

**Final Report**

**Design of Cathodic Protection Systems for Deep  
Water Compliant Petroleum Production Risers**

**submitted to**

**United States Department of the Interior  
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**June 20, 2005**

## BACKGROUND

Offshore petroleum production has now been ongoing in the Gulf of Mexico and elsewhere worldwide for in excess of 50 years. A major change has transpired during the past one to two decades, however, as emphasis has shifted from relatively shallow to deep water locations. This has presented unique challenges in numerous technological areas, including the advent of 1) deep water fixed structures, 2) sub-sea production units and 3) floating production, storage, and offshore loading (FPSO) systems.

Structural steel pipelines, either resting upon or buried beneath the sea floor, have historically served as the primary production product transportation mode between structures and to shore. With the advent of sub-sea production units, however, such transport also is necessary from the bottom production unit and the topside platform or vessel. For deep water sub-sea production, catenary risers, which extend from the ocean floor to a topside platform facility, often serve as a component for this transport.

Because of strength and economic considerations, structural and high strength steels are the most viable material of construction for pipelines and risers. However, the relatively high native reactivity of steels requires that one or more corrosion control measures be taken. Consequently, pipe and riser interiors are protected by inhibitors and external surfaces by a combination of coatings and cathodic protection (cp).

The fundamental principle of marine pipeline and riser cp involves polarization of the steel from its native potential (approximately  $-0.65V_{Ag/AgCl}$ ) to the range  $-0.90$  to  $-1.05V_{Ag/AgCl}$  where corrosion rate is nil. This is normally accomplished using galvanic aluminum or zinc bracelet anodes according to standardized methods and recommended practices.<sup>1,2</sup> Accordingly, the size of a bracelet anode that can be deployed from a lay barge and that can be structurally supported by the pipeline and, at the same time, achieve a realistic design life (20-plus years) limits anode spacing of about 250 m. However, weight and fatigue considerations preclude such an approach for the suspension portion of risers, which may extend over thousands of feet. This poses a particular challenge with regard to cp design, since protection attenuates with increasing distance from anodes. Some companies have opted to preclude galvanic anodes from such risers, whereas others permit a limited number. An added consideration is that riser coatings can be of very high quality (no holidays and zero coating breakdown factor) except perhaps at field joints, such that attachment of bracelet anodes may do more harm than good because of locally compromised coating quality.

Compliant risers may receive cp from the protection system on the host platform or vessel. However, if this is the case and potential of any anodes on the riser or at and beyond touchdown (or both) is more negative than those on the topside structure, then the structure may drain current from these anodes and cause them to rapidly deplete. For this reason, the riser is often, although

not always, isolated from the structure near where the former terminates. However, it is possible for the isolation fitting that affects this to fail, in which case the riser and structure become inadvertently electrically connected. Thus, two situations must be addressed; the first where the structure is electrically connected to the structure and the second where it is not.

## **PROJECT OBJECTIVE**

The objective of this project was to develop a cp design protocol for deep water petroleum production compliant risers. This was accomplished by focusing both existing and newly developed pipeline cp principles and concepts upon the specific geometric and operational aspects of these risers, as explained below.

## **PROJECT TASKS**

The research was performed in terms of the following project tasks.

- I. Literature Review and Definition of Design Parameters.
- II. Definition of Riser CP Design Alternatives.
- III. Design and Modeling of Anodes at Riser Ends.
- IV. Attenuation Modeling.
- V. Software Development.
- VI. Final Report.

## **LITERATURE REVIEW AND DEFINITION OF DESIGN PARAMETERS**

Within this task, the internet posted documents listed below were reviewed and employed to technically define the state-of-the-art from which the present research proceeded.

### 1. Cathodic Protection of Risers:

13112N\_STEEL WATER TANKS & RISER.pdf

L51540toc\_Corrosion Criteria For J-Tube Risers.pdf

V4Preprint8\_Novel Cathodic Protection of Subsea Flowlines and Risers.pdf

### 2. Cathodic Protection of Marine Pipelines

ISO\_DIS\_13628-11\_(E)\_Flexible pipe systems for subsea and marine applications.pdf

Cathodic Protection for Deepwater Pipelines.htm

### 3. General Aspects of Marine Cathodic Protection

M-503\_NORSOK STANDARD COMMON REQUIREMENTS for CP.pdf

V4Preprint9\_Cathodic Misconceptions.pdf

V4Preprint13\_A review of galvanic anode cathodic protection design.pdf

#### 4. Other

Offshore Service Specification OSS-302\_Offshore Riser Systems\_Oct 2003.pdf

OS-F101\_Offshore Standard\_Submarine Pipeline Systems\_Jan 2000.pdf

OS-F201\_Offshore Standard\_Dynamic Risers\_2001.pdf

### DEFINITION OF RISER CP DESIGN ALTERNATIVES

The project efforts have involved development of models that are based upon a zero resistance source at one end of a riser and a non-zero resistance source at the other. The zero resistance source is represented by any structure with a large number of distributed anodes, such as a production jacket, tension leg platform, or FPSO. Thus, the individual anodes are assumed to be identical and to act as resistors in parallel, such that,

$$R_t = \frac{R_a}{N} \quad (1)$$

where  $R_t$  is the total resistance of all anodes,  $R_a$  is resistance of an individual anode, and  $N$  the number of anodes. Considering that  $R_a = 0.03 \Omega$ , which is a typical value, and  $N = 200$ , then  $R_t = 1.5 \times 10^{-4} \Omega$ , which is assumed to be negligible (zero).

Examples of non-zero anode resistance sources are bracelet anodes distributed along a flowline or on a pipeline end manifold (PLEM). In the flowline case, only anodes within about 1,000 m of each other serve as resistors in parallel, since pipe metallic path resistance and the associated voltage drop from current returning to ground limits interaction progressively with increasing distance beyond this. A common compliant riser design involves clustering bracelet anodes on the flowline near the riser connection. Only a limited number of anodes ( $N$  in Equation 1) are deployed on a PLEM.

Based on practical cases, two different catenary riser configurations were considered, as listed below:

1. A riser that is a) connected at a non-zero resistance source at the bottom end b) has no anodes along the suspension length, and c) electrically isolated from the surface structure where it terminates.
2. A riser that is a) connected at a non-zero resistance source at the bottom end b) has no anodes along the suspension length, and c) electrically connected to the surface structure where it terminates (zero resistance source).

Each of these is illustrated respectively in Figures 1 and 2. In the former case, the clustered bracelet anodes that are illustrated at the deep end could alternatively be the protection system on a PLEM.

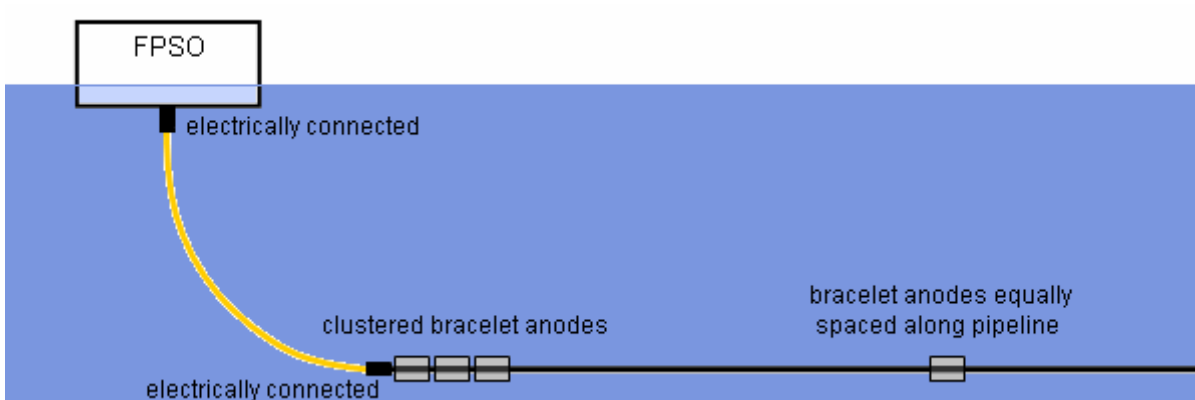


Figure 1: Schematic illustration of Case 1.

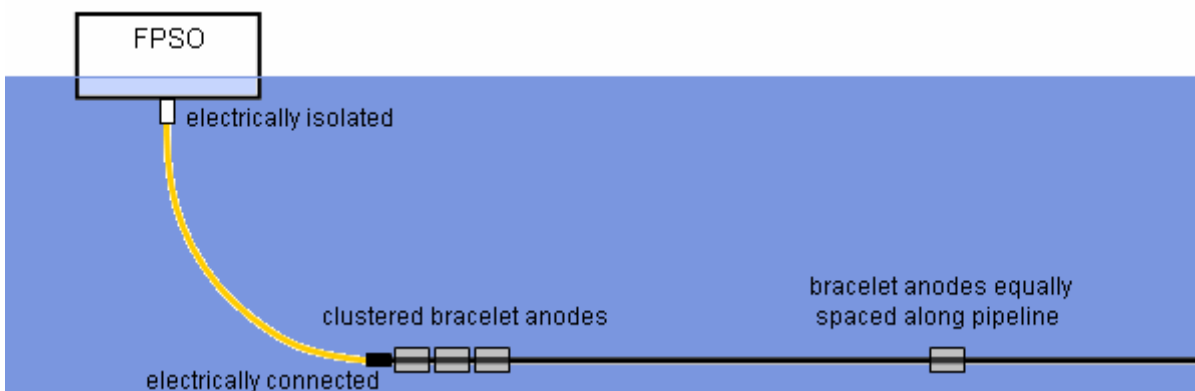


Figure 2: Schematic illustration of Case 2.

For purposes of attenuation modeling, the above representations can be treated as one-dimensional. Accordingly, Figures 3 and 4 show schematic illustrations of the physical components and of the associated potential distribution for each of the two cases, respectively. Thus, potential for the surface structure is uniform, whereas potential attenuates along the riser. The critical task in cp design is to assure that potential nowhere along the riser becomes positive to the protection potential ( $-0.80 \text{ V}_{\text{Ag/AgCl}}$ ) during the design life. The illustrations assume that potential for anodes on both the surface structure and flowline (anode cluster) are the same, which is not necessarily the case. Situations where this assumption is not valid is addressed subsequently. Also, in these illustrations, the anode cluster has been replaced by a single anode of the same resistance as that of the cluster. Methods whereby the size of such an equivalent resistance anode can be calculated are presented and discussed below.

### DESIGN AND MODELING OF ANODE ARRAYS (CLUSTERS)

The catenary riser can be protected from the sea bottom by either a group of bracelet anodes

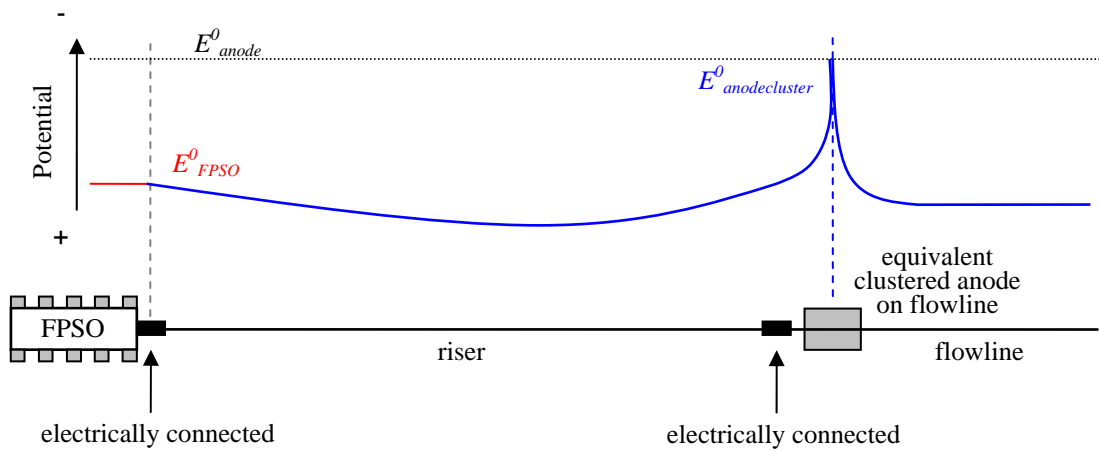


Figure 3: Schematic model of riser potential profile for Case 1.

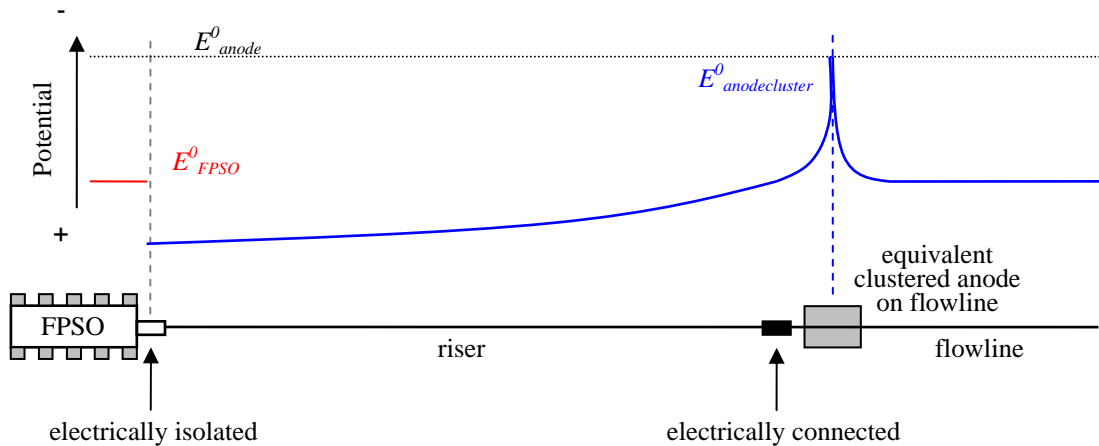


Figure 4: Schematic model of riser potential profile for Case 2.

or an anode array (cluster). The overall resistance of the anode configuration is a key parameter that has to be calculated in order to determine if the cathodic protection performance achieves the required criterion.

In the case where the riser is protected by a group of identical bracelet anodes, these can be treated as a single anode of extended length with the same diameter as the actual anodes for purposes of the resistance calculation. This extended length is entered into calculation software, such as CPexp<sup>®</sup>, is the sum of all the bracelet anode length in the group.

If the riser is to be protected by an anode array, a method which incorporates Sunde's one dimensional equation for identical, equally spaced anodes<sup>3</sup> into a numerical algorithm has been introduced.<sup>4</sup> This is also programmed in the cathodic protection design software CPexp<sup>®</sup>.

Figure 5 is the screen shot of the anode resistance calculation of an array showing a schematic drawing of the selected array and the input and output parameters.

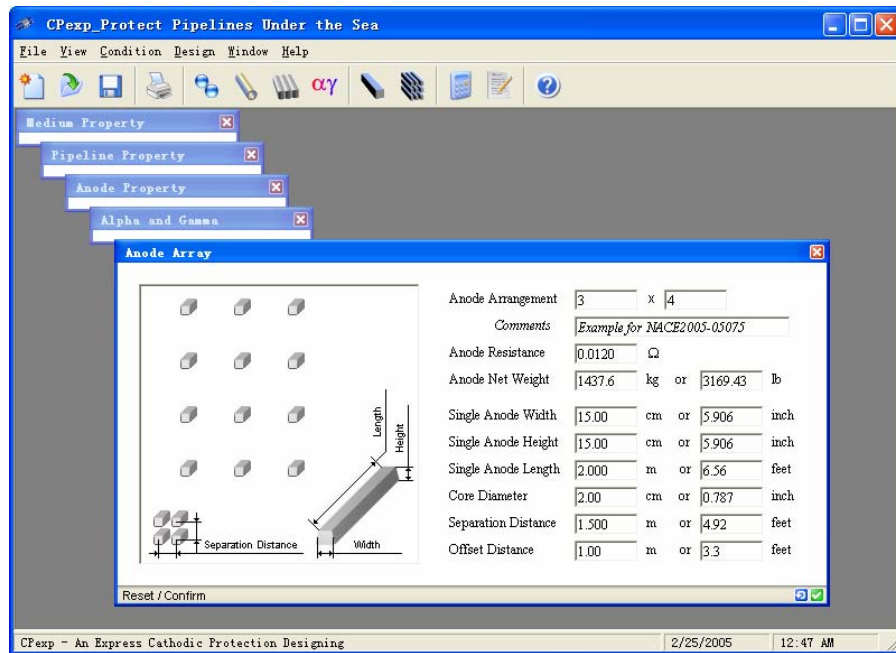


Figure 5: Computer screen reproduction of an anode array resistance calculation.

## ATTENUATION MODELING

### General

The potential attenuation modeling is based on the equations of Morgan and Uhlig,<sup>5,6</sup> La Fontaine and Gibson,<sup>7</sup> and the Slope Parameter,<sup>8-12</sup> as well as numerical methods. This can be supplemented by the CPexp<sup>®</sup> software mentioned above for execution of intermediate steps.

As noted above, equivalent mathematical models for the two riser configurations are based upon 1) a zero resistance source to a non-zero resistance source (case 1) and 2) an isolated to a non-zero resistance source (case 2). The modeling for these is different as described below. Generally, the two modeling procedures are derived from Uhlig's potential attenuation equation which applies to an infinite pipeline polarized by identical, equally spaced, equi-potential anodes,<sup>6</sup>

$$E_x = MPP \cdot \cosh \left[ B \cdot \left( x - \frac{L}{2} \right) \right] + E_{\text{corr}}, \quad (2)$$

where  $E_x$  is the potential at distance  $x$  from the drainage point,  $MPP$  is polarization at the mid-point between any two anodes,  $L$  is the distance between two anodes,  $E_{\text{corr}}$  is corrosion potential, and  $B$  is potential attenuation constant, which is expressed as

$$B = \sqrt{\frac{\pi \cdot d \cdot R_L}{\alpha \cdot \gamma}} \quad (3)$$

where  $d$  is outer pipe diameter of the flowline,  $R_L$  is linear Ohmic resistance,  $\alpha$  is polarization resistance and  $\gamma$  is the reciprocal of coating breakdown factor.

### Case 1: Zero Resistance Source to a Non-zero Resistance Source

La Fontaine and Gibson<sup>7</sup> introduced a modified form of the Uhlig equation to solve the potential attenuation problem for situations where anode potentials are not equal. To accomplish this, they introduced what was termed a “length factor,”  $\xi$ . The reasoning was to “stretch” the Uhlig equation calculated potential profile until it fits through the potential at the non-zero resistance source end at  $L$ . Thus the Uhlig equation was re-written as:

$$E_x = MPP \cdot \cosh \left[ B \cdot \left( x - \frac{\xi \cdot L}{2} \right) \right] + E_{\text{corr}} \quad (4)$$

The generalized schematic solution to this problem is shown graphically in Figure 6.

To use this approach to solve potential attenuation problems of this type, two constraints are imposed. First, the potential at the drain point must be equal to the potential of the anode minus the IR voltage drop in the seawater. Second, the current at the drain point must equal the current delivered by the anode. Thus, the following boundary conditions result:

$$\text{At } x=0, E(0)=E_O \quad E_o = MPP \cdot \cosh \left[ B \cdot \left( \frac{\xi \cdot L}{2} \right) \right] + E_{\text{corr}}, \quad (5)$$

$$\text{At } x=L, E(L)=E_{XO} \quad E_a - I_a \cdot R_a = MPP \cdot \cosh \left[ B \cdot \left( L - \frac{\xi \cdot L}{2} \right) \right] + E_{\text{corr}}, \text{ and } (6)$$



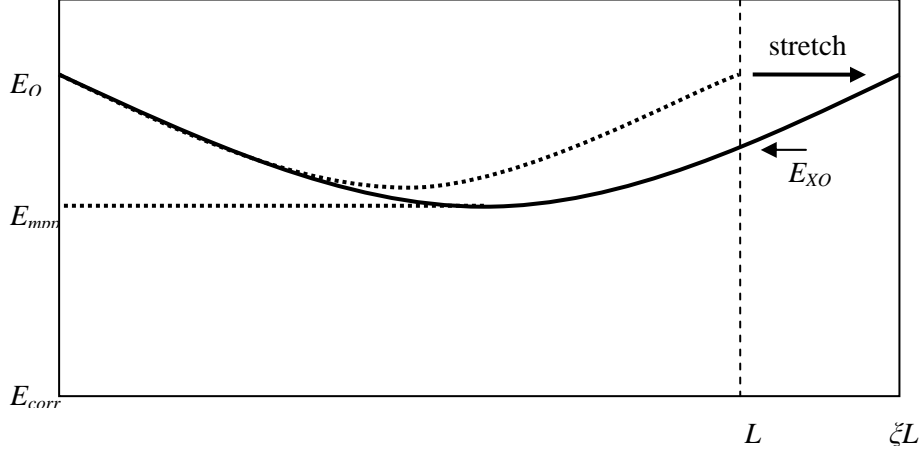


Figure 6: Graphical depiction of the potential profile along a pipe or riser with a zero resistance source at one end and a non-zero resistance source at the other.

$$\text{At } x=L, I(L)=I_a \quad I_a = \frac{MPP \cdot B}{R_L} \cdot \sinh \left[ B \cdot \left( L - \frac{\xi \cdot L}{2} \right) \right] \quad (7)$$

These include three unknowns:  $MPP$ ,  $I_a$ , and  $\xi$ . A numeric method was derived to solve the boundary condition equations for  $\xi$ . Thus, from combining (6) and (7),

$$\frac{E_a - E_{corr}}{MPP} = \frac{R_a \cdot B}{R_L} \cdot \sinh \left[ B \cdot \left( L - \frac{\xi \cdot L}{2} \right) \right] + \cosh \left[ B \cdot \left( L - \frac{\xi \cdot L}{2} \right) \right], \quad (8)$$

and from (5) and (6),

$$\frac{E_a - E_{corr}}{MPP} = \frac{E_a - E_{corr}}{E_o - E_{corr}} \cdot \cosh \left[ B \cdot \left( \frac{\xi \cdot L}{2} \right) \right] \quad (9)$$

The length factor  $\xi$  is calculated from the cross point of the solutions to Equations (8) and (9) in Descartes coordinates. The calculation is performed numerically by programmed software. Once  $\xi$  is determined,  $I_a$  can be calculated from Equation (7) and  $MPP$  using the expression,

$$MPP = \frac{E_o - E_{corr}}{\cosh \left[ B \cdot \left( L - \frac{\xi \cdot L}{2} \right) \right]} \quad (10)$$

Thus, given 1) the riser dimensions and material properties, 2) potential and resistance of the

zero resistance source, 3) anode potential, 4) pipe corrosion potential, and 5) criteria for calculating  $B$ , the potential attenuation profile and mid-point potential of the riser can be calculated. Once this is done, the current required from each source can also be determined.

### Case 2: Isolated to a Non-zero Resistance Source

The potential attenuation that results in an isolated to a non-zero resistance source case (that is, for a situation where the top-side riser end is electrically isolated from the host structure and the bottom end is protected by anodes with finite resistance) can be determined by modeling this as one-half of a symmetric repeated unit comprised of equally spaced, identical anodes along a line of infinite length, as illustrated schematically in Figure 7. The potential attenuation in this case can be calculated by either Uhlig's equation<sup>6</sup> or the Slope Parameter Method.<sup>8-12</sup> In doing this, it was recognized that the actual system is the same as one with equally spaced anodes on infinite pipe, where resistance of each anode is one-half and spacing twice the actual values.

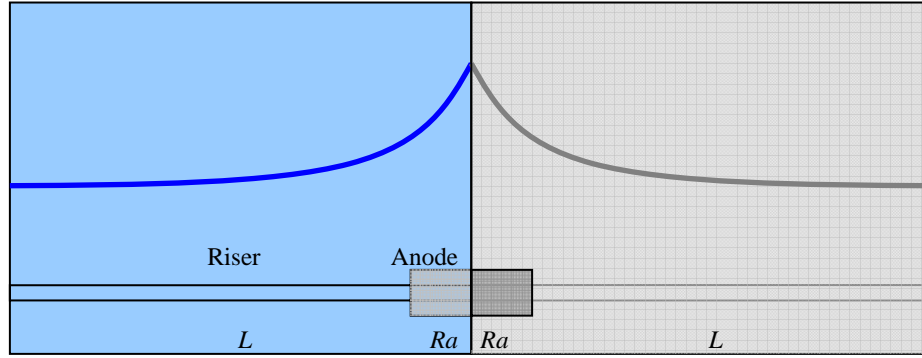


Figure 7: Illustration of the equivalent model.

Thus, the equivalent calculation conditions are

$$R_{a, \text{equ}} = \frac{1}{2} R_a \quad \text{and} \quad (11)$$

$$L_{\text{equ}} = 2 L \quad (12)$$

where  $R_{a, \text{equ}}$  and  $L_{\text{equ}}$  are the equivalent anode resistance and length, respectively, for calculation of the actual resistance and length ( $R_a$  and  $L$ ). The Slope Parameter Method<sup>12</sup> is used to calculate the  $MPP$ , which is actually the isolated end potential, and anode current output,  $I_a$ . The drain point (anode end) potential,  $E_d$ , is in turn,

$$E_d = E_a - \frac{1}{2} I_a \cdot R_a . \quad (13)$$

Once get middle point and drain point potentials are obtained, the potential attenuation curve can be simulated by solving Equation 4. Software was Developed for this calculation purpose, as explained below.

### SOFTWARE DEVELOPMENT

A software program was written for performing riser cp design in each of the two cases defined above. These are Windows based simply require only design parameter inputs from the user. The calculation result is stored in computer hard drive as a text file for future reference. Figures 8 and 9 are screen shots for each of the two riser cases.

As noted above, the cathodic protection design software CPexp<sup>®</sup> is a supplemental tool for calculation of anode resistance. Figure 5 showed an example of this for the case of an anode array. Figure 10, on the other hand, illustrates this calculation for a bracelet anode.

The design protocol for the presently developed software is based upon entering assumed or specified parameters for the riser, anodes, and cathodic protection criteria. The software then calculates the potential attenuation constant ( $B$  (Equation 3)), length factor ( $\zeta$ ), drain point potential and current, and mid point potential (MPP) and polarization and provides a graphical illustration of the potential profile. Iterations are subsequently performed, as required, until the above calculated parameters achieve the protection specifications in an acceptable manner. A listing of the program input parameters is provided below.

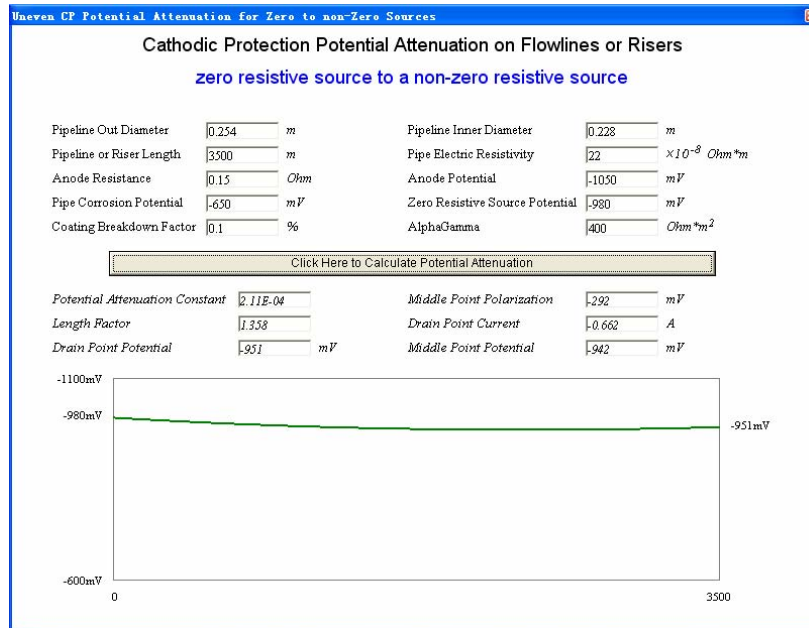


Figure 8: Riser cp design input parameter selections and output results for a zero resistance source to a non-zero resistance source example.

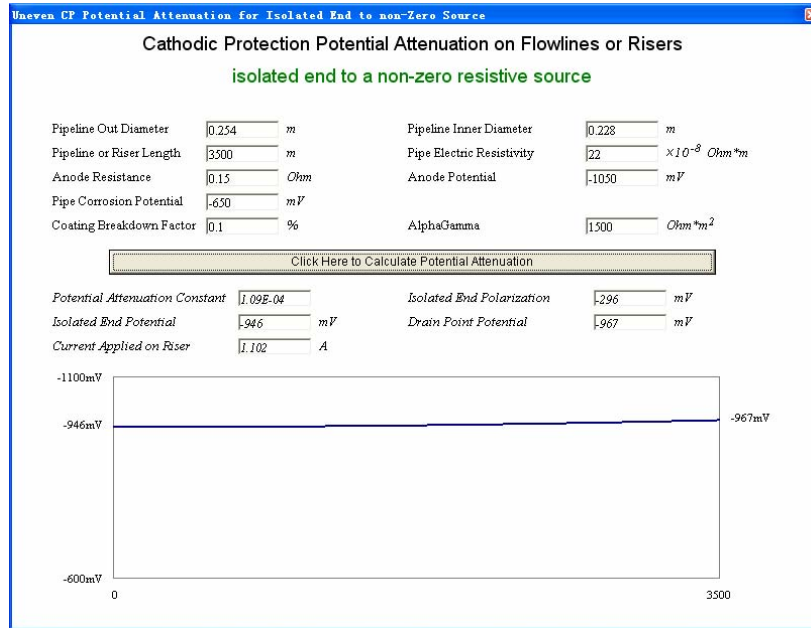


Figure 9: Riser cp design input parameter selections and output results for an isolated to a non-zero resistance source example.

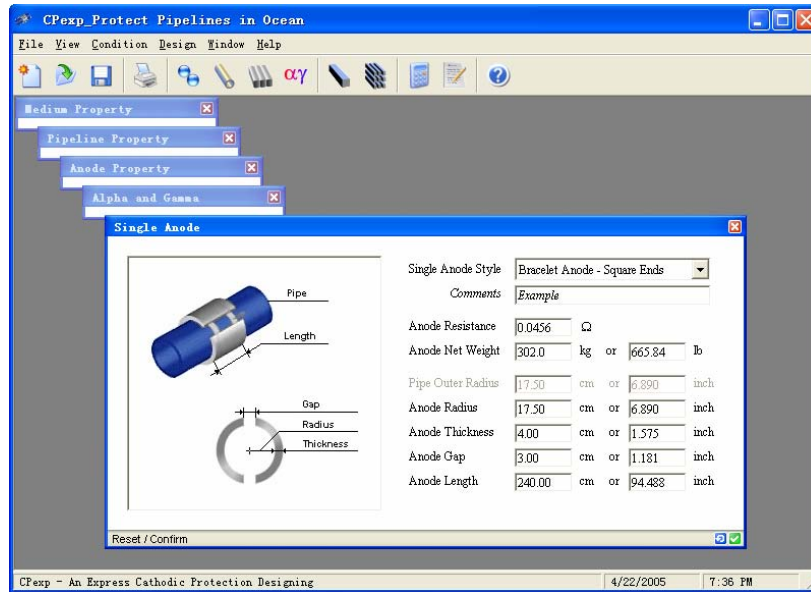


Figure 10: Screen shot of an anode resistance calculation for a bracelet anode.

Seawater Resistivity,  $\Omega \cdot \text{cm}$ : \_\_\_\_\_  
 Or Salinity, % \_\_\_\_\_  
 and Seawater Temperature,  $^{\circ}\text{C}/^{\circ}\text{F}$  \_\_\_\_\_  
 Riser Steel Resistivity,  $\Omega \cdot \text{m}$  \_\_\_\_\_  
 Corrosion Potential of Pipe Steel,  $\text{V}(\text{Ag}/\text{AgCl})$  \_\_\_\_\_  
 Outer Pipe Diameter,  $\text{cm}/\text{inch}$  \_\_\_\_\_  
 Inner Pipe Diameter,  $\text{cm}/\text{inch}$  \_\_\_\_\_  
 Pipe Outer Wall Temperature,  $^{\circ}\text{C}/^{\circ}\text{F}$  \_\_\_\_\_  
 Polarization Resistance,  $\Omega \cdot \text{m}^2$  \_\_\_\_\_  
 Coating Breakdown Factor, % \_\_\_\_\_  
 or  $\alpha\gamma$  for the above two,  $\Omega \text{cm}^2$  \_\_\_\_\_  
 Anode Density,  $\text{kgm}^{-3}/\text{lbmft}^{-3}$  \_\_\_\_\_  
 Anode Potential,  $\text{V}(\text{Ag}/\text{AgCl})$  \_\_\_\_\_  
 Anode Current Capacity,  $\text{Ahkg}^{-1}/\text{Ahlbm}^{-1}$  \_\_\_\_\_  
 Anode Utilization Factor, % \_\_\_\_\_  
 Single Anode, dimensions \_\_\_\_\_  
 Anode Array, dimensions and spacings \_\_\_\_\_  
 Required Cathode Protection Potential,  $\text{V}(\text{Ag}/\text{AgCl})$  \_\_\_\_\_

### BIBLIOGRAPHY

1. "Cathodic Protection Design," DNV Recommended Practice RP401, Det Norske Veritas Industri Norge AS, 1993.
2. "Corrosion Control of Steel-Fixed Offshore Platforms Associated with Petroleum Production," NACE Standard RP 0176-03, NACE International, Houston, 2003.
3. E.D., Sunde, *Earth Conduction Effects in Transaction Systems*, Dover Publishing Inc., New York, NY, 1968.
4. X. Zhang, W. Chu, and W.H. Hartt, "Anode Array Resistance for Cathodic Protection of Marine Structures and Pipelines," paper no. 05075 presented at CORROSION/05, April 3-7, 2005, Houston.
5. J. Morgan, *Cathodic Protection*, Macmillian, New York, 1960, pp. 140-143.
6. H.H. Uhlig, *Corrosion and Corrosion Control*, J. Wiley and Sons, New York, 1962, pp. 421,422.
7. J.P. La Fontaine and G. Gibson, "Cathodic Protection Design of Pipelines Using an Improved Attenuation Model", paper no. 04091 presented at CORROSION/04, March 28-April 1, 2004, New Orleans.
8. W. Wang, W.H. Hartt and S. Chen, "Sacrificial Anode Cathodic Protection of Steel in Sea Water - Part I: A Novel Experimental and Analysis Methodology," *Corrosion*, Vol. 52, 1996, p. 419.
9. W.H. Hartt, S. Chen, and D.W. Townley, *Corrosion*, Vol. 54, 1998, p 317.

10. D.W. Townley, "Unified Design Equation for Offshore Cathodic Protection," CORROSION 1997, NACE International, Houston, 1997, paper no. 97473.
11. K. Bethune and W.H. Hartt, Corrosion, Vol. 57. 2001, p. 78.
12. W.H. Hartt and D.K. Lysogorski, "The Slope Parameter Approach in Design and Analysis of Cathodic Protection Systems, paper no. 03196 presented at CORROSION/03, March 16-20, 2003, San Diego.