

# COMPUTER PREDICTION OF STRAY CURRENT CORROSION

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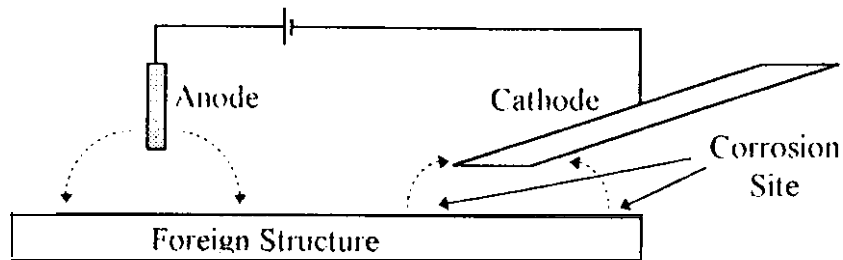
## SUMMARY

The likelihood of CP interference on steel structures located in proximity to large cathodically protected chemical storage tanks was evaluated using one of the latest computer modelling techniques. Application of the Boundary Element Analysis System (BEASY) allowed CP interference to be assessed in terms of current density, which is directly proportional to the corrosion rate, rather than having to use the qualitative approach of measuring the potential shift of the soil. Furthermore, the computer modelling approach enables results to be obtained at the design stage, allowing CP systems to be optimised so that interference is minimised.

**Key Words:** Computer Modelling, Cathodic Protection Interference, Boundary Element Method

## 1. INTRODUCTION

Cathodic protection (CP) systems are used extensively to prevent steel structures from corroding, especially when failure of the structure will have serious consequences, such as loss of life and/or injury, and damage to property and/or environment. When correctly designed and operated, these CP systems significantly reduce the rate of corrosion and thereby extend the useful life expectancy of the structure. Nevertheless, the use of this technique can interfere with other structures. CP interference can occur when neighbouring steel structures (ie. foreign structures), are located within the electric fields of a CP system. For example, when cathodically protected pipelines cross over other pipelines, ships dock at cathodically protected jetties, or pipelines approach cathodically protected tanks, etc. In these situations, the CP systems can accelerate the rate of corrosion on the foreign structure (see Figure 1).



**Figure 1:** CP inducing corrosion on a foreign steel structure

When designing or operating a CP system, it is important to ensure that foreign structures are not damaged by the system. In the past, predicting CP interference before a CP system was installed was difficult. Mitigating unwanted CP interference was a task of adopting very conservative designs combined with extensive post-commissioning programmes of measuring potential shifts on foreign structures. Moreover, defining a criterion for CP interference in terms of a potential shift is fraught with danger. In some cases a particular potential shift may pose a serious threat while in other circumstances the same shift may be insignificant. It is notable that, in recent publications of the Australian Standard on cathodic protection [1,2], the authors leave the assessment of CP interference to the professional judgement of the CP engineer. Clearly, such subjective assessment is unsatisfactory. This article suggests a more scientific approach to the problem.

Ideally, the best approach to assessing CP interference is to determine the change in current density on the foreign structure induced by the CP system. Current density is a more reliable parameter with which to assess CP interference because it is directly proportional to metal loss. However, in the past, the lack of a technique for determining how the CP affects the distribution of current on the foreign structure has prevented this approach from being adopted. Determining the response of the foreign structure to the CP system is not trivial because it is a function of three things: the location of the foreign structure with respect to electric fields generated by the CP system, the magnitude of the electric fields, and the electrochemical response of the foreign structure to the interference. Until the development of high speed computers and new computer modelling techniques this has been an insurmountable problem. However, the development of finite and boundary element methods have finally provided the necessary tools to accomplish these tasks [3,4].

In this particular study, the Boundary Element Analysis System (BEASY), loaded on a Pentium PC, was used to predict levels of CP interference on buried structures located close to cathodically protected steel tanks. This information was used in an effort to optimise the CP design and thereby minimise CP interference.

## 2. MODEL DESCRIPTION

### 2.1. Mathematical Approach

The problem of predicting the magnitude of CP interference can be summarised as follows: There is a volume,  $V$ , containing electrolyte in which a potential field is created by electrodes located on the surface,  $S$  (see Figure II). Also on the surface of  $V$  there is an isolated steel structure which is influenced by the electric fields within  $V$ . It is important to stress that, although the following diagram shows  $V$  to be finite, one of the advantages of the Boundary Element Method (BEM) is that the potential field within  $V$  can also be modelled when  $V$  is infinite.

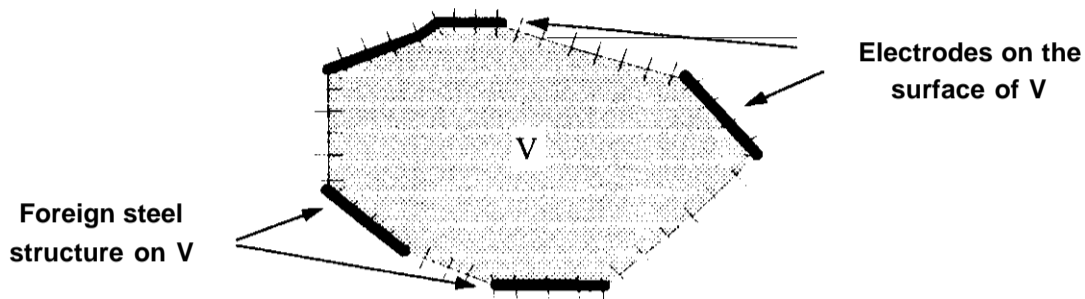


Figure II: The cathodic protection interference model. It consists of a volume,  $V$ , containing electrolyte and a number of electrodes located on the surface ( $S$ ) of  $V$ . Also located on the surface of  $V$  is the foreign steel structure. In order to numerically integrate the problem, the entire surface of  $V$  is divided into small segments or boundary elements

Within  $V$ , and assuming that all current sources are located at the boundary of  $V$  (as is the case with CP systems), the potential field must satisfy the following equation:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0 \quad \dots(1)$$

This is known as the Laplace equation, the solution of which must comply with certain boundary conditions on  $V$ . Solving this equation can be achieved by integration using elements of volume (as is the case with the Finite Element Method). However, by considering two functions that are continuous throughout  $V$ , namely  $u^*$ , which is a carefully chosen arbitrary function known as the Fundamental Solution and having properties that are based on the Dirac delta function, and  $u$ , which is the actual potential field to be determined. it is possible to derive a form of Green's Second Identity equation which only involves the evaluation of surface integrals, ie.

$$c(p)u(p) + \int_S q^* u dS = \int_S u^* q dS \quad \dots(2)$$

where for two dimensions  $u^* = \frac{1}{2\pi} \ln \frac{1}{r}$ ,

$$q^* = \frac{-1}{2\pi r^2} (r_x n_x + r_y n_y),$$

or, for three dimensions  $u^* = \frac{1}{4\pi r}$

$$q^* = \frac{-1}{4\pi r^3}(r_x n_x + r_y n_y + r_z n_z), \text{ and}$$

$u(p)$  = potential at the source point  $p$ ,

$c(p)$  = a parameter that depends upon the geometry of the system at  $p$ ,

$r_x, r_y$  = the  $x$  and  $y$  components of the distance between the source point and the point at which the effect of the source is to be evaluated, and

$n_x, n_y$  = the  $x$  and  $y$  components of the unit normal with respect to the boundary surface

Note that the functions  $u$  and  $q$  represent the potential and flux, or current density, respectively, resulting from a point source in an infinite material.

The derivation of equation 2, known as the boundary integral equation, is not trivial and is beyond the scope of this article. However, it is detailed in a number of other publications [5-7].

For some special cases the boundary integral equation can be solved analytically, but in most applied situations it is necessary to use numerical integration. To numerically integrate  $u^*$  and  $q^*$ , the surface is divided into small, non-overlapping segments as shown in Figure II. Integration is then performed on each of the boundary elements and summed together to complete the surface integral. By substituting the surface with boundary elements, the boundary integral equation can be rewritten in its discrete form

$$c(p)u(p) + \sum_{\text{element } S} \int q^* u dS_{\text{element}} = \sum_{\text{element } S} \int u^* q dS_{\text{element}} \quad \dots(3)$$

This equation has as its unknowns the distributions of potential and current density over the surface  $S$ . These distributions can be approximated by a series of discrete values (known as nodes) over the surface of each boundary element. Evaluating potential or current density at any point on the boundary element surface, other than at nodes, is achieved by interpolation. Using vector notation this can be expressed as:

$$u = \Phi^T \mathbf{u} \text{ and } q = \Phi^T \mathbf{q} \quad \dots(4)$$

where the vector quantities  $\mathbf{u}$  and  $\mathbf{q}$  define the potential and current density at the nodes on the element at which the potential or current density is to be evaluated, and  $\Phi^T$  is the vector representation of the interpolation function. As a result of this approximation the vector quantities  $\mathbf{u}$  and  $\mathbf{q}$ , which are constants, can be removed from the integrals in equation 3. The equation can now be written as:

$$c(p)u(p) + \sum_{\text{element } S} \int q^* \Phi^T dS_{\text{element}} \mathbf{u} = \sum_{\text{element } S} \int u^* \Phi^T dS_{\text{element}} \mathbf{q} \quad \dots(5)$$

The resulting integrals now involve terms that are completely defined. The integrals of the fundamental solutions  $u^*$  and  $q^*$  multiplied by the interpolation function give a series of coefficients which, in turn, multiply the potential and current density nodal values. This can be expressed in matrix notation as:

$$\mathbf{H}\mathbf{u} = \mathbf{G}\mathbf{q} \quad \dots(6)$$

where the square matrices  $\mathbf{H}$  and  $\mathbf{G}$  contain the coefficients created by integrating  $q^*$  and  $u^*$ , respectively. Note that the function  $c(p)$  has been incorporated into matrix  $\mathbf{H}$ .

By inserting the known boundary conditions that define some of the potential and current density values, and rearranging the simultaneous equations so that all unknown values appear on the left hand side and all known values on the right hand side, equation 6 can be rewritten as:

$$\mathbf{Ax} = \mathbf{By} \dots(7)$$

Multiplying out the right hand side then reduces the problem to a standard exercise of solving a series of simultaneous equations:

$$\mathbf{Ax} = \mathbf{z} \dots(8)$$

There are a number of important advantages of modelling CP systems using surface rather than volume elements:

- it considerably reduces the number of nodes required to model a particular system
- it minimises data preparation and data analysis.
- it only gives solutions at the boundary. While it is possible to determine potential and current density within the electrolyte, surface potentials and current densities are more significant in terms of modelling CP systems. Consequently, computer resources are not wasted on determining potential and current values within the electrolyte unless required to do so.
- it allows modelling to be performed on systems having an infinite domain (a common requirement in solving CP problems).

## 2.2. Incorporating Electrode Kinetics

To model cathodic protection systems it is necessary to introduce the electrochemical behaviour of the steel and anodes into the above equations. This electrochemical behaviour manifests itself as a non-linear relationship between the potential and current density at the metal-to-electrolyte interface, ie.

$$i = f(u - u_0) \dots(9)$$

where  $u_0$  is the open circuit potential,

this functional relationship, known as the polarisation curve, is dependent upon the type of metal, ionic species in the electrolyte, temperature, velocity, etc. However, it can be measured in the laboratory or from field data and accurately approximated as a series of data points with intermediate values being evaluated by interpolation.

The polarisation behaviour is incorporated into the model via the known right hand vector  $\mathbf{z}$  using the following iterative process:

- Estimate the current density at the electrode interface and incorporate it into the right hand vector  $\mathbf{z}$ .
- Calculate the potential at the metal-to-electrolyte interface.
- Evaluate the new current density using the polarisation behaviour of the steel.
- Compare new current density with the previous estimate and, if the difference is outside a given tolerance, repeat the process from the second step.

Convergence is usually rapid Furthermore, because the non-linear behaviour is incorporated into the right hand vector, the use of the LU Decomposition type algorithm to compute the inverse of matrix A results in only a modest increase in the computer time required to model the non-linear system

The validity of using the above techniques to model a cathodic protection system on a naval vessel has been established by others [8].

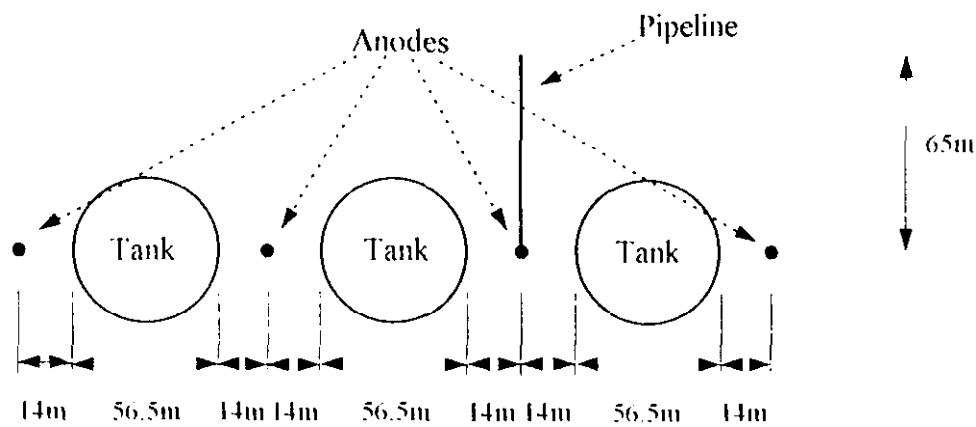
### 3. MODELLING CP INTERFERENCE

Designing a CP system to protect the external surface of floors on a number of large, above ground chemical storage tanks located in close proximity to each other offers a significant challenge if CP interference is to be minimised. What makes this task difficult is that, in some cases, the tank floors are uncoated. Thus large CP currents are required to fully protect the steel. The effect of this large current, combined with the steel floor being located at ground level and immediately adjacent to buried pipelines and steel foundations. creates the ideal situation for CP interference.

West Australian Petroleum Pty Ltd. who operate a number of oil fields off the north-west coast of Western Australia, is faced with a problem of this nature. In their case, concern was raised about the magnitude of CP interference on a buried pipeline, which may have defects in its protective coating. situated between the tanks.

#### 3.1. Description of the CP System

Three 56.5m diameter tanks are positioned 28m apart (84.5m from tank centre to tank centre) and aligned in a row. The external floors of all three tanks are cathodically protected using four anode groundbeds, as shown in Figure III. Each tank was protected using its own DC power source employing a current of 80A per tank (ie. total current 240A). The DC circuit was designed so that each tank floor was protected by the two anodes diametrically positioned 14m from the edge of each tank. with each anode contributing to 50% of the total current requirement for the tank. Thus, the two outer anodes carried a current of 40A each while the two inner anodes discharged a current of 80A each



**Figure III:** Top view showing the general arrangement of the tanks, the pipeline, and the anodes. Coating defects on the pipeline were located at the extremities of the pipeline.

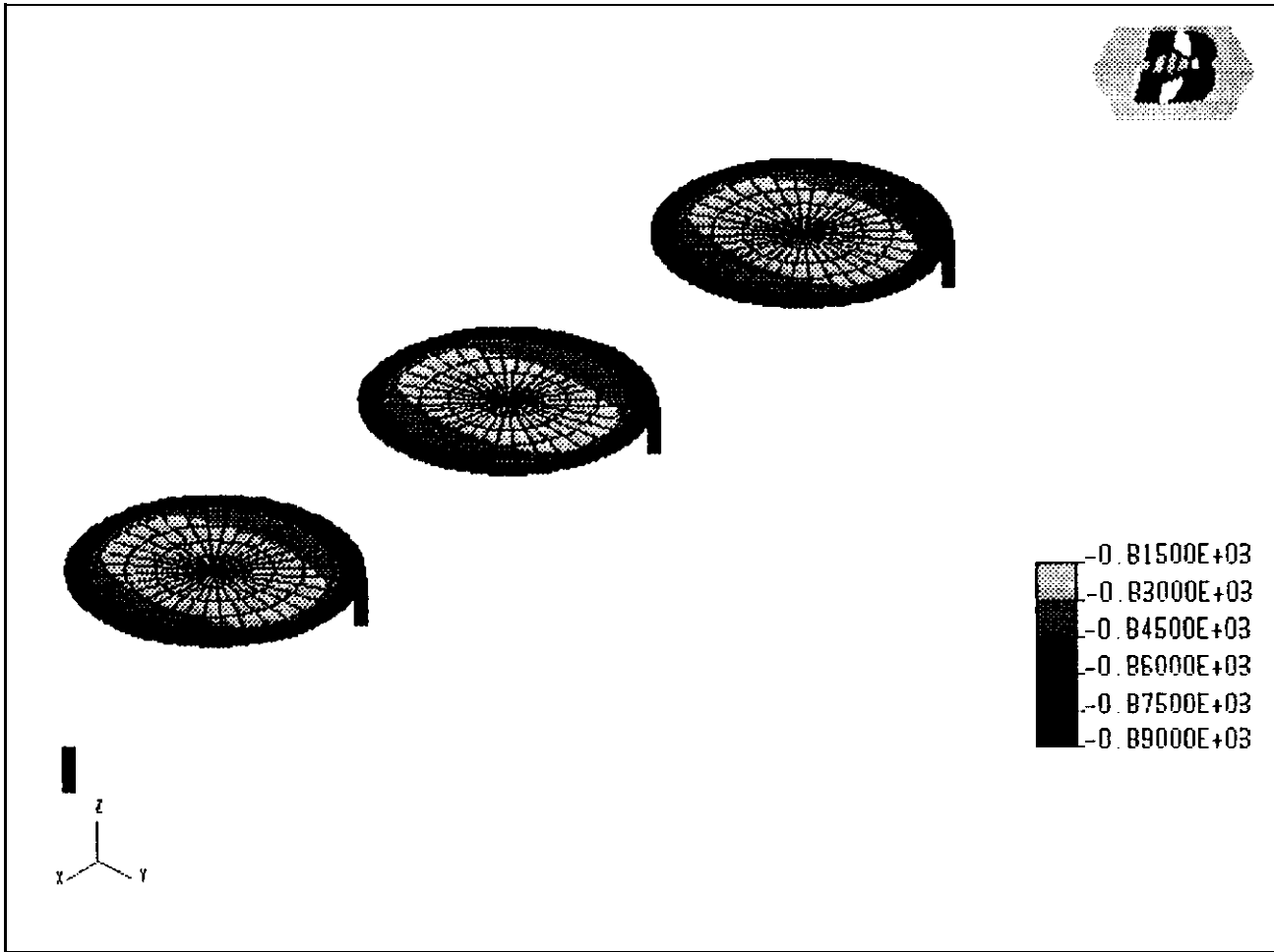
The anodes were 0.2m in diameter, 10m long, and initially buried vertically so that the tops of the anodes were located 20m below the ground surface. To ensure that the CP interference was not underestimated the soil resistivity was assumed to be uniform and equal to the surface resistivity of 50Ωm.

The pipeline that was subjected to the CP interference was located immediately above one of the inner anodes and extended in a direction away from both the tanks and the anodes. Once again, to ensure that the CP interference was not underestimated, the coating defects were located immediately above the anode and at the extremity of the pipe, ie. 65m from the anode.

### 3.2. Results and Discussion

#### 3.2.1. General Cathodic Response of the Tank Floors

Figure IV reveals the potential distribution over the tank floor with respect to a saturated Cu/CuSO<sub>4</sub> reference electrode. It shows, as predicted, that the centre of the tank receives less protection than do the tank edges. Notably, potentials at the centre of the tank are slightly more positive (approximately -820mV) than the ideal protection criterion of -850mV, suggesting that, initially, 80A may not be sufficient to fully protect the tank. The oval shape of the contours is indicative that the anodes are positioned too close to the tanks. To achieve a more symmetrical distribution of protection the anodes would have to be buried at a greater depth



**Figure IV:** The potential distribution over the tank floors. The four small rectangles designate the position of the anodes.

### 3.2.2. Cathodic Interference on the Buried Pipeline

Table I summarises the effect of CP interference on the pipe as a function of the size of the coating defect. As intuition may suggest, locating the pipeline within the influence of the anodic field results in CP current being picked up by the pipeline in the vicinity of the anode and being discharged at the remote end of the pipeline. Assuming the worst case scenario, that the corrosion process involves formation of  $Fe^{2+}$  (ie. the loss of 2 electrons), current densities corresponding to current discharge can be converted to metal loss per year. The severity of this interference is now readily apparent and the results suggest that it would be prudent to undertake further measures to help minimise the interference.

**Table I**  
**CP Interference on the Buried Pipeline**  
**Top of the Anodes Located 20m Below Ground Level**

Area of Coating Defect (cm <sup>2</sup> )	Current Density Adjacent to Anode (mA m <sup>-2</sup> )	Induced Corrosion Rate Adjacent to Anode (mm year <sup>-1</sup> )	Current Density at the Remote End (mA m <sup>-2</sup> )	Induced Corrosion Rate at the Remote End (mm year <sup>-1</sup> )
500	-198		198	0.2
5	-442		442	0.5

Note that positive current densities reflect current discharge. Corrosion is expected to be induced at these sites.

It is interesting to note that the corrosion rate is predicted to be higher when the coating defects are smaller. This suggests that smaller coating defects tend to focus the interference effects, and thus increase the damage caused by the interference on the pipeline.

One possible measure to help minimise the interference effects is to bury the anodes at a greater depth and thereby minimise the anodic interference. Table II summarises the effect of lowering the anodes so that the top of the anodes is located at a depth of 70m.

**Table II**  
**CP Interference on the Buried Pipeline**  
**Top of the Anodes Located 70m Below Ground Level**

Area of Coating Defect (cm <sup>2</sup> )	Current Density Adjacent to Anode (mA m <sup>-2</sup> )	Induced Corrosion Rate Adjacent to Anode (mm year <sup>-1</sup> )	Current Density at the Remote End (mA m <sup>-2</sup> )	Induced Corrosion Rate at the Remote End (mm year <sup>-1</sup> )
500	969	1.1	-969	
5	2370	2.7	-2370	

The model predicts that repositioning the anodes has major effect on interference levels. It not only increases the effect of CP interference but also relocates the corrosion site. Corrosion that was initially located at the remote end of the pipe is now located immediately above the groundbed. This occurs because lowering the anodes removes the anodic field at the ground level. The pipeline is now subjected only to the cathodic field of the tanks. As result, current is picked up at the remote end of the pipeline and conducted along the pipeline before being discharged back into the ground at the point where the pipeline closely approaches the tank floors.

The fact that the current flow induced by CP interference is reversed by positioning the anodes at greater depths suggests that there is an optimum depth at which anodes could be buried so that interference is minimised. Given that it takes, on average, 1.5 hours to adjust, run and analyse the model using a Pentium

processor. determining the optimum depth could be evaluated efficiently using computer modelling. This would help to minimise the number of field tests to be undertaken. However, the assumption that the earth resistance is uniformly  $50\Omega\text{m}$  must be reviewed before further modelling can proceed. The actual location of the anodes is expected to be very dependent upon the actual resistivity profile of the soil.

#### 4. CONCLUSION

Using BEM it is possible to model CP interference in a manner which is enlightening regarding the processes at work. It can provide information about the level of interference in terms of a parameter (ie. current density) that more clearly defines the severity of the effect. Furthermore, it can provide important insight into the factors that influence the magnitude of the effect. This makes BEM a useful tool for the design of CP systems.

#### 5. ACKNOWLEDGMENTS

The authors wish to thank the management of West Australian Petroleum Pty. Ltd., operator on behalf of its participant companies:- Chevron Asiatic Ltd., Texaco Oil Development Company, Ampolex (AOE) Ltd., Shell Development (Australia) Pty. Ltd. and Western Mining Corporation Ltd., as well as Rustec Pty Ltd. for their permission to publish this paper.

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