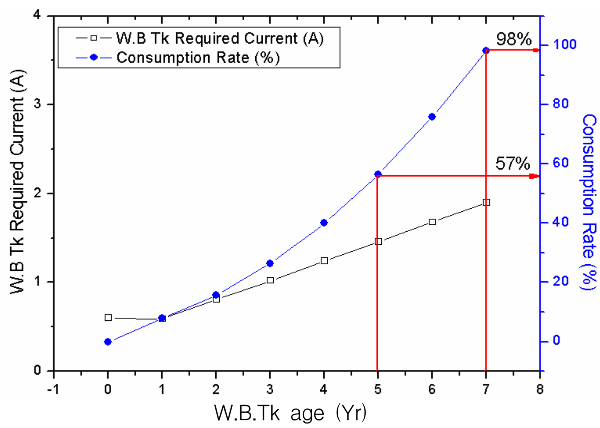


(a) Anode consumption rate with over time

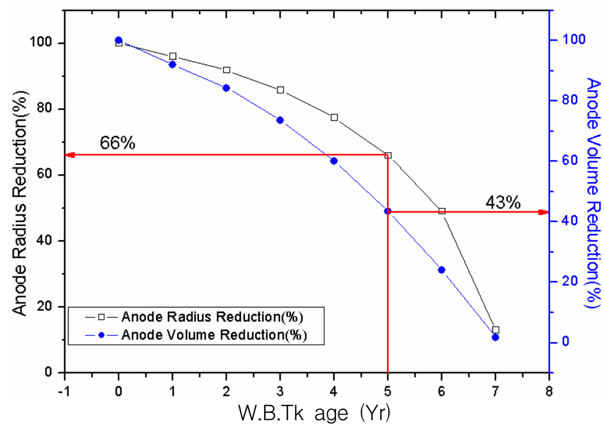


(b) Anode volume reduction with over time

Fig. 3. Anode reduction in Side W.B.Tank.

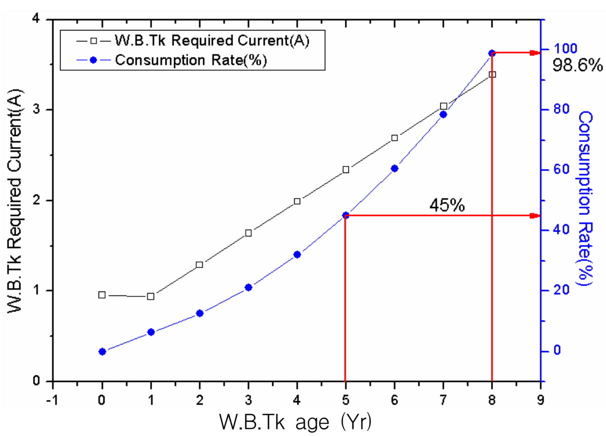


(a) Anode consumption rate with over time

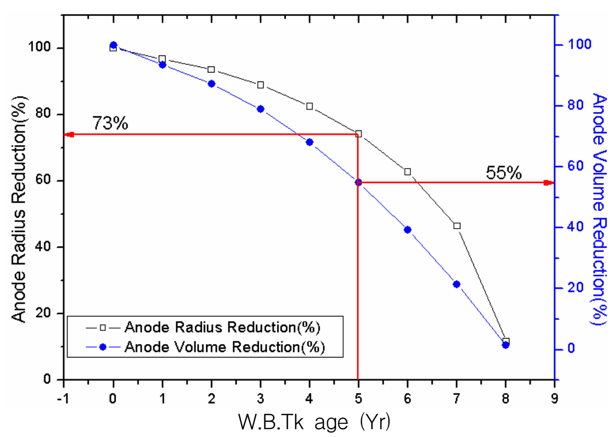


(b) Anode volume reduction with over time

Fig. 4. Anode reduction in Hopper W.B.Tank



(a) Anode consumption rate with over time



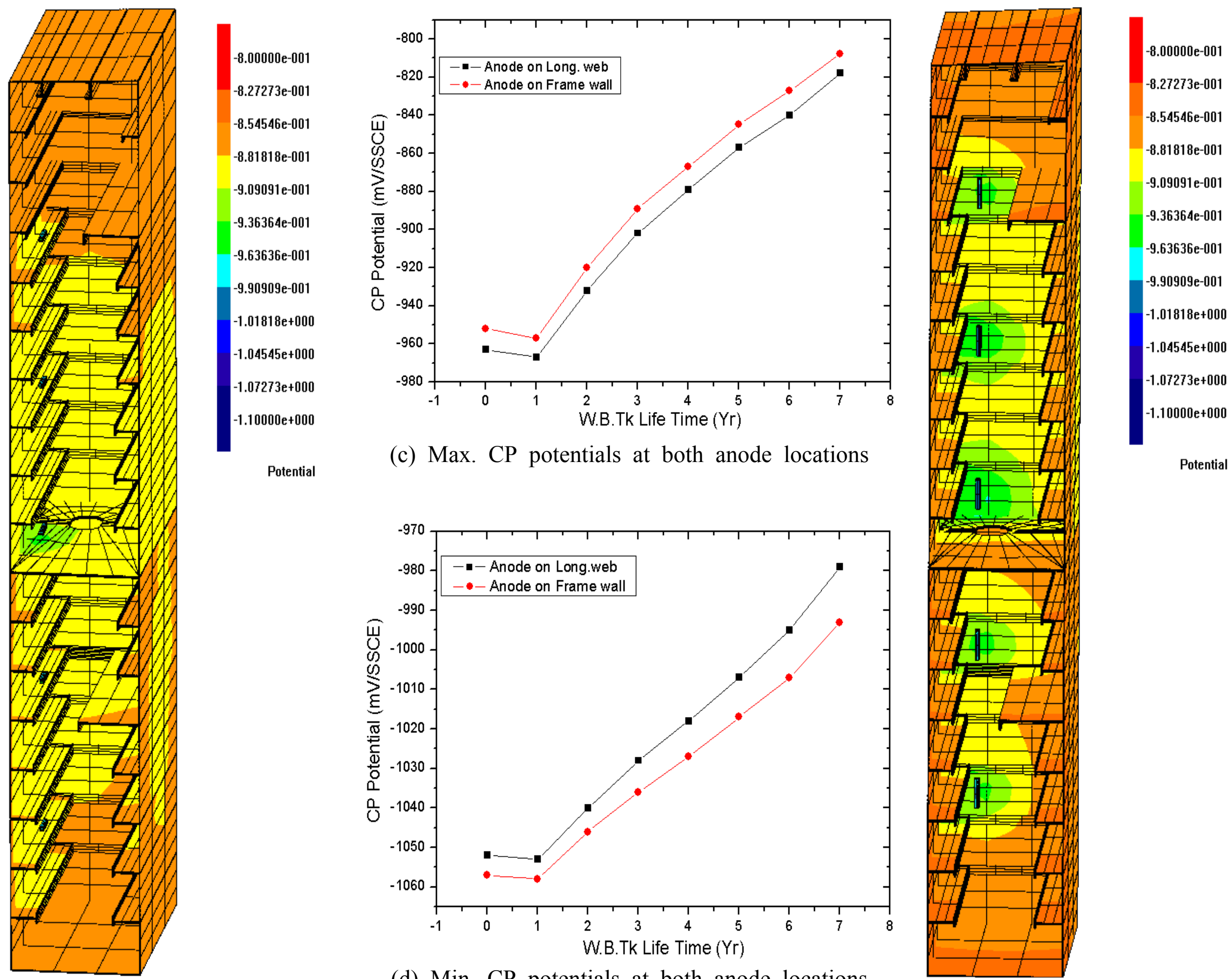
(b) Anode volume reduction with over time

Fig. 5. Anode reduction in Bottom W.B.Tank

3.2 Analysis results of cp potential in W.B. tanks

Ballast tanks are one of the parts subject to the most severe corrosion on a marine vessel. Most ballast tanks on ships are sub-divided into three parts as mentioned in section 3.1(Fig. 2). For accuracy of the analyses, these components were separated into three geometric models. The number of sacrificial anodes and their locations were decided from the suggestions of the anode manufacturer who designed the sacrificial anode system on the subject vessel. The positions of anodes were in two different locations, i.e. longitudinal web (long. web.) and frame wall.

Figs. 6-8 presents both the simulated potential contours and the CP potential variations with time for the three types of ballast tanks. For the side W.B. Tank in Fig. 6, more concentrated potential contours around anode were at frame wall. Therefore, the CP potential distribution was more uniform at the anodes on longi. web than at frame wall. The range between the maximum and the minimum potential variations with time as indicated in Fig. 6 (c) & (d) was narrower in the longi. web. than frame wall. Consequently it was determined that an anode location of longi. web. was better for the optimum CP design than frame wall. This trend was repeated both in hopper and bottom sections of a W.B. Tank. As represented in Fig. 7 and 8 the potential distribution was more uniform at anode on a longi. web. and the potential range between maximum and minimum ones at the same location was also more beneficial than at frame wall. Especially the life-time difference between the two anode locations at the -800 mV/SSCE known as the minimum CP potential were 1.3 years in hopper and 1.1 years in bottom, and in both cases the long. web. showed the favorable position.



(a) Anodes on the long. web.

(b) Anodes on frame wall

(c) Max. CP potentials at both anode locations

(d) Min. CP potentials at both anode locations

Fig. 6. CP potential results of Side W.B. Tank

4. Summary

Computer modeling for confirming the potential distribution by sacrificial anode cathodic protection in ballast tanks has been carried out using a commercially available BEM program, BEASY CP. In order to evaluate the effectiveness of a traditional CP design, the amount of anode consumption has been calculated by the series of conventional equations with more realistic boundary conditions considering paint degradation condition over time. Better locations for sacrificial anodes have been determined both for uniform CP potential distribution and for longer life-time of sacrificial anodes. More study regarding the relationship between the remaining amount of anode and the paint degradation condition is needed for quantifying the life-time of cathodic protection not only for ballast tanks but also for other steel structures in marine environment.

References

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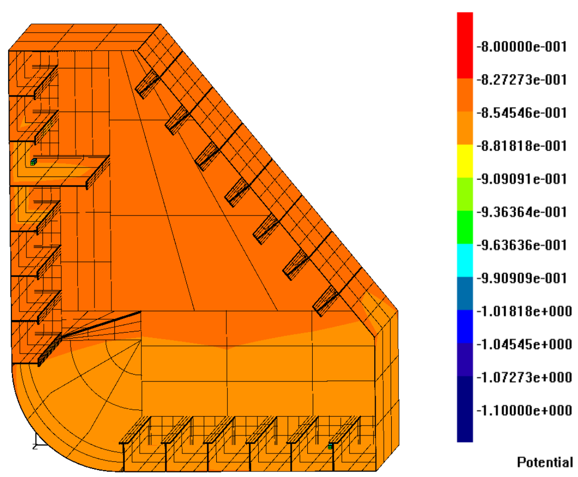
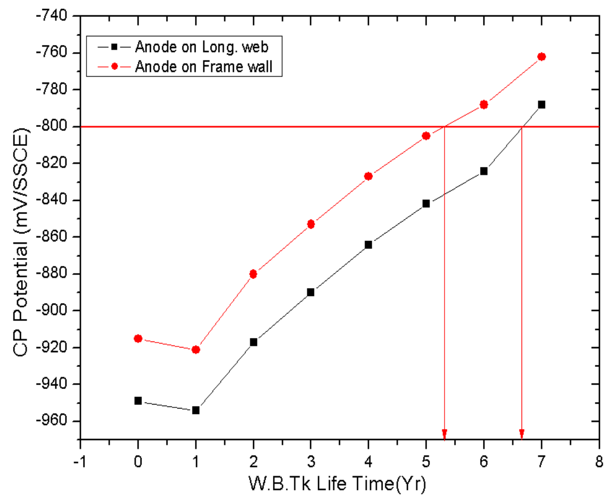
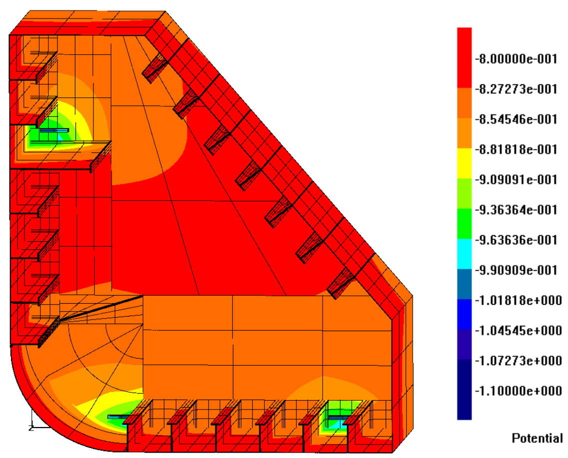


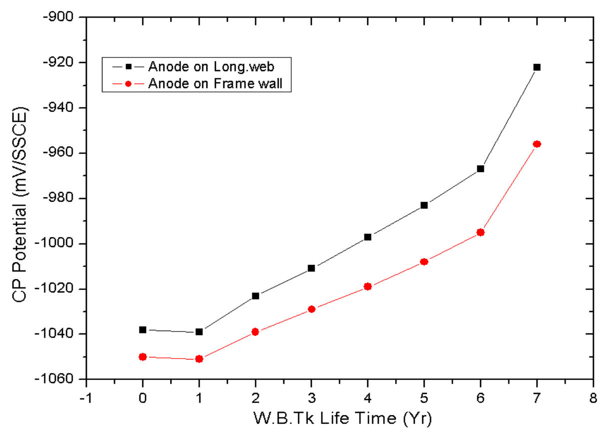
(a) Anodes on the long. web.



(c) Max. CP potentials at both anode locations

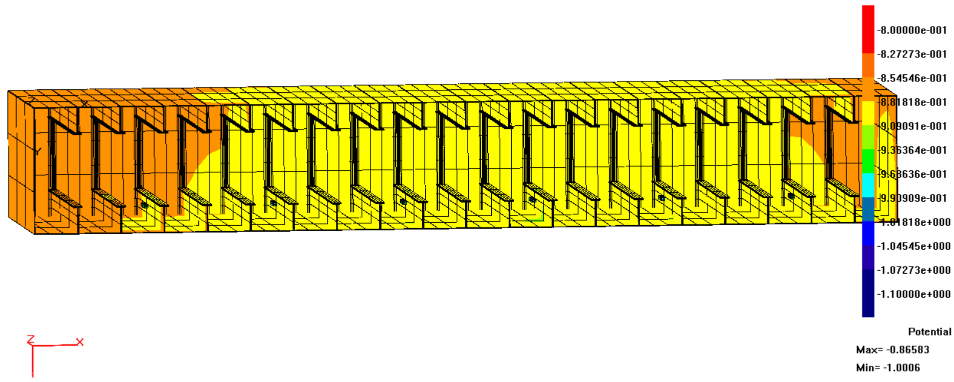


(b) Anodes on frame wall

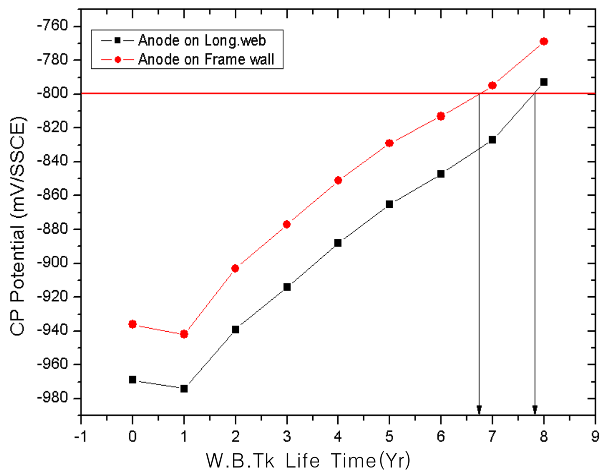


(d) Min. CP potentials at both anode locations

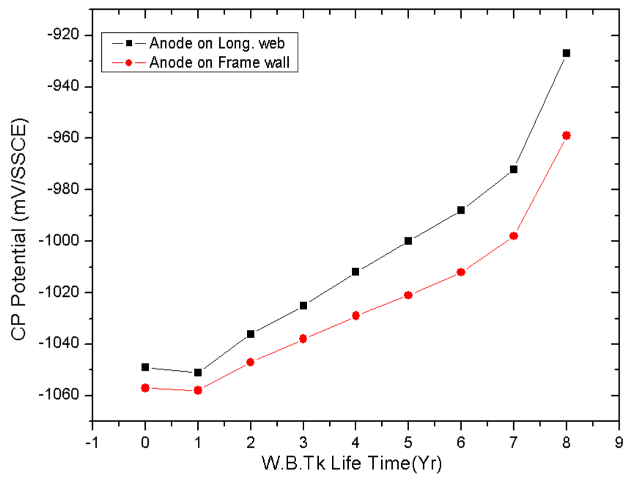
Fig. 7. CP potential results of Hopper W.B. Tank



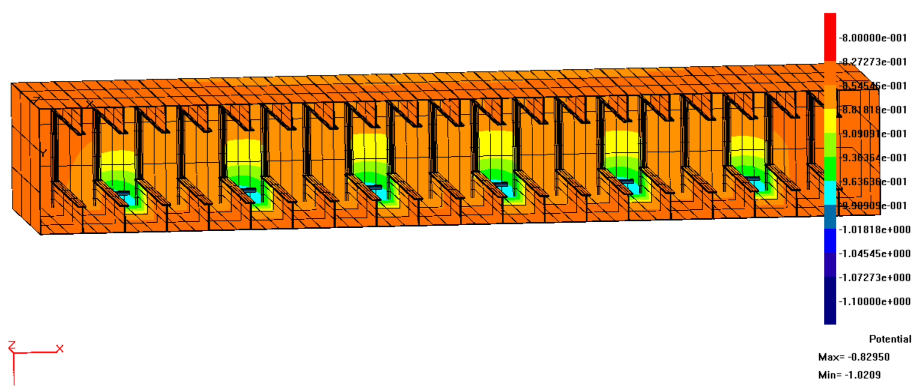
(a) Anodes on the long. web.



(c) Max. CP potentials at both anode locations



(d) Min. CP potentials at both anode locations



(b) Anodes on frame wall

Fig. 8. CP potential results of Bottom W.B. Tank