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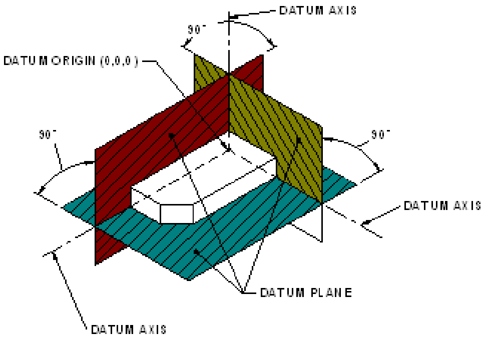

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TECHNICAL MANUAL

ELECTRICAL DESIGN, CATHODIC PROTECTION

HEADQUARTERS, DEPARTMENT OF THE ARMY
22 APRIL 1985

Technical Manual

No. 5-811-7

HEADQUARTERS
DEPARTMENT OF THE ARMY
WASHINGTON, D.C. *22 April 1985*

ELECTRICAL DESIGN, CATHODIC PROTECTION

LIST OF FIGURES

This manual supersedes Sections VII, VIII, and IX of TM 5-811-4, 1 August 1962.

LIST OF FIGURES (CONT'd)

LIST OF TABLES

CHAPTER 1
INTRODUCTION TO CATHODIC PROTECTION

1-1. Purpose.

This manual presents design guidance for cathodic protection systems.

1-2. References.

a. Government publications.

Department of Transportation

Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402

Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards, Subpart 1 - Requirements *Register,* Vol 36, No. 126 (June 30, 1971).

b. Nongovernment publications.

National Association of Corrosion Engineers (NACE), P.O. Box 218340, Houston, TX 77084

Standard RP-01-69 (1972 revision	Control of External Corrosion on Underground or Submerged Metallic Piping Systems
Standard RP-02-72	Direct Calculation of Economic Appraisals of Corrosion Control Measures

1-3. Corrosion.

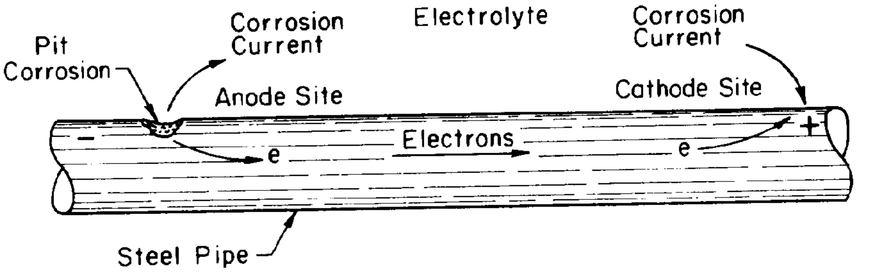
Corrosion is an electrochemical process in which a current leaves a structure at the anode site, passes through an electrolyte, and reenters the structure at the cathode site as figure 1-1 shows. For example, one small section of a pipeline may be anodic because it is in a soil with low resistivity compared to the rest of the line. Current would leave the pipeline at that anode site, pass through the soil, and reenter the pipeline at a cathode site. Current flows because of a potential difference between the anode and cathode. That is, the anode potential is more negative than the cathode potential, and this difference is the driving force for the corrosion current. The total system—anode, cathode, electrolyte, and metallic connection between anode and cathode (the pipeline in fig 1-1)—is termed a *corrosion cell.*

1-4. Cathodic protection.

Cathodic protection is a method to reduce corrosion by minimizing the difference in potential between anode and cathode. This is achieved by applying a current to the structure to be protected (such as a pipeline) from some outside source. When enough current is applied, the whole structure will be at one potential; thus, anode and cathode sites will not exist. Cathodic protection is commonly used on many types of structures, such as pipelines, underground storage tanks, locks, and ship hulls.

1-5. Types of cathodic protection systems.

There are two main types of cathodic protection systems: galvanic and impressed current. Figure 1-2 shows these two types. Note that both types have anodes (from which current flows into the



Reprinted from Cathodic Protection, L.M. Applegate, 1960, with permission of Mc Graw-Hill Book Company

Figure 1-1. Corrosion of a pipeline due to localized anode and cathode sites.

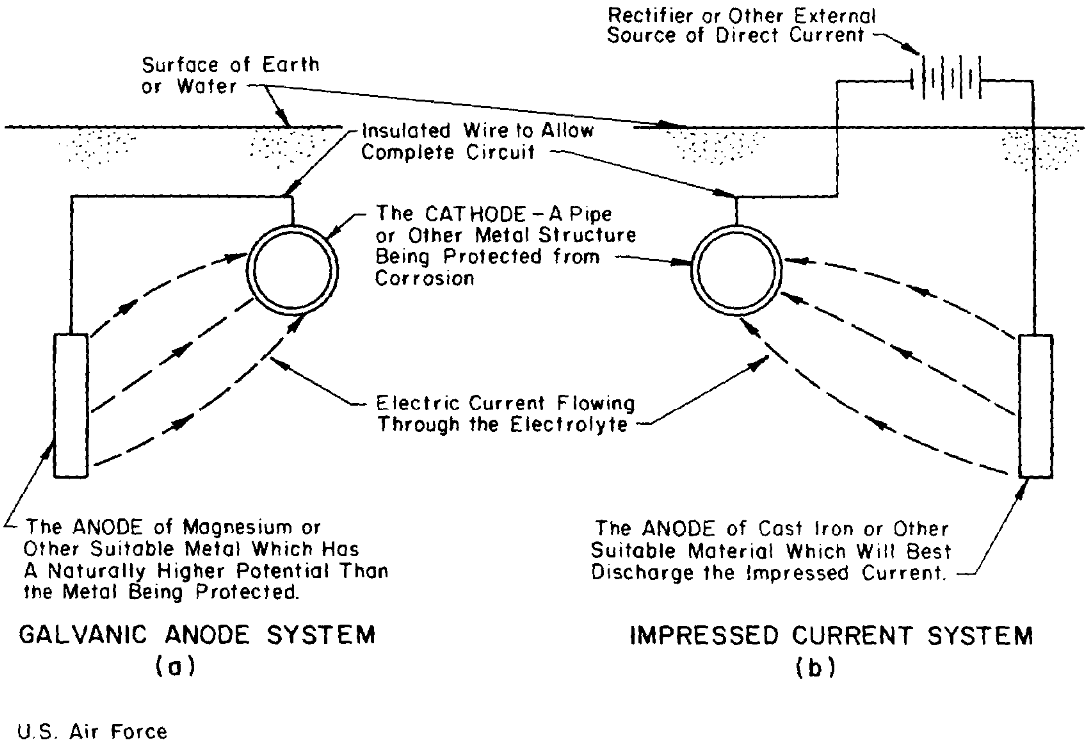


Figure 1-2. (a) Galvanic and (b) impressed current systems for cathodic protection.

electrolyte), a continuous electrolyte from the anode to the protected structure, and an external metallic connection (wire). These items are essential for all cathodic protection systems.

a. Galvanic system. A galvanic cathodic protection system makes use of the corrosive potentials for different metals. Without cathodic protection, one area of the structure exists at a more negative potential than another, and corrosion results. If, however, a much less inert object (that is, with much more negative potential, such as a magnesium anode) is placed adjacent to the structure to be protected, such as a pipeline, and a metallic connection (insulated wire) is installed between the object and the structure, the object will become the anode and the entire structure will become the cathode. That is, the new object corrodes sacrificially to protect the structure as shown in figure 1-2. Thus, the galvanic cathodic protection system is called a *sacrificial anode cathodic protection system* because the anode corrodes sacrificially to protect the structure. Galvanic anodes are usually made of either magnesium or zinc because of these metals' higher potential compared to steel structures.

b. Impressed current systems. Impressed current cathodic protection systems use the same elements as the galvanic protection system, only the structure is protected by applying a current to it from an anode. The anode and the structure are connected by an insulated wire, as for the galvanic system. Current flows from the anode through the electrolyte onto the structure, just as in the galvanic system. The main difference between galvanic and impressed current systems is that the galvanic system relies on the difference in potential between the anode and structure, whereas the impressed current system uses an external power source to drive the current, as figure 1-2b shows. The external power source is usually a rectifier that changes input a.c. power to the proper d.c. power level. The rectifier can be adjusted, so that proper output can be maintained during the system's life. Impressed current cathodic protection system anodes typically are high-silicon cast iron or graphite.

CHAPTER 2
CATHODIC PROTECTION DESIGN

2-1. Required information.

Before deciding which type, galvanic or impressed current, cathodic protection system will be used and before the system is designed, certain preliminary data must be gathered.

a. Physical dimensions of structure to be protected. One important element in designing a cathodic protection system is the structure's physical dimensions (for example, length, width, height, and diameter). These data are used to calculate the surface area to be protected.

b. Drawing of structure to be protected. The installation drawings must include sizes, shapes, material type, and locations of parts of the structure to be protected.

c. Electrical isolation. If a structure is to be protected by the cathodic system, it must be electrically connected to the anode, as figure 1-2 shows. Sometimes parts of a structure or system are electrically isolated from each other by insulators. For example, in a gas pipeline distribution system, the inlet pipe to each building might contain an electric insulator to isolate inhouse piping from the pipeline. Also, an electrical insulator might be used at a valve along the pipeline to electrically isolate one section of the system from another. Since each electrically isolated part of a structure would need its own cathodic protection, the locations of these insulators must be determined.

d. Short circuits. All short circuits must be eliminated from existing and new cathodic protection systems. A short circuit can occur when one pipe system contacts another, causing interference with the cathodic protection system. When updating existing systems, eliminating short circuits would be a necessary first step.

e. Corrosion history of structures in the area. Studying the corrosion history in the area can prove very helpful when designing a cathodic protection system. The study should reinforce predictions for corrosivity of a given structure and its environment; in addition, it may reveal abnormal conditions not otherwise suspected. Facilities personnel can be a good source of information for corrosion history.

f. Electrolyte resistivity survey. A structure's corrosion rate is proportional to the electrolyte resistivity. Without cathodic protection, as electrolyte resistivity decreases, more current is allowed to flow from the structure into the electrolyte; thus, the structure corrodes more rapidly. As electrolyte resistivity increases, the corrosion rate decreases (table 2-1). Resistivity can be measured either in a laboratory or at the site with the proper instruments. Appendix A explains the methods and equipment needed to complete a soil resistivity survey. The resistivity data will be used to calculate the sizes of anodes and rectifier required in designing the cathodic protection system.

Table 2-1. Corrosivity of soils on steel based on soil resistivity

Soil resistivity range (ohm-cm)	Corrosivity
0 to 2000	Severe
2000 to 10,000	Moderate to severe
10,000 to 30,000	Mild
Above 30,000	Not likely

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g. Electrolyte pH survey. Corrosion is also proportional to electrolyte pH (see glossary for definition of pH and other terms). In general, steel's corrosion rate increases as pH decreases when soil resistivity remains constant.

h. Structure versus electrolyte potential survey. For existing structures, the potential between the structure and the electrolyte will give a direct indication of the corrosivity. According to NACE Standard No. RP-01, the potential requirement for cathodic protection is a negative (cathodic) potential of at least 0.85 volt as measured between the structure and a saturated copper-copper sulfate reference electrode in contact with the electrolyte. A potential which is less negative than -0.85 volt would probably be corrosive, with corrosivity increasing as the negative value decreases (becomes more positive).

i. Current requirement. A critical part of design calculations for cathodic protection systems on existing structures is the amount of current required per square foot (called *current density)* to change the structure’s potential to -0.85 volt. The current density required to shift the potential indicates the structure's surface condition. A well coated structure (for example, a pipeline well coated with coal-tar epoxy) will require a very low current density (about 0.05 milliampere per square foot); an uncoated structure would require high current density (about 10 milliamperes per square foot). The average current density required for cathodic protection is 2 milliamperes per square foot of *bare* area. The amount of current required for complete cathodic protection can be determined three ways:

—An actual test on existing structures using a temporary cathodic protection setup.

—A theoretical calculation based on coating efficiency.

—An estimate of current requirements using tables based on field experience.

(1) The second and third methods above can be used on both existing and new structures. Appendix B contains a detailed review of current requirement testing.

(2) Current requirements can be calculated based on coating efficiency and current density (current per square foot) desired. The efficiency of the coating as supplied will have a direct effect on the total current requirement, as equation 2-1 shows:

$$I = (A)(I')(1.0\text{-}CE), \qquad \text{(eq 2-1)}$$

where I is total protective current, A is total structure surface area in square feet, I' is required current density, and CE is coating efficiency. Equation 2-1 may be used when a current requirement test is not possible, as on new structures, or as a check of the current requirement test on existing structures. Coating efficiency is directly affected by the type of coating used and by quality control during coating application. The importance of coating efficiency is evident in the fact that a bare structure may require 100,000 times as much current as would the same structure if it were well coated.

(3) Current requirements also can be estimated from table 2-2. The table gives an estimate of current, in milliamperes per square foot, required for complete cathodic protection. That value, multiplied by the surface area of the structure to be protected (in square feet) gives the total estimated current required. Caution should be used when estimating, however, as under- or overprotection may result.

Table 2-2. Typical current density requirements for cathodic protection of uncoated steel

Environment	Current density (mA/sq ft)	
	AFM 88-9[a]	Gerrard[b]
Neutral soil	0.4 to 1.5	0.4 to 1.5
Well aerated neutral soil	2 to 3	2 to 3
Wetsoil	1 to 6	2.5 to 6
Highly acidic soil	3 to 15	5 to 15
Soil supporting active sulfate-reducing bacteria	6 to 42	Up to 42
Heated soil	3 to 25	5 to 25
Stationary freshwater	1 to 6	5
Moving freshwater containing dissolved oxygen	5 to 15	5 to 15
Seawater	3 to 10	5 to 25

[a] Data are from Air Force Manual AFM 88-9, *Corrosion Control* (U.S. Air Force, August 1962), chap 4, p 203.

[b] Data are from J.S. Gerrard, "Practical Applications of Cathodic Protection," *Corrosion,* Vol 2 (L.L. Shreir, Ed.), Newnes-Butterworths, London, 1976, p 11:65. Used with permission.

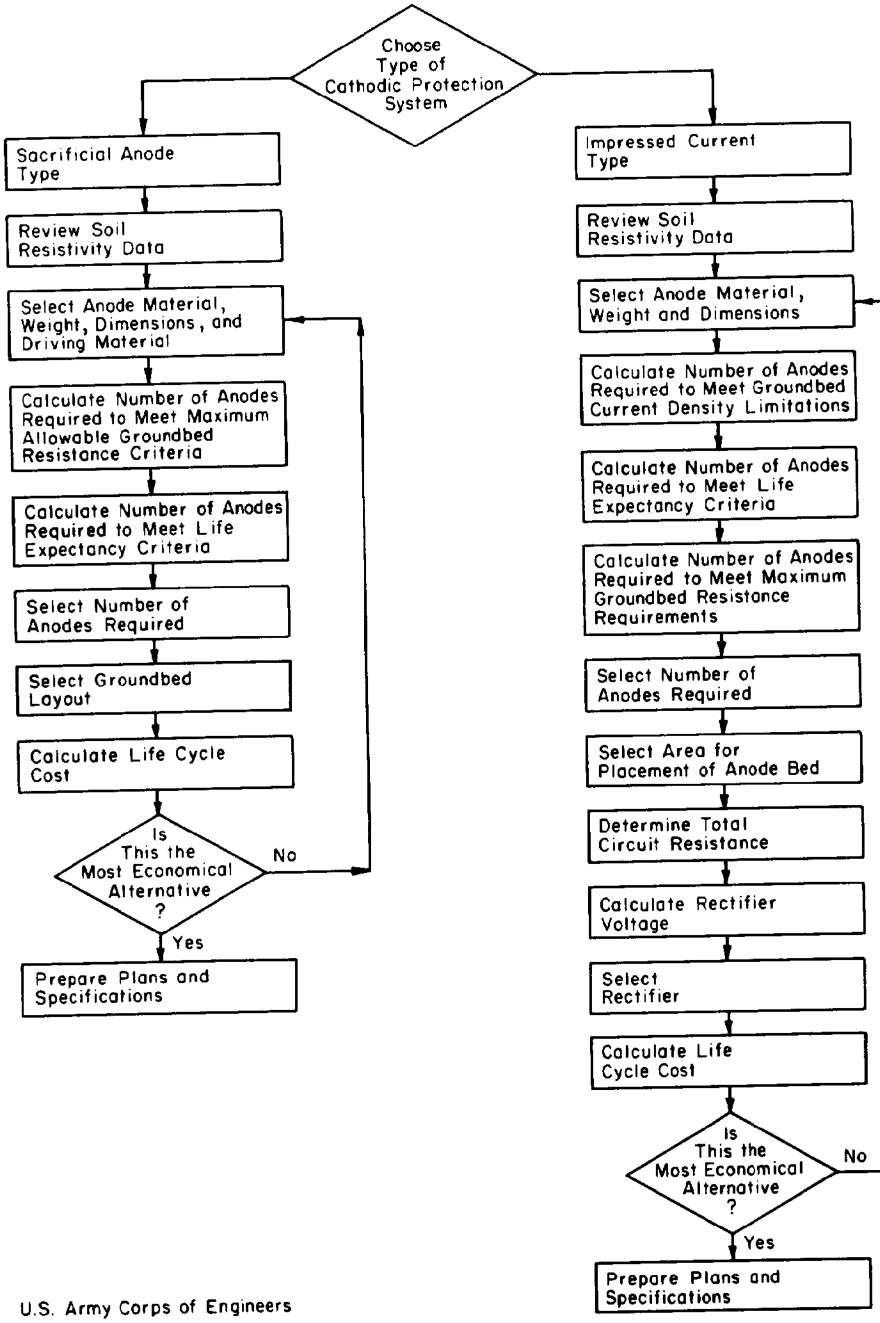
j. Coating resistance. A coating's resistance decreases greatly with age and directly affects structure-to-electrolyte resistance for design calculations. The coating manufacturers supply coating resistance values.

k. Protective current required. By knowing the physical dimensions of the structure to be protected, the surface area can be calculated. The product of the surface area multiplied by current density obtained previously in *I* above gives the total current required.

l. The need for cathodic protection. For existing structures, the current requirement survey *(I* above) will verify the need for a cathodic protection system. For new systems, standard practice is to assume a current density of at least 2 milliamperes per square foot of bare area will be needed to protect the structure. (However, local corrosion history may demand a different current density.) In addition, cathodic protection is *mandatory* for underground gas distribution lines (Department of Transportation regulations—Title 49, *Code of Federal Regulations,* Oct 1979) and for water storage tanks with a 250,000-gallon capacity or greater. Cathodic protection also is required for underground piping systems located within 10 feet of steel reinforced concrete because galvanic corrosion will occur between the steel rebar and the pipeline.

2-2 Determining type and design of cathodic protection system.

When all preliminary data have been gathered and the protective current has been estimated, the design sequence can begin. The first question to ask is: which type (galvanic or impressed current) cathodic protection system is needed? Conditions at the site sometimes dictate the choice. However, when this is not clear, the criterion used most widely is based on current density required and soil resistivity. If the soil resistivity is low (less than 5000 ohm-centimeters) and the current density requirement is low (less than 1 milliampere per square foot), a galvanic system can be used. However, if the soil resistivity and/or current density requirement exceed the above values, an impressed current system should be used. Figure 2-1 will be used in the design sequence. Design sequences for each type of cathodic protection system are given in paragraphs a and *b* below.



U.S. Army Corps of Engineers

Figure 2-1. Design sequence for cathodic protection systems.

a. Sacrificial anode (galvanic) cathodic protection system design. The following eight steps are required when designing galvanic cathodic protection systems. Appendix C gives examples of galvanic cathodic protection designs.

(1) Review soil resistivity. The site of lowest resistivity will likely be used for anode location to minimize anode-to-electrolyte resistivity. In addition, if resistivity variations are not significant, the average resistivity will be used for design calculations.

(2) Select anode. As indicated in paragraph 1-4, galvanic anodes are usually either magnesium or zinc. Zinc anodes are used in extremely corrosive soil (resistivity below 2000 ohm- centimeters). Data from commercially available anodes must be reviewed. Each anode specification will include anode weight, anode dimensions, and package dimensions (anode plus backfill), as table 2-3 shows for magnesium-alloy anodes. In addition, the anode's driving potential must be considered (para a[3] below). The choice of anode from those available is arbitrary; design calculations will be made for several available anodes, and the most economical one will be chosen.

Table 2-3. Weights and dimensions of selected high-potential magnesium-alloy anodes for use in soil or water

Weight (lb)	Size (in.)	Packaged wt (lb)	Packaged size (in.)
3	3.75 x 3.75 x 5	12	6 x 10
5	3.75 x 3.75 x 7.5	17	6 x 12
9	2.75 x 2.75 x 26	35	6 x 31
9	3.75 x 3.75 x 13.25	27	6 x 17
12	3.75 x 3.75 x 18	36	6 x 23
14	2.75 x 2.75 x 41	50	6 x 46
14	3.75 x 3.75 x 21	42	6.5 x 26
17	2.75 x 2.75 x 50	60	6 x 55
17	3.75 x 3.75 x 26	45	6.5 x 29
20	2.5 x 2.5 x 59.25	70	5 x 66
24	4.5 x 4.5 x 23	60	7 x 30
32	5.5 x 5.5 x 21	74	8 x 28
40	3.75 x 3.75 x 59.25	105	6.5 x 66
48	5.5 x 5.5 x 30	100	8 x 38
48	8 x 16	100	12 x 25
60	4.5 x 4.5 x 60	—	—

Note: Core material is a galvanized 20-gage perforated steel strip. Anodes longer than 24 inches have a 9-gage core. The connecting wire is a 10-foot length of solid No. 12 AWG TW insulated copper wire, silver-soldered to the core with joints sealed against moisture. Special wires or other lengths are available.

U.S. Air Force.

(3) Calculate net driving potential for anodes. The open-circuit potential of standard alloy magnesium anodes is approximately -1.55 volts to a copper-copper sulfate half-cell. The open-circuit potential of high-manganese magnesium anodes is approximately -1.75 volts to a copper-copper sulfate half-cell.

(a) The potential of iron in contact with soil or water usually ranges around -0.55 volt relative to copper-copper sulfate. When cathodic protection is applied using magnesium anodes, the iron potential assumes some value between -0.55 and -1.0 volt, depending on the degree of protection provided. In highly corrosive soils or waters, the natural potential of iron may be as high as -0.82 volt relative to copper-copper sulfate. From this, it is evident that -0.55 volt should not be used to calculate the net driving potential available from magnesium anodes.

(b) A more practical approach is to consider iron polarized to -0.85 volt. On this basis, standard alloy magnesium anodes have a driving potential of 0.70 volt (1.55-0.85 0.70) and high-potential magnesium anodes have a driving potential of 0.90 volt (1.75-0.85 0.90). For cathodic protection design that involves magnesium anodes, these potentials, 0.70 and 0.90 volt, should be used, depending on the alloy selected.

(4) Calculate number of anodes needed to meet groundbed resistance limitations. The total resistance (RT) of the galvanic circuit is given by equation 2-2:

$$R_T = R_a + R_w + R_c, \qquad \text{(eq 2-2)}$$

where R_a is the anode-to-electrolyte resistance, R_w is the anode lead wire resistance, and R_c is the structure-to-electrolyte resistance. The total resistance also can be found by using equation 2-3:

$$R_T = \frac{\Delta E}{I}, \qquad \text{(eq 2-3)}$$

where ΔE is the anode's driving potential discussed in a(3) above and I is the current density required to achieve cathodic protection (para 2-1). R_c in equation 2-2 can be calculated by using equation 2.4:

$$R_c = \frac{R}{A}, \qquad \text{(eq 2-4)}$$

where R is the average coating resistance, in ohms per square feet, at the end of the proposed lifetime for the system (R is specified by the supplier), and A is the structure's surface area in square feet. Assuming R_w in equation 2-2 is negligible, that anode-to-electrolyte resistance can then be calculated from equation 2-5:

$$R_a = R_T - R_c, \qquad \text{(eq 2-5)}$$

which gives the maximum allowable groundbed resistance; this will dictate the minimum number of anodes required (as number of anodes decreases, groundbed resistance increases). To calculate the number of anodes required, equation 2-6 is used:

$$N = \frac{(0.0052)(D)}{(R_a)(L)}\left[\ln \frac{8L}{d} - 1\right], \qquad \text{(eq 2-6)}$$

where N is the number of anodes,   is the soil resistivity in ohms, R_a is the maximum allowable groundbed resistance in ohms (as computed in eq 2-5), L is the length of the backfill column in feet (specified by supplier), and d is the diameter of the backfill column in feet (specified by supplier).

(5) Calculate number of anodes for system's life expectancy. Each cathodic protection system will be designed to protect a structure for a given number of years. To meet this lifetime requirement, the number of anodes (N) must be calculated using equation 2-7:

$$N = \frac{(L)\ (I)}{49.3\ (W)}, \qquad \text{(eq 2-7)}$$

where L expected lifetime in years, W is weight (in pounds) of one anode, and I is the current density required to protect the structure (in milliamperes).

(6) Select number of anodes to be used. The greater value of equation 2-6 or 2-7 will be used as the number of anodes needed for the system.

(7) Select groundbed layout. When the required number of anodes has been calculated, the area to be protected by each anode is calculated by equation 2-8:

$$A = \frac{A_T}{N}, \qquad \text{(eq 2-8)}$$

where A is area to be protected by one anode, A_T is total surface area to be protected, and N is the total number of anodes to be used. For galvanic cathodic protection systems, the anodes should be spaced equally along the structure to be protected.

(8) Calculate life-cycle cost for proposed design. NACE Standard RP-02 should be used to calculate the system's life-cycle cost. The design process should be done for several different anode choices to find the one with minimal life-cycle cost.

(9) Prepare plans and specifications. When the design procedure has been done for several different anodes and the final anode has been chosen, plans and specifications can be completed.

b. Impressed current cathodic protection system design. Thirteen steps are required when designing impressed current cathodic protection systems. Appendix D gives examples of impressed current cathodic protection designs.

(1) Review soil resistivity. As with galvanic systems, this information will contribute to both design calculations and location of anode groundbed.

(2) Review current requirement test. The required current will be used throughout the design calculations. The calculated current required to protect 1 square foot of bare pipe should agree with the values in table 2-2.

(3) Select anode. As with the galvanic system, the choice of anode is arbitrary at this time; economy will determine which anode is best. Table 2-4 gives common anode sizes and specifications. The anodes used most often are made of high-silicon chromium-bearing cast-iron (HSCBCI). When impressed current-type cathodic protection systems are used to mitigate corrosion on an underground steel structure, the auxiliary anodes often are surrounded by a carbonaceous backfill. Backfill materials commonly used include coal coke breeze, calcined petroleum coke breeze, and natural graphite particles. The backfill serves three basic functions: (a) it decreases the anode-to-earth resistance by increasing the anode's effective size, (b) it extends the system's operational life by providing additional anode material, and (c) it provides a uniform environment around the anode, minimizing deleterious localized attack. The carbonaceous backfill, however, cannot be expected to increase the groundbed life expectancy unless it is well compacted around the anodes. In addition to HSCBCI anodes, the ceramic anode should be considered as a possible alternative for long-term cathodic protection of water storage tanks and underground pipes in soils with resistivities less than 5000 ohm-centimeters. The ceramic anode consumption rate is 0.0035 ounce per ampere-year compared to 1 pound per ampere-year for HSCBCI anodes. Appendix E gives the design and specifications for the ceramic anode.

Table 2-4. Weights and dimensions of selected circular high-silicon chromium-bearing cast iron anodes

Anode weight (lb)	Anode dimensions (in.)	Anode surface size (in.)	Package area (sq ft)
12	1 x 60	1.4	10 x 84
44	2 x 60	2.6	10 x 84
60	2 x 60	2.8	10 x 84
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is length of the anode backfill column in feet, P is the paralleling factor from table 2-6, and S is the center-to-center spacing between anode backfill columns in feet.

Table 2-5. Shape functions (K) for impressed current cathodic protection anodes where L is effective anode length and d is anode/backfill diameter.

L/d	K	L/d	K
5	0.0140	20	0.0213
6	0.0150	25	0.0224
7	0.0158	30	0.0234
8	0.0165	35	0.0242
			0.0249
			0.0255
			0.0261
			0.0266
			0.0270

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(b) Calculate groundbed header cable resistance. The cable is typically supplied with a specified resistance in ohms per 100 feet. The wire resistance then is calculated from equation 2-12: