APPENDIX

CATHODIC PROTECTION DESIGN

from Swain Classnotes (1996)

STRUCTURE
Metal, Design Life, Dimensions, Coatings, Other

LOCATION
Environmental Conditions, Other Structures

C.P. CRITERIA
Potential for Cathodic Protection

C.P. CURRENT DEMAND
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1.0 INTRODUCTION

Metallic structures in contact with water, soil, concrete, and moist air are subject to corrosion. Cathodic protection (CP) is one of the few methods that successfully mitigates corrosion. It can be applied in any situation where the environment surrounding the metal acts as a conductor for electric current. It has been successfully applied to offshore structures, ships, boats, propellers, moorings, pipelines, storage tanks, piers, jetties, bridges, aquaria, instrumentation etc.

This handout is designed as an introduction to CP design. As such, it does not cover all aspects of the subject. Therefore, the student should realize the limitations of his/her knowledge and consult other literature or experts in the field when necessary.

2.0 STRUCTURE

CP design begins with a thorough understanding of the structure to be protected. This includes the following information:

- Metal type(s)
- Operating conditions
- Dimensions and surface area
- Coatings
- Data from previous structures and CP systems
- Design life

3.0 LOCATION

The environmental conditions are determined by the location of the proposed installation. Factors such as climate, electrolyte conductivity and chemistry, physical loading, and biological activity, all impact CP requirements. These factors are generally allowed for in the CP current demand and polarization potential criteria.

4.0 CP CRITERIA

Potential measurements are the most commonly used criteria to ascertain the level of CP afforded to metals and alloys. CP potential values vary according to the metal and the environment. Corrosion is likely to occur at potentials which are more positive than the protected value. Damage may also occur if the metal is overprotected (i.e. the potential too negative). The most common error associated with potential measurements is a result of IR drop. This is the displacement of measured metal potential due to current flow through the electrolyte. High electrolyte resistivity and high current densities can cause significant differences between the measured and actual metal potential.

4.1 Potential Values

The measurement of potential with respect to a standard reference electrode is probably the most common method of evaluating the degree of cathodic protection afforded to a structure. Typical cathodic protection potentials for commonly used metals ref. Ag/AgCl reference electrode (seawater) are provided in Table 4.1. A more detailed summary of protection potentials for steel in seawater is provided in Table 4.2.

Table 4.1 Approximate freely corroding and protected potentials of metals in seawater (may vary according to velocity and conditions).

Metal or Alloy	Freely Corroding Potential (V) ref. Ag/AgCl	Protected Potential (V) ref. Ag/AgCl
316,304 Stainless (passive)	-0.10	-0.75
Copper Alloys	-0.35	-0.70
316,304 Stainless (active)	-0.50	-0.75
Steel	-0.60	-0.80
Aluminum Alloys	-0.75	-1.00
Zinc/Aluminum Anodes	-1.05	
Magnesium Anodes	-1.50	

Table 4.2 Potential values for corrosion and protection of steel in seawater

V ref. Ag/AgCl	Condition	V ref. Zn
	Heavy Corrosion	
-0.60	Freely Corroding Steel	+0.50
-0.70	Some Protection	+0.40
-0.80	Cathodic Protection	+0.30
-0.90	Some Over	+0.20
-1.00	Protection	+0.10
-1.10		0.00
-1.20	Over Protection	-0.10
-1.30	May Cause	-0.20
-1.40	Paint Blistering and Flaking	-0.30
-1.50		-0.40

4.2 300 mV Shift

The NACE Standard, RP-02-85 states that a minimum negative (cathodic) voltage shift of 300mV, produced by the application of protective current should provide CP to iron and steels. The voltage shift is measured between structure surface and a stable reference electrode contacting the electrolyte. This criteria does not apply to structures in contact with dissimilar metals.

4.3 100 mV Shift

The NACE Standard, RP-02-85 states that a minimum negative (cathodic) voltage shift of 100mV measured between the structure surface and a stable reference electrode contacting the electrolyte should provide CP to iron and steel. This polarization voltage shift is determined by interrupting the protective current and measuring the instant off and polarization decay. The instant off value is obtained immediately following the interruption of the CP current. The voltage shift is equivalent to the IR drop created by the CP current and electrolyte resistance. The polarization decay is measured as the change in potential over a period of time from the instant off value.

4.4 E-log-I Curve

The NACE Standard, RP-02-85 states that a structure-to-electrolyte voltage at least as negative (cathodic) as that originally established at the beginning of the Tafel segment of the E-log-I-curve should provide CP to iron and steel. This structure-to-electrolyte voltage shall be measured between the structure surface and a stable reference electrode contacting the electrolyte at the same location where voltage measurements were taken to obtain the E-log-I curve.

4.5 Anodic Current Discharge Points

The NACE Standard, RP-02-85 states that a net protective current from the electrolyte into the structure surface as measured by an earth current technique applied to predetermined current discharge (anodic) points of the structure should provide CP to iron and steel.

5.0 CATHODIC PROTECTION CURRENT DEMAND

The cathodic protection current demand is the amount of electricity required to polarize the structure to a level that meets the criteria described in Section 4. This may be obtained from a trial polarization of the structure at the installation site, a trial polarization of a metal test coupon at the installation site, or from conservative estimates obtained from historical information obtained from previous structures operating under the prescribed conditions.

For planning and design purposes, it is often possible to rely on conservative estimates provided by recommended practice. There are several sources for this information. The most current one is Recommended Practice RP B401, Cathodic Protection Design, Det Norske Veritas Industri Norge AS, 1993.

5.1 Recommended Practice RP B401, Det Norske Veritas

The CP current densities are calculated for different environmental conditions and conditions of the steel (i.e. uncoated, coated, concrete reinforcing steel, pipeline).

5.1.1 Uncoated Steel

Three design current densities are given: initial, final, and average.

Initial This is the current density required to effect polarization of the initially exposed bare steel surface. It assumes some atmospheric rusting and/or millscale. The initial current density is higher because of lack of calcareous scales (cathodic chalks). A proper initial current density enables rapid formation of protective calcareous scales.

Final This is the current density required to protect the metal surface with established marine growth and calcareous layers. It takes into account the current density required to repolarize the structure in the event of removal of these layers by storms, cleaning operations etc.

Average This is the anticipated current density required once the cathodic protection system has reached its steady state. The average or maintenance current density is used to calculate the minimum mass of anode material required to protect the structure throughout the design life.

Table 5.1 Initial, final, and average current densities for various climatic conditions and depths (climatic conditions are based on yearly range of average surface water temperatures).

	Design Current Densities (A/m^2)											
	Tropical >20^{o}C			Sub-Tropical 12^o-20^{o}C			Temperate 7^o-12^{o}C			Arctic <7^{o}C		
Depth (m)	Initial	Final	Average	Initial	Final	Average	Initial	Final	Average	Initial	Final	Average
0 - 30	0.150	0.090	0.070	0.170	0.110	0.080	0.200	0.130	0.100	0.250	0.170	0.120
>30	0.130	0.080	0.060	0.150	0.090	0.070	0.180	0.110	0.080	0.220	0.130	0.100

5.1.2 Coated Steel

The use of coatings on steel dramatically reduces the current demand on the cathodic protection system. This can save on the cost and structural weight associated with sacrificial anode systems. The CP current demand of a coated offshore jacket may be estimated by multiplying the bare steel current demand by a coating breakdown factor (f_c). The coating breakdown factor does not allow for mechanical damage to paint coatings. These areas are treated as bare metal surface. For CP design purposes the average and final coating breakdown factors for a design life of t_r years are as follows:

$$f_c(average) = k_1 + k_2 \frac{t_r}{2}$$

$$f_c(final) = k_1 + k_2 t_r$$

When the design life of the CP system exceeds that of the coating system then f_c (average) is calculated as follows:

$$f_c(average) = 1 - \frac{\left(1 - k_1^{\,2}\right)}{2k_2 t_r}$$

If the calculated value exceeds 1, then f_c = 1 shall be applied to the design.

Table 5.2 Constants (k_1 and k_2) for calculation of paint coating breakdown factors.

Category	**Description**	**k_1**	**k_2 0-30m**	**k_2 >30m**
I	One layer of primer coat, about 50 μm nominal DFT.	0.10	0.10	0.05
II	One layer of primer coat, plus minimum one layer of intermediate top coat, 150 - 250 μm nominal DFT.	0.05	0.03	0.02
III	One layer of primer coat, plus minimum two layers of intermediate/top coats, 300 μm nominal DFT.	0.02	0.015	0.012
IV	One layer of primer coat, plus minimum three layers of intermediate/top coats, 450 μm nominal DFT.	0.02	0.012	0.012

5.1.3 Pipeline Coatings

The coating breakdown factors as shown in table 5.2 apply equally to both buried and non-buried pipelines. It is assumed that coatings and field joint systems have been chosen to be compatible with the maximum design temperature of the pipeline.

For pipelines with the following coating systems, another coating breakdown factor is calculated.

⇒ asphalt + concrete weight coating

⇒ fusion bonded epoxy + adhesive + polyethylene or polypropylene

⇒ polychloroprene rubber

⇒ equivalent coating systems based on an inner layer dedicated to corrosion protection and one or more outer layers for mechanical protection.

This is as follows:

$$f_c(average) = 0.05 + 0.002(t_r - 30)$$

$$f_c(final) = 0.07 + 0.004(t_r - 20)$$

5.1.4 Concrete

It is now recognized that cathodic protection of concrete reinforcing steel is necessary to ensure the long term integrity of the structure. Also, any CP system designed to protect metallic appendages and components must be designed to allow for current drain from CP to the reinforcement. The cathodic current density is determined by transport of oxygen to the steel by capillary action of pore water driven by evaporation in the atmospheric zone and internal dry compartments. The current densities are, therefore, dependent on depth and climatic conditions.

Table 5.4 Design current densities for concrete reinforcing steel.

(NOTE: design currents refer to the area of the reinforcing steel)

	Design Current Densities (A/m^2)			
Depth (m)	**Tropical >20°C**	**Sub-Tropical 12°-20°C**	**Temperate 7°-12°C**	**Arctic <7°C**
5 to -10	0.0030	0.0025	0.0015	0.0010
<-10	0.0020	0.0015	0.0010	0.0008

5.2 Current Requirements for Pipelines in Soils of Different Types

The current demands for steel pipelines are determined by the soil type (conductivity, pH, moisture, temperature) and the condition of the steel (coating type). An example of typical CP current demand for a pipeline with different coating conditions is presented as follows.

Table 5.3 Range of current required to protect 10 miles of 36" diameter pipe in soil with average resistivity of 1000 ohm-centimeters. Current required is that needed to cause a 0.3 Volt drop across the effective resistance between pipeline and remote earth. [from A.W.Peabody, Control of Pipeline Corrosion,NACE, 1967]

Effective Coating Resistance in Ohms for One Average Square Foot	**Current Required, Amps**
Bare Pipe (minimum 1 mA/ft^2)	500
10,000	14.91
25,000	5.964
50,000	2.982
100,000	1.491
500,000	0.2982
1,000,000	0.1491
5,000,000	0.0298
Perfect Coating	0.000058

5.3 Current Requirements for Ship Protection

Information with regard to current density requirements for ship hull protection is limited. One source of information is the Technical and Research Report R-21, Fundamentals of Cathodic Protection for Marine Service, The Society of Naval Architects and Marine Engineers, January 1976. It must be remembered that this was compiled before the development of modern day bottom coatings. It may, therefore, be better to use the DNV practice for coated steel and to include an allowance for damaged surfaces.

Table 5.5 Protective current densities for ships. [from Technical and Research Report R-21, Fundamentals of Cathodic Protection for Marine Service, The Society of Naval Architects and Marine Engineers, January 1976]

Specific Area	Current Density, mA/m^2
External Hull	22-54
Rudders (Coated and for velocities not exceeding 5 knots. Current demand maybe 3 or more times greater underway)	490
Propellers (For velocities not exceeding 5 knots. Current demand maybe 3 or more times greater underway)	150 -170
Coated Tanks	11
Segregated Ballast	150
Washed Cargo / Clean Ballast	130
Dirty Ballast Tanks	86

6.0 CP TYPE

The CP type determines how the cathodic current is supplied to the structure. CP can be applied by either an impressed current system or by a sacrificial anode system. Impressed current CP systems use an external DC current source and a variety of anode materials to supply the cathodic current. Sacrificial anode CP systems generate the cathodic current from the corrosion of metals less noble than the metal to be protected.

The choice between impressed and sacrificial cathodic protection depends many factors and may be just personal preference. There are, however, situations where one or the other provides the correct choice. The advantages and disadvantages of each type of CP system are described in Table 6.1.

Table 6.1 Advantages and disadvantages of impressed current and sacrificial anode CP systems.

Impressed Current	Sacrificial Anodes
Advantages	
Variable control of current and potential	Self contained
Can be automated	Can be self adjusting
Light weight and fewer anodes	Polarity of connections always correct
Varied anode geometry	Needs no supervision
Long life with inert anodes	Simple to install
Disadvantages	
Complex installation and maintenance	Expensive method of generating electricity
Requires external power source	No variable control
Anodes require dielectric shields	Anodes add weight
Anodes may be damaged	Anodes have finite life
Probability of stray current corrosion	Small lead resistance reduces current

7.0 ANODE SELECTION

Anodes, for both impressed current and sacrificial anodes, are selected according to their size and chemical composition. This determines the current output and design life. Specifications for impressed current anodes are provided in Table 7.1 and for sacrificial anodes in Tables 7.2 and 7.3.

Table 7.1 Impressed current anodes.

Anode Material	Recommended Current density A/m^2	Maximum Voltage, V	Consumption Rate, g/A-yr	Comments
Scrap Steel	Varies	-	200 - 9,000	Difficult life prediction
Graphite	10	-	30 - 450	Very brittle
Silicon-Chromium-Cast Iron	10 - 100	-	90 - 250	Very brittle
Lead-Silver	250 - 500	-	30 - 90	Heavy, Poor mechanical properties
Lead-Platinum	100	-	2 - 60	
Magnetite	10 - 500	-	40	Very Brittle
Platinized Titanium	250 - 700	9	0.01	5 μm thick Pt film provides 10 year life
Platinized Tantalum	500 - 1000	100	0.01	5 μm thick Pt film provides 10 year life
Platinized Columbium	500 - 1000	100	0.01	5 μm thick Pt film provides 10 year life
Lithium-Ferrite Ceramic	15 - 2000	9.7	1-2	Lightweight and tough

Table 7.2 Sacrificial anode types and use.

Anode	Preferred Use	Approx. Potential Volts ref. Ag/AgCl
Magnesium, High Potential	Soils with resistance > 2000 Ω-cm	-1.75
Magnesium, Standard	Soils with resistance < 2000 Ω-cm, and in aqueous environments with controllers if necessary	-1.50
Zinc, Hi-Amp	Seawater, brackish water, saline mud. Temps < 60°C	-1.05
Zinc, Hi-Purity	Underground, fresh water, and saline environments > 60°C	-1.05
Galvalum I	Submerged seawater, max. temp 25 °C	-1.05
Galvalum II	Saline mud	-1.04
Galvalum III	Seawater, brackish water, saline mud	-1.10
Reynode		-1.05
Al-Sn-In Alloy		-1.05

Table 7.3 Sacrificial anode properties.

Property	Anode Material Type				
	Magnesium	Zinc	Galvalum 1	Galvalum II	Galvalum III
Density, kg/m^3	1940	7130	2700	2700	2700
Electrochem Equiv, g/coulomb	0.126E-3	0.339E-3	0.093E-3	0.093E-3	0.093E-3
Theoretical Ah/Kg	2,205	819	2,987	2,987	2,987
Current Efficiency %	0.55	0.95	0.95	0.57	0.85
Actual Ah/Kg	1,212	780	2,830	1,698	2,535
Actual Kg / Amp / Year	7.95	11.25	3.10	5.16	3.46
Potential V, ref. Ag/AgCl	-1.75	-1.05	-1.05	-1.04	-1.10

Table 7.4 Sacrificial Anode Composition.
Percent of Total Weight

	Mg	Zn	Al	Cd	Cu	Fe	Hg	In	Mn	Ni	Pb	Si
Magnesium, High Potential	rem		0.01		0.02	0.03			0.50 - 1.30	0.001		
Magnesium, Standard	rem	2.5 - 3.5	5.3 - 6.7		0.05	0.003			0.15	0.003		0.30
Zinc, Hi-Amp		rem	0.1 - 0.4	0.025 - 0.060		0.005					0.006	
Zinc, Hi-Purity		rem		0.003		0.0014					0.003	
Galvalum I		0.35 - 0.48	rem				0.035 - 0.048					0.14 - 0.21
Galvalum II		3.5 - 5.0	rem				0.035 - 0.048					
Galvalum III		2.8 - 3.5	rem					0.01 - 0.02				0.08 - 0.12

7.1 Anode Resistance to Ground

The current output from an anode is determined by its shape, electrolyte resistance, and driving potential. The shape and electrolyte resistance determine the anode resistance to ground which is calculated from standard anode resistance formulae. The most commonly used formulae are presented in Table 7.4 and seawater conductance values in Table 7.5.

Table 7.4 Anode resistance to ground formulae.

Anode Type	**Resistance Formula**	
Long Slender stand-off L ≥ 4r	$R = \frac{\rho}{2\pi L}\left(\ln\left(\frac{4L}{r}\right) - 1\right)$	(Modified Dwight)
Long Slender stand-off L < 4r	$R = \frac{\rho}{2\pi L}\left[\ln\left\{\frac{2L}{r}\left(1 + \sqrt{1 + \left(\frac{r}{2L}\right)^2}\right)\right\} + \frac{r}{2L} - \sqrt{1 + \left(\frac{r}{2L}\right)^2}\right]$	
Long flush mounted L ≥ 4 x width and thickness	$R = \frac{\rho}{2S}$	(Lloyds)
Short flush-mounted, bracelet and other flush mounted shapes	$R = \frac{0.315\rho}{\sqrt{A}}$	(McCoy)

where:

- R is anode resistance, ohms
- ρ is electrolyte resistivity, ohm-cm
- L is anode length, cm
- S is the mean of the anode sides $= \frac{a+b}{2}$
- r is equivalent radius, cm, $= \sqrt{\frac{\text{anode cross-sectional area}}{\pi}}$
- A is the exposed surface area of anode, cm^2

Table 7.5 Specific Conductance of Seawater

Note: Resistivity, ρ, is the reciprocal of conductance. Tabled values are expressed in in (Ω^{-1}-cm^{-1}).

Chlorinity, ppt	Temperature, °C					
	0	5	10	15	20	30
1	0.001839	0.002134	0.002439	0.002763	0.003091	0.003431
2	0.003556	0.004125	0.004714	0.005338	0.005971	0.006628
3	0.005187	0.006016	0.006872	0.007778	0.008702	0.009658
4	0.006758	0.007845	0.008958	0.010133	0.011337	0.012583
5	0.008327	0.009653	0.011019	0.012459	0.013939	0.015471
6	0.009878	0.011444	0.013063	0.014758	0.016512	0.018324
7	0.011404	0.013203	0.015069	0.017015	0.019035	0.021121
8	0.012905	0.014934	0.017042	0.019235	0.021514	0.023868
9	0.014388	0.016641	0.018986	0.021423	0.023957	0.026573
10	0.015852	0.018329	0.020906	0.023584	0.026367	0.029242
11	0.017304	0.020000	0.022804	0.025722	0.028749	0.031879
12	0.018741	0.021655	0.024684	0.027841	0.031109	0.034489
13	0.020167	0.023297	0.026548	0.029940	0.033447	0.037075
14	0.021585	0.024929	0.028397	0.032024	0.035765	0.039638
15	0.022993	0.026548	0.030231	0.034090	0.038065	0.042180
16	0.024393	0.028156	0.032050	0.036138	0.040345	0.044701
17	0.025783	0.029753	0.033855	0.038168	0.042606	0.047201
18	0.027162	0.031336	0.035644	0.040176	0.044844	0.049677
19	0.028530	0.032903	0.037415	0.042158	0.047058	0.052127
20	0.029885	0.034454	0.039167	0.044114	0.049248	0.054551
21	0.031227	0.035989	0.040900	0.046044	0.051414	0.056949
22	0.032556	0.037508	0.042614	0.047948	0.053556	0.059321

7.2 Anode Ground Beds

Anode ground beds are used to increase the anode current output in soils. They typically comprise an excavation which is filled with low conductance carbonaceous material into which the anode(s) are placed. The total resistance of the system then becomes the resistance of the anode to the carbonaceous backfill plus the resistance to earth of the backfill itself. The anode resistance is reduced by the low resistance of the backfill (typically 50 ohm-cm for coke breeze), and the resistance of the backfill to earth is reduced by the large surface area of the backfill in contact with the soil. Standard anode to ground resistance formulae are used to obtain the resistance values.

Because of the variables involved in ground bed sites, experience is invaluable in attaining competence in their design. They are designed with regard to the current demand of the structure to be protected, to the soil resistance, and to other structures and stray current effects.

7.3 Anode Current Output

Anode current output is calculated using Ohm's Law:

$$I = \frac{V}{R}$$

This is where V is the driving potential, and R is the anode resistance. The driving potential is determined by the anode type. The driving potential for sacrificial CP systems is determined by the environment (Table 7.2), but for impressed current systems it is determined by the rectifier and controller voltage output (Table 7.1). The anode resistance to ground is found from the anode resistance formulas (Table 7.4).

7.4 Anode Size, Weight, Number, Distribution and Design Life

The CP system must be designed to provide the required current to every part of the structure for the required design life. This requires determining anode size, weight, number, and distribution.

The calculations for impressed current CP systems are relatively simple. In this case, it is only necessary to match the number of anodes of known current output to the total current demand of the structure, and to be sure that the anode distribution insures an even and well balanced current distribution.

The calculations for sacrificial CP systems are a little more complex. Not only must the number of anodes satisfy the current demand of the structure, but they must also have sufficient mass to provide electricity for the design life of the structure.

Anode size and shape are determined by the following factors:

- Requirements for minimum and maximum current output
- Requirement for mounting and attachment
- Requirement for streamlining
- Requirement for weight of anode material (sacrificial)
- Commercial availability

The minimum and maximum current outputs are calculated as described in sections 7.1 and 7.2. The types of mounting methods range from welding steel cores, cast into the anode materials, directly to the structure, to mounting complex dielectric shields with screw in platinized titanium impressed current anodes. Where streamlining is required, recesses may be built into the structure to house both impressed and sacrificial anode types.

Sacrificial CP design requires that the weight of anode material is sufficient to supply current for the design life of the structure. This is calculated by the following formula:

$$W = \frac{\left(8760\,\frac{h}{yr}\right)YC}{ZU}$$

$$\begin{gathered} \textit{where}: \\ W = \text{weight of anode material} \\ Y = \text{design life (yrs)} \\ C = \text{current demand (Amps)} \\ Z = \text{anode capacity} \\ U = \text{utilization factor (0.9 for aluminum and zinc)} \end{gathered}$$

Finally, due to practical considerations, anode selection may ultimately be determined by commercial availability. It is often too expensive to customize anode size and geometry for one job. Therefore, except for large and specialized requirements, CP design centers around standard, commercially available anode types.

8.0 COST AND IMPLEMENTATION

There are many permutations possible in CP design, however to be successful it must satisfy economic constraints and be easy to install and operate. Examples of CP designs are presented for an oil platform and ship.

8.1 Oil Platform Example

8.1.1 Structural Details

Water Depth	110m
No. of Legs	4
No. Horizontal Frames	5
No. of Nodes Below Surface	75
Total Submerged Surface Area	63,000 m^2
Total Pile Surface Area in Mud	6,000 m^2
Allowance for Risers, Conductors, Wells	220 Amps
Design Life	35 years

8.1.2. Current Demand

$$\mathit{Total} = (\text{submerged S. A.})(\text{CP current density}) + (\text{pile S. A.})(\text{CP current density}) + \text{allowance}$$

	Submerged Steel (A)	Piles (A)	Allowance (A)	Total (A)
North Sea				
Initial	11,340	150	220	11,710
Mean	5,670	120	220	6,010
Final	7,560	90	220	7,870
Gulf of Mexico				
Initial	6,930	150	220	7,300
Mean	3,780	120	220	4,120
Final	5,040	90	220	5,350

The following design current densities were used for calculating the current demand shown in the previous table:

	Submerged Steel (mA/m^2)	Piles (mA/m^2)
North Sea		
Initial	180	25
Mean	90	20
Final	120	15
Gulf of Mexico		
Initial	110	25
Mean	60	20
Final	80	15

Example calculation (for North Sea, Initial)

$$\text{CP current for submerged steel} = (\text{submerged S.A.})(\text{CP current density}) = (63{,}000\text{m}^2)(0.180\,\tfrac{\text{A}}{\text{m}^2})$$

$$\text{CP current for submerged steel} = 11{,}340A$$

$$\text{CP current for piles} = (\text{pile S.A.})(\text{CP current density}) = (63{,}000\text{m}^2)(0.025\,\tfrac{\text{A}}{\text{m}^2})$$

$$\text{CP current for piles} = 150A$$

$$\text{Total CP current} = 11{,}340A + 150A + 220A$$

$$\text{Total CP current} = 11{,}710A$$

8.1.3. Sacrificial Anode Design for Uncoated Structure

The following table is the weight required for 35 year CP design life (using mean current density)

Location	Zinc, kg	Aluminum, kg
NORTH SEA	2,624,880	723,462
GULF OF MEXICO	1,799,419	495,953

Example calculation for the weight of zinc required, North Sea:

$$W = \frac{\left(8760\,\frac{h}{yr}\right)YC}{ZU}$$

$$W = \frac{\left(8760\,\frac{h}{yr}\right)\left(35\,yr\right)\left(6{,}010\,A\right)}{\left(780\,\frac{Ah}{kg}\right)\left(0.9\right)}$$

$$W = 2{,}624{,}880\,kg$$

Number of Anodes Required to Provide Initial Current Demand to Polarize the Structure

Assume the following anode dimensions: 2,500 mm long
250 mm width
207 mm thick

	NORTH SEA	GULF OF MEXICO
Seawater Resistivity, ohm-cm	30	20
Anode Resistance, Ohms	0.0641	0.0427
Anode Current Output, Amps	3.900	5.855
Number of Anodes for Initial Current Demand	3003	1247
Mass of Zinc Anodes, kg	2,768,766	1,149,734
Mass of Aluminum Anodes, kg	1,048,047	435,203

The previous table was created using the following methodology:

Find Mass of One Anode, Zinc

$$m = \rho_{zinc} \forall$$
$$m = (7{,}130\,\tfrac{kg}{m^3})(2.5m)(0.25m)(0.207m)$$
$$m = 922kg$$

Find Mass of One Anode, Aluminum

$$m = \rho_{Al} \forall$$
$$m = (2{,}700\,\tfrac{kg}{m^3})(2.5m)(0.25m)(0.207m)$$
$$m = 349kg$$

Find the Resistance of the Anode Using Table 7.4 (example for North Sea)

$$R = \frac{\rho}{2\pi L}\left(\ln\left(\frac{4L}{r}\right) - 1\right)$$
$$R = \frac{30\Omega cm}{2\pi(250cm)}\left(\ln\left(\frac{4(250cm)}{\sqrt{\frac{(25cm)(20.7cm)}{\pi}}}\right) - 1\right)$$
$$R = 0.0641\Omega$$

Calculate single anode current output (example for North Sea):

$$I = \frac{V}{R}$$
$$I = \frac{(-0.800V - (-1.05V))}{0.0641\Omega}$$
$$I = 3.90A$$

Find the # of Anodes Necessary to Produce the Initial Current (example for North Sea):

$$\#\text{ of anodes} = \frac{\text{Initial current demand}}{\text{current output per anode}}$$
$$\#\text{ of anodes} = \frac{11{,}710\text{A}}{3.90\,\frac{\text{A}}{\text{anode}}} = 3002.5\text{ anodes} = 3003\text{ anodes}$$

Find the Mass of the Anodes (example for zinc anodes, North Sea):

$$\text{Total Mass of Zinc Anodes} = (\#\ \text{of anodes})(\text{mass per anode})$$
$$\text{Total Mass of Zinc Anodes} = (3003\ \text{anodes})(922\ \tfrac{\text{kg}}{\text{anode}}) = 2{,}768{,}766\ \text{kg}$$

Let us then compare the mass of anodes required for the design life and the mass required for the initial polarization of the structure:

	NORTH SEA	**GULF OF MEXICO**
Mass of Zinc to protect the structure for 35 years, kg	2,624,880	**1,799,419**
Mass of Zinc required to provide the initial current, kg	**2,768,766**	1,149,734
Mass of Aluminum to protect the structure for 35 years, kg	723,462	**495,953**
Mass of Aluminum required to provide the initial current, kg	**1,048,047**	435,203
# of Zinc Anodes Needed	3003	1952
# of Aluminum Anodes Needed	3003	1421

Anode Distribution and Spacing

For sacrificial anodes this maybe based on the current demand of the structure and the maximum current output of the anode.

NORTH SEA

Maximum Current Output	3.900 Amps
Maximum Current Demand	180 mA/m^2
Maximum Area Protected	3.900 A/(0.180A/m^2) = 21.7m^2

GULF OF MEXICO

Maximum Current Output	5.855 Amps
Maximum Current Demand	110 mA/m^2
Maximum Area Protected	5.855 A/(0.110 A/m^2) = 53.2m^2

If the structural member is relatively large, say 3 m diameter, then a single anode placed in the center of a 22 or 53 m^2 area will not be too far from the extremities of the cathode it is protecting. For smaller members, allowances have to be made for attenuation, and anode sizes must be selected to ensure that the anode protects half way to the next anode.

8.1.4 Sacrificial Anode Design Coated Structure

The effect of coating a structure on CP design can be seen by applying the DNV criteria to Example 1. It can be seen that significant savings in anode material can be achieved if a Category 2, 3 or 4 coating is used. The category 1 coatings are only helpful for short design life. This interpretation of the interaction between coatings and CP is still open to debate with many experts in the Oil Industry questioning the low performance criteria assigned to Category I coatings.

Structure Area, m^2:			63,000					
Allowance, Amps			220					
Piles, Amps:			120					
Zinc Anodes, Ah/kg			780		Cost, $/tonne, Feb 1995			1,025
Aluminum Anodes, Ah/kg			2,830		Cost, $/tonne, Feb 1995			2,000
CD mA/m^2	tr, years	Category	k1	k2	f (ave)	f (final)	CP (ave) mA/m^2	CP (final) mA/m^2
North Sea								
90	35	1	0.1000	0.1000	1.8500	3.6000	90	90
90	35	1	0.1000	0.0500	0.9750	1.8500	88	90
90	35	2	0.0500	0.0300	0.5750	1.1000	52	90
90	35	2	0.0500	0.0200	0.4000	0.7500	36	68
90	35	3	0.0200	0.0150	0.2825	0.5450	25	49
90	35	3	0.0200	0.0120	0.2300	0.4400	21	40
90	35	4	0.0120	0.0120	0.2220	0.4320	20	39
90	35	4	0.0120	0.0120	0.2220	0.4320	20	39
Category			I	II	III	IV		
Total Current Demand, Amps			6,010	3,600	1,942	1,599		
Wt Aluminum, kg			723,465	433,387	233,745	192,451		
Cost Aluminum			1,446,931	866,774	467,490	384,903		
Number of Anodes			3,003	3,000	2,500	2,500		
Weight/Anode, kg			482	289	187	154		
Cost, $ / Anode			1,156	693	449	370		
Cost Installation $ / Anode			450	400	400	400		
Total Cost CP, $			**4,823,983**	**3,280,258**	**2,121,975**	**1,923,767**		
Gulf of Mexico								
60	35	1	0.1000	0.1000	1.8500	3.6000	60	60
60	35	1	0.1000	0.0500	0.9750	1.8500	59	60
60	35	2	0.0500	0.0300	0.5750	1.1000	35	60
60	35	2	0.0500	0.0200	0.4000	0.7500	24	45
60	35	3	0.0200	0.0150	0.2825	0.5450	17	33
60	35	3	0.0200	0.0120	0.2300	0.4400	14	26
60	35	4	0.0120	0.0120	0.2220	0.4320	13	26
60	35	4	0.0120	0.0120	0.2220	0.4320	13	26
Category			I	II	III	IV		
Total Current Demand			4,120	2,514	1,408	1,179		
Wt Aluminum			233,535	142,473	79,802	66,839		

8.1.5 Impressed Current Anode Design

Assuming the use of platinized titanium anodes with the following dimensions.

length = 1000 mm

diameter = 25 mm

Maximum driving potential = 9V

Then the surface area of the anode is:

$$\pi dL = 0.078m^2$$

	NORTH SEA	**GULF OF MEXICO**
Anode Resistance, Ohms	0.2277	0.1518
Maximum Anode Current Output, Amps	39.5	59.3
Maximum current density on anode surface, A/m^2	506	760
Number of anodes required	296	123

The distribution of the anodes is critical.

8.2 Ship Hull Protection

Ship Hulls require protection from both corrosion and the development of biofouling accumulations. The former is achieved by both coating and cathodic protection systems and the latter by antifouling coatings. In addition to the basic costs of the coating and cathodic protection systems, allowances must be made for dry dock costs, loss of revenue, and increased fuel consumption and lost performance due to the increase in skin friction drag caused by poor hull maintenance and biofouling.

SHIP HULL COATING

GRIT BLAST

NACE #1, with 1 - 2 mil anchor profile

BARRIER COAT

Hard Boiled Mastic, two component epoxy amine

Two coats, 3 mils D.F.T.

Coverage per one mil dry - 564 sq.ft./gal.

Cost, $23.00/gal.

Cost for 6 mils D.F.T. $0.24/sq.ft.

CATHODIC PROTECTION DESIGN

SHIP	ORIANA
TYPE	PASSENGER
LENGTH, m	245
BREADTH, m	30
DRAFT, m	9.75
BLOCK COEFFICIENT, C_b	0.6
WETTED SURFACE AREA (1.7xLxD)+(C_bxLxB) m^2	8,471
CURRENT DEMAND FOR HULL, (@22mA/m^{2}) Amps	186
CURRENT DEMAND FOR RUDDERS, Amps	15
CURRENT DEMAND FOR PROPELLERS, Amps	35
TOTAL CURRENT DEMAND, AMPS	236

Sacrificial Anode Calculations

Current Output per Anode

Assume anode dimensions: 500mm x 115mm x 65mm

The current output, $I = \frac{V}{R}$

R = the anode resistance calculated using Lloyds' Formula for plate anodes

Lloyds' Formula

$$R = \frac{\rho}{2S}$$

$$R = \frac{20\Omega - cm}{2(30.75cm)}$$

$$R = 0.325\Omega$$

Current output per anode,

$$I = \frac{V}{R}$$

$$I = \frac{0.25V}{0.325\Omega} = 0.769A$$

Number of anodes required to supply current,

$$\#\text{ of anodes needed} = \frac{\text{Total current required}}{\text{Current output per anode}}$$

$$\#\text{ of anodes needed} = \frac{236A}{0.384\frac{A}{anode}} = 307\text{ anodes}$$

The total current capacity for one anode is:

Volume of Anodes * Density * Capacity of Galvalum 1

= 3.738×10^{-3} m^3 * 2,700 kg/m^3 * 2,830 Ah/kg = 28,558 Ah

The design life of the system will be

$$= \frac{28{,}558\text{ A hrs} * 307\text{ anodes} * (0.9)}{236\text{ Amps}} = 33{,}435\text{ hrs or } 3.8\text{ years}$$