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MAT-112 EXAM PREVIEW

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Exam Preview:

1. Corrosion will be defined as the destructive attack of a metal through interaction with its environment. the basic mechanism of corrosion of metals is the electrochemical cell.
    a. True
    b. False

2. As in all chemical reactions, corrosion reactions occur through an exchange of:
    a. Electrolytes
    b. Anodes
    c. Cathodes
    d. Electrons

3. Which of the following is not a component required for an electrochemical reaction to occur?
    a. Anode
    b. Cathode
    c. electron cell
    d. electrolyte

4. For each specific cathodic reaction a characteristic number of electrons are produced in the reaction of one metal ions. Thus, all other things being equal, the metal loss is proportional to the number of electrons that are produced.
    a. True
    b. False

5. Most metals tend to corrode in any environment where moisture is present. However, the rate of corrosion can often be controlled to acceptable levels. The site where the electrochemical activity is most ___ controls the overall reaction rate.
   a. Active
   b. Reactive
   c. Passive
   d. Limited

6. In some cases the core of a metal is naturally covered by a film of reaction products. Stainless steels and titanium alloys are resistant to corrosion in many environments due to the presence of such reactive films.
   a. True
   b. False

7. Which of the following is not a form of corrosion?
   a. Immunity
   b. Uniform Corrosion
   c. Galvanic Corrosion
   d. Shear Corrosion

8. When two different metals are electrically connected in an electrolyte, the electrochemical cell formed is called a galvanic cell. Galvanic corrosion is a similar but undesirable form of electrochemical action.
   a. True
   b. False

9. Pitting is likely to occur whenever anodic and cathodic sites do not move with time. One mechanism which results in pitting is the local breakdown of passive films. As in both stainless steels and aluminum alloys, the metals are covered by a passive oxide film.
   a. True
   b. False

10. Soils contain mineral matter, organic matter, water, and air. The electrical ____of the soil can be affected by many factors but the amount of water and the soluble salts in the mineral and organic matter have the greatest effect.
    a. Conductivity
    b. Resistivity
    c. Potential
    d. Current

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Corrosion Control

PART 1 OF 2

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FOREWORD

Corrosion of shore and waterfront facilities is a common and serious problem. Naval shore establishment losses to corrosion are estimated at over one-half billion dollars annually. Corrosion related costs and the adverse impact on mission readiness are of increasing concern. Additionally a corrosion leak in a POL tank or pipeline could be very expensive for cleanup and could effect the mission adversely. Action to control corrosion or to repair corrosion damage are among the most frequent reasons for performing maintenance on shore and waterfront facilities.

Additional information or suggestions that will improve this manual are invited and should be submitted through appropriate channels to the Naval Facilities Engineering Command, (Attention: Code 1632), 200 Stovall Street, Alexandria, VA 22332-2300.

This publication has been reviewed in accordance with the Secretary of the Navy Instruction 5600.16A and is certified as an official publication of the Naval Facilities Engineering Command.

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ABSTRACT

The purpose of this manual is to serve as a technical guide for both Naval and civilian personnel in identifying existing or potential corrosion problems, determining the proper corrective actions, and implementing the corrective actions. As corrosion and corrosion control are affected by both original design and construction and maintenance, information is presented regarding all methods for reducing corrosion even though the information is primarily oriented toward maintenance and repair.

This manual describes the mechanisms of corrosion, the types of corrosion commonly experienced in naval shore facilities and waterfront structures, the methods that can be used to control corrosion and methods for implementing an effective corrosion control program. This manual emphasizes methods for determining the most cost effective means of controlling corrosion and practical application of corrosion control to typical problems encountered in the Naval shore establishment.

CHANGE CONTROL SHEET

Document all changes, page replacements, and pen and ink alterations posted in this manual.

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CHAPTER 1. INTRODUCTION TO CORROSION CONTROL

1.1 INTRODUCTION. Corrosion of shore and waterfront facilities is a common and serious problem. Action to control corrosion or to repair corrosion damage are among the most frequent reasons for performing maintenance on shore and waterfront facilities.

Knowledge about the mechanisms of corrosion, corrosion control methods, and common corrosion problems in shore and waterfront facilities is vital to the effective control of corrosion in the Naval Shore Establishment.

1.2 PURPOSE. The purpose of this manual is to serve as a technical guide for both Naval and civilian personnel in identifying existing or potential corrosion problems, determining the proper corrective actions, and implementing the corrective actions. As corrosion and corrosion control are affected by both original design and construction and maintenance, information is presented regarding all methods for reducing corrosion even though the information is primarily oriented toward design and construction.

1.3 DEFINITION OF CORROSION. For the purpose of this manual, corrosion will be defined as the destructive attack of a metal through interaction with its environment. For the purposes of this manual, the degradation of non-metallic materials will not be described as corrosion.

As will be described in a subsequent section of this manual the basic mechanism of corrosion of metals is the electrochemical cell. An understanding of the mechanisms and forms of corrosion attack can lead to an understanding of the causes of a wide variety of corrosive attack and the proper means for controlling corrosion.

1.4 SCOPE OF MANUAL. This manual describes the mechanisms of corrosion, the types of corrosion commonly experienced in naval shore facilities and waterfront structures, the methods that can be used to control corrosion and methods for implementing an effective corrosion control program. This manual emphasizes methods for determining the most cost effective means of controlling corrosion and practical application of corrosion control to typical problems encountered in the Naval shore establishment.

1.5 IMPORTANCE OF CORROSION CONTROL. Control of corrosion is important to the Naval Facilities Engineering Command as it is extremely costly and can also affect the ability of the Facilities Engineering Command to provide critical Fleet support. It is important to maintain facilities in an operational condition at the lowest overall cost. If too little emphasis is placed on corrosion control, corrosion can cause failures that interrupt Fleet support and often result in either maintenance cost or replacing the total facility. However, it is also possible to expend excessive funds on an attempt to needlessly eliminate all corrosion. Through an economic and mission analysis, a proper balance can be maintained between the potential impact of corrosion and the cost to prevent it.

1.5.1 Cost. It has been estimated that the direct cost of corrosion in the U.S. exceeds $70,000,000 per year with about 25% of these costs being avoidable. It has been estimated that the total annual cost of corrosion within the naval shore establishment exceeds $1,000,000 and that equipment and facilities with a value of over $6,000,000,000 are at risk from corrosion. It is important that a maximum value be obtained from the application of corrosion control measures as the limited available funds for maintenance and repair of facilities must be effectively applied to meeting critical mission requirements. It is also important that corrosion control be considered during the design and construction of new facilities or during major additions and repairs to existing facilities. It is often significantly less costly to eliminate those features that contribute to corrosion and to use corrosion resistant materials than to correct the problem once construction is complete. In other cases, corrosion control must be carefully considered for application to facilities that have exceeded their original design life, but must be operated for extended periods due to long lead times and limited funds for new construction. In these cases, corrosion control measures that are not cost effective must be applied simply to maintain the ability to provide Fleet support.

1.5.2 Mission. The mission of the Naval Facilities Engineering Command is to serve as the Navy’s expert for: Facilities, Public Works, Environment Ashore, and Seabees. As part of the mission, NAVFAC is assigned as the construction agent for the Navy. Many of the facilities constructed by Naval Facilities Engineering Command are at risk from corrosion and failure of a facility can adversely affect Fleet readiness. This is particularly true for facilities such as utility systems, waterfront structures, and aviation operational facilities where there is a direct interface between the facility and the Fleet.

1.5.3 Readiness. Corrosion can adversely affect Fleet readiness. A fuel line that is shut down due to leaks can interrupt the flow of vital fuel to ships or aircraft as effectively as enemy action. In many cases, redundant systems are provided to insure an uninterrupted ability to provide Fleet support. In these cases, redundancy can be reduced if one or more of the sections of a facility is out of service for the repair of corrosion damage. In addition, corroded systems are more prone to unexpected failure due to wind, wave, earthquake, or enemy action. Nearly all of this corrosion can be anticipated, detected, and effectively controlled.

1.5.4 Safety. Corrosion can have a significant effect on the safety of the operations performed by the Naval Facilities Engineering Command. Aside from the obvious dangers from structural collapse and leakage of hazardous or flammable materials, corrosion can cause more insidious problems. Corroded systems are more prone to failure from other causes as described above. Corrosion products can also contaminate fuel and water supplies causing health and operational problems. Corrosion of safety systems can also render them unable to perform their required function when needed.

1.5.5 Corrosivity of Environment. As the majority of Naval Shore Facilities are located in marine or industrial environments, the corrosivity of the environment at most activities is significantly greater than average. Commercial equipment is normally produced to be resistant to conditions of average severity and additional protection may be necessary when the equipment is used at a site with increased corrosivity. This is particularly true for tropical marine and industrial marine sites.

1.5.6 Environmental Contamination. Environmental contamination from leaking fuel and hazardous material poses a significant environmental concern. The cost to handle hazardous materials that leak from corroded facilities usually exceeds the costs associated with the control of the corrosion responsible for the leak. In addition, operating facilities, such as power plants, which have a potential for adverse environmental impact, can be adversely affected by corrosion. The impact of corrosion on operating conditions can cause increased emissions of pollutants. In some cases, the products of corrosion themselves are hazardous and corrosion must be controlled to prevent direct environmental damage.

1.5.7 Manpower. Corrosion control can also reduce manpower requirements. It is usually a more effective use of manpower to control corrosion than to correct corrosion damage. For example, inspection and maintenance of a cathodic protection system on a 5-mile section of fuel pipeline can be performed on a routine basis using approximately 24 man hours per year. Over 200 man hours are usually required to repair a single leak in such a system even without considering environmental cleanup and an unprotected pipeline can experience several leaks per year. In addition, corrosion control can be performed on a planned basis so that available manpower can be effectively used.

CHAPTER 2. CORROSION CONTROL POLICY

2.1 POLICY. Corrosion control is an integral part of the design, construction, operation, and maintenance of all facilities. Petroleum, oil, and lubricant (POL) systems; buildings; utility systems; and antenna systems have the most critical facilities in terms of a combination of risk from corrosion, the need to provide a continuity of direct Fleet support, and the cost effectiveness of using appropriate corrosion control systems. In addition to the general requirements outlined above, cathodic protection systems shall be installed and maintained on the buried portions of all natural gas pipelines, compressed gas pipelines, POL pipelines, and liquid fuel pipelines in accordance with References (1) and (2). Code of Federal Regulations (CFR) Title 49, Chapter 1, Part 192, Subpart I and CFR Title 49, Chapter 1, Part 195 (References 1 and 2, respectively). Buried surfaces of all POL storage facilities, and liquid fuel storage facilities shall also be cathodically protected. Cathodic Protection Systems should be installed on all new buried or submerged metallic structures and repair or replacement of buried or submerged facilities unless the soil resistivity makes the cathodic protection system uneconomical. Coatings shall be used in conjunction with cathodic protection systems.

CHAPTER 3. IMPORTANCE OF ECONOMIC ANALYSIS

3.1 INTRODUCTION. This chapter describes the economics of corrosion prevention and control. Included is an explanation of the economic analysis process and a description of potential (additional) maintenance and operation costs. Several examples illustrate the analysis process and provide the corrosion technician or engineer with general guidelines for performing an economic analysis.

Economic analysis is used to compare quantitative information and to select alternatives based on economic desirability. An economic analysis provides additional information that enhances the evaluation of system performance to determine the best method of corrosion control, if any, to be used. Thus, an assessment of the alternatives can be made in the context of such other factors as safety, health, and operational necessity.

It is the responsibility of the Navy to have a thorough knowledge of corrosion control and to implement the best strategy. All relevant costs and benefits must be considered. Sometimes projections are required to determine the savings that will result if a specific application of corrosion prevention and control is applied throughout the Navy. Savings are projected using values derived from an individual project analysis. These projections are based on the assumption that a savings generating alternative will be adopted Navy wide and produce multiple savings. Care should be taken when making such projections. Many corrosion related problems are site specific and require individual analysis. It is questionable to assume comparable savings for similar sites. Still, such projections are useful in providing an approximate estimate of the savings that the Navy will realize by adopting an alternative Navy wide.

3.2 ECONOMIC ANALYSIS PROCESS. To properly perform the economic analysis process, the following six steps should adhere to Reference 3 (NAVFAC P-442).

1. Define the Objective

2. Generate Alternatives

3. Formulate Assumptions

4. Determine Costs and Benefits

5. Compare Costs and Benefits and Rank Alternatives

6. Perform Sensitivity Analysis

A flowchart of the economic analysis process is shown in Figure 3-1. This analysis process consists of six consecutive steps with the performance of the sensitivity analysis providing feedback to reiterate the process. All six steps must be performed to prepare a thorough and objective analysis.

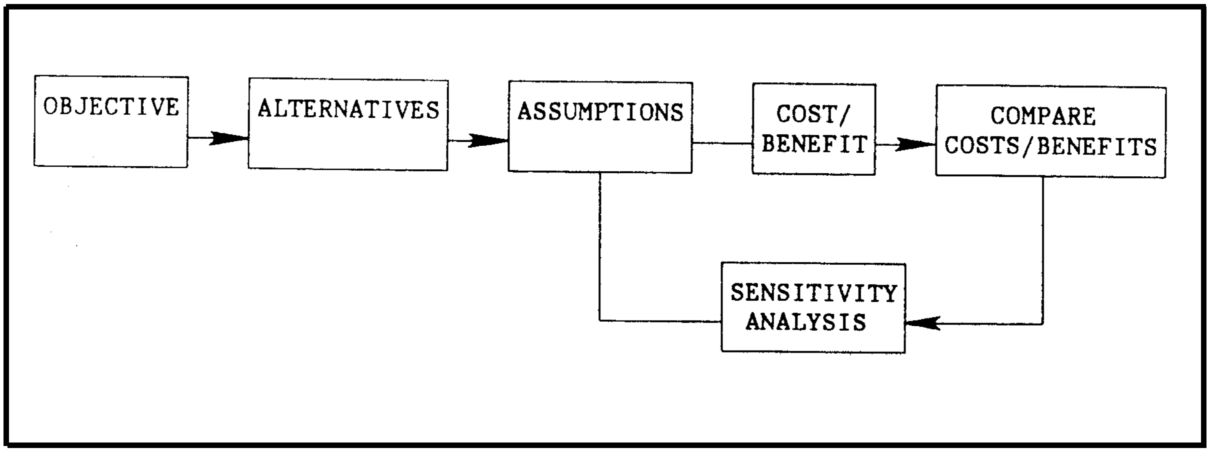


Figure 3-1
Six Steps of Economic Analysis

Step 1. Define the Objective.

The objective statement defines the purpose of the analysis. For example, provide corrosion control for a sheet of steel piling seawall for the lowest life cycle cost. The statement should be unbiased, well defined, and incorporate a measurable standard of performance. The objective statement example is unbiased because no specific method of corrosion control is stipulated. The statement is well defined because it states the desired outcome, corrosion control, of the project. Finally, the objective statement incorporates a measurable standard of performance by selecting an alternative based on the life cycle cost proposal with the least associated cost.

Step 2. Generate Alternatives.

After the objective statement is defined, all feasible alternatives should be generated that will meet that objective. For example:

1. Provide no corrosion prevention or control.

2. Coat the seawall.

3. Provide cathodic protection and coat the seawall.

Undesirable alternatives should also be considered. They provide additional information that is useful to the decision maker.

Step 3. Formulate Assumptions.

The economic process involves estimates of future expenditures and uncertainty, Thus, assumptions often must be formulated in order to analyze various alternatives. For example:

1. The economic life of the seawall varies depending on the alternative selected:

   a. Alternative 1 (no corrosion prevention or control): 15 years

   b. Alternative 2 (coated): 20 years

   c. Alternative 3 (cathodic protection and coated): 25 + years

2. It is assumed that a salvage value of $20/foot will be remitted when the seawall is replaced at the end of its economic life.

3. To compute present values, a 10% discount rate is assumed.

4. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation. Assumptions should be clearly defined and documented. Thorough documentation requires that all sources be cited.

Step 4. Determine Costs and Benefits.

Determine the costs and benefits required for collecting and analyzing the data. Data must be analyzed for the entire economic life of the proposal. This requires discounting the estimated future costs and benefits and determining the period of time to be analyzed.

The economic life is defined as the period of time during which a proposal provides a positive benefit to the Navy (Ref 3). The specific factors limiting the period of time for the economic life include:

1. The mission life or period over which a need for the asset(s) is anticipated.

2. The physical life or period over which the asset(s) may be expected to last physically.

3. The technological life or period before obsolescence would dictate replacing the existing (or prospective) asset(s) (Ref 3).

Although the physical life of an asset may be quite long, the mission or technological life is often limited to a shorter period of time. Anticipated need of an asset and possible obsolescence are difficult to predict beyond 25 years. Therefore, the economic life is determined to be the least of the mission life, physical life, and technological life. The method of discounting used to determine the present value of costs and benefits also suggests that 25 years is the maximum economic life. Appendix A, Economic Life Guidelines, provides a listing of established economic lives for general investment classifications.

- **Costs.** Cost estimates provide dollar values of materials, labor, maintenance, and, acquisition of a proposed alternative. Discounting these values allows estimating the total cost to the Government of that alternative over its entire life (Ref 3). When the economic lives of the alternatives are equal, a net present value cost comparison is used to determine the life cycle cost proposal with the least associated cost. The net present value cost of an alternative is the present worth of all costs and benefits totaled over the life cycle of an alternative. Uniform annual costs are calculated when alternatives have different economic lives. The net present value cost is divided by the Nth year Table B discount factor where N is the length of the economic life (Ref 3). A uniform annual cost comparison is then made. To compute present values, a 10% discount rate is assumed and used for most Government investments. This discount rate accounts for the general inflation rate (Ref 3). See Appendix B for Project Year Discount Factors and Appendix C for Present Value Formulae.

1. Sunk Costs. Sunk costs are costs that have already been spent, such as research and development and previous acquisition of an asset. These costs occur before the decision point (time of analysis) and are irretrievable. Sunk costs do not effect the outcome of the decision and are not considered in the economic analysis.

2. One-Time Costs. One-time costs are costs that occur at one point in time. Maintenance and operation costs that vary over an extended period of time (economic life) are also considered one-time costs. Examples are acquisition costs, research and development costs (after the decision point), varying maintenance costs, and the terminal or salvage values of assets at the end of their economic lives.

3. Recurring Annual Costs. Recurring annual costs are equal costs that occur annually, over an extended period of time (economic life). Personnel, operating, and maintenance costs are examples of recurring annual costs.

4. Depreciation. Depreciation has no effect on cash flow for Government investments (Ref 3).

5. Inflation. Costs are measured in constant dollars or in terms of a base year (year 0 of the analysis). When costs of labor and materials are expected to increase (or decrease) with the general inflation rate, no special treatment of inflation is needed. As stated, using a 10% discount factor adjusts for the general inflation rate. Occasionally cost estimates require special treatment when costs increase (or decrease) in excess of the general inflation rate, for example, oil prices escalated faster than the general inflation rate in the 1970's. A thorough treatment of inflation and its impact on performing economic analysis can be found in Chapter 6 of the Economic Analysis Handbook (Ref 3).

6. Cost Documentation. Cost source data should always be documented for each cost element of the economic analysis. The specific data source, method of data derivation (if applicable), and an assessment of the accuracy of the cost element are required (Ref 3)

- **Benefits.** Benefits are an important consideration in the economic analysis process. Special caution must be taken when evaluating benefits. For example: (1) All potential benefits must be identified for each alternative and quantified whenever possible, (2) unquantifiable benefits must also be identified. A qualitative statement will provide the decision maker with additional information, (3) negative aspects should also be identified, and (4) source data should always be documented.

NAVFAC P-442 (Ref 3) specifies four types of benefits: (1) Direct cost savings, (2) efficiency/productivity increases, (3) other quantifiable output measures, and (4) non-quantifiable output measures.

A thorough treatment of benefit documentation can be found in Reference 3 (NAVFAC P-442, Chapter 4).

Step 5. Compare Costs and Benefits and Rank Alternatives.

After the present value costs and benefits are determined, a comparison of the alternatives should be produced. Alternatives should be ranked based on economic desirability.

Step 6. Perform Sensitivity Analysis.

Following the ranking of alternatives, a sensitivity analysis should be performed to determine the consequences of varying the cost estimates and assumptions. The sensitivity analysis gives credibility to the final results and provides feedback within the economic process (see Figure 3-1). It further refines the assumptions and indicates that values are sensitive to change. In this way, the decision maker can be certain that all relevant information has been considered. A thorough treatment of sensitivity analysis can be found in Reference 3 (NAVFAC P-442, Chapter 7).

3.3 MAINTENANCE AND OPERATION. Justification of recurring maintenance and operation costs requires an economic analysis. Some costs can be directly measured and are more easily quantified using the economic process. Examples include the costs of acquisition and recurring maintenance. Some costs can not be measured directly and are more difficult to quantify, but still require documentation. These include the costs of increased maintenance resulting from uncontrolled corrosion, costs associated with the loss of material and cleanup of spills, and the cost of initial overdesign.

3.3.1 Costs of Increased Maintenance Resulting From Uncontrolled Corrosion. Costs of uncontrolled corrosion must, eventually, include direct loss of a facility and/or replacement of the facility. Maintenance and repair costs due to increasing leakage over time, must also be considered. Although estimates can be made, it is difficult to predict precisely when a facility will fail or when leaks will occur.

3.3.2 Costs Associated With Loss of Material and Cleanup of Spills. Costs associated with spills are assumed to be high and should be included in the analysis as additional information. Several predictions must be made to determine the costs associated with the loss of material and cleanup of spills: (1) Forecast the timing and frequency of spills, (2) predict how much material will be lost, and (3) estimate the value of the lost material.

These costs can not be ignored. Costs associated with hazardous spills are the most difficult to quantify risk and uncertainty are evident when estimating a cost value for human life or the environment. There exists some methods of risk analysis to analyze these costs. Risk analysis is covered briefly in Reference 3 (Chapter 7).

3.3.3 Cost of Initial Overdesign. Overdesign refers to increasing construction costs to prevent corrosion losses. The selection of corrosion-resistant metal, or the use of additional metal thickness to compensate for corrosion loss, are two examples of overdesign. Preventing unnecessary overdesign requires trade-off analysis between the cost of corrosion control versus the costs incurred when no prevention or control is practiced. One way to accomplish this is to evaluate all feasible alternatives and select the least costly alternative.

3.4 CORROSION PREVENTION AND CONTROL FOR PIPELINES

Example 1. Existing Steel Fuel Pipeline

Objective. To provide corrosion control for an existing steel fuel pipeline (15 years old), 8 inches in diameter, and 15,000 feet long.

Alternatives

1. Continue repairs on existing line.

2. Retrofit cathodic protection on existing line.

3. Replace existing line.

This list is not exhaustive. All feasible alternatives should be examined that will meet the objective. For clarity of demonstration, only three alternatives will be considered in this example.

Assumptions

1. The soil resistivity is equal to 5,000 ohm-cm. The soil's pH is about 6, which is a moderately aggressive corrosion environment.

2. The economic life of the fuel pipeline, after it begins to leak, is 25 years. No salvage value will be remitted unless total replacement is cost justified.

3. The pipeline is 15 years old and has experienced its first leak.

4. The predicted number of leaks, due to corrosion failures on the existing steel line without cathodic protection, increase exponentially after the first leak. This prediction is based on historical data and technical expertise. The cost to repair the first leak is considered a sunk cost (has already occurred) and is not included in the analysis.

5. The predicted number of leaks due to corrosion failures on the replacement steel line without cathodic protection increase exponentially after the first leak in year 15.

6. A major rehabilitation of the cathodic protection system is required every 15 years. Continued maintenance and protection is assumed. Thus, the predicted number of leaks on the steel line with cathodic protection is zero. This prediction is based on historical data and technical expertise.

7. To compute present values, a 10% discount rate is assumed.

8. Costs of labor and materials increase (or decrease) with the general inflation rate. Cost of fuel, however, requires special treatment when determining the value lost (dis-benefit) from a pipeline leak. Otherwise, this analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Continue repairs on existing line.

Cost to repair leaks: at $25,000 each (number of leaks increase exponentially)

Terminal value: $24,000

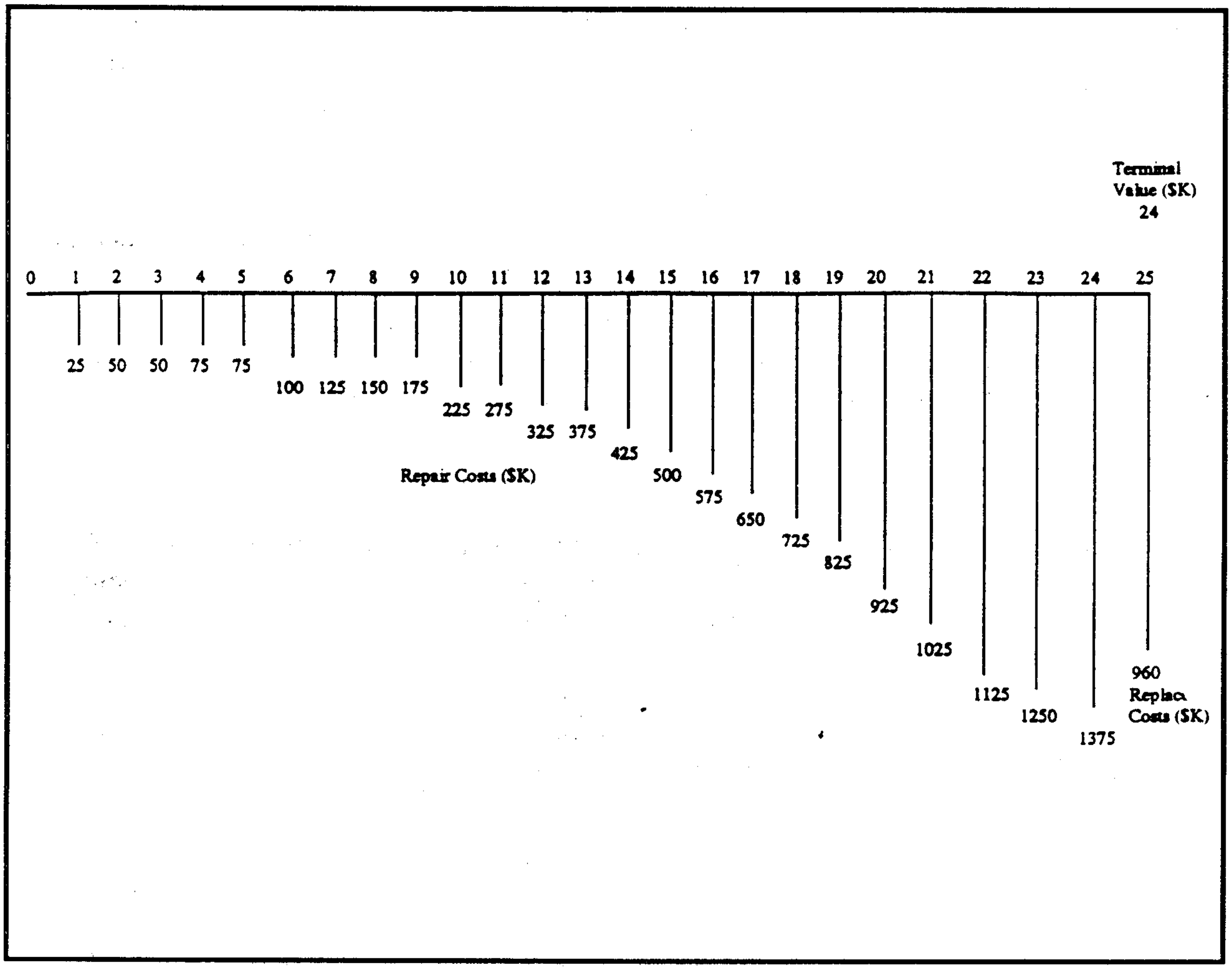


Figure 3-2
Cash Flow Diagram - Continue Repairs on Existing Line.
The Cash Flow Diagram Represents the Magnitudes and Timing of Costs and Benefits for the Entire Economic Life of an Alternative

Alternative 1 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
1	Repair leaks	$ 25,000		0.909	$ 22,725
2	Repair leaks	50,000		0.826	41,300
3	Repair leaks	50,000		0.751	37,550
4	Repair leaks	75,000		0.683	51,225
5	Repair leaks	75,000		0.621	46,575
6	Repair leaks	100,000		0.564	56,400
7	Repair leaks	125,000		0.513	64,125
8	Repair leaks	150,000		0.467	70,050
9	Repair leaks	175,000		0.424	74,200
10	Repair leaks	225,000		0.386	86,850
11	Repair leaks	275,000		0.350	96,250
12	Repair leaks	325,000		0.319	103,675
13	Repair leaks	375,000		0.290	108,750
14	Repair leaks	425,000		0.263	111,775
15	Repair leaks	500,000		0.239	119,500
16	Repair leaks	575,000		0.218	125,350
17	Repair leaks	650,000		0.198	128,700
18	Repair leaks	725,000		0.180	130,500
19	Repair leaks	825,000		0.164	135,300
20	Repair leaks	925,000		0.149	137,825
21	Repair leaks	1,025,000		0.135	138,375
22	Repair leaks	1,125,000		0.123	138,375
23	Repair leaks	1,250,000		0.112	140,000
24	Repair leaks	1,375,000		0.102	140,250
25	Replacement	960,000		0.092	88,320
25	Terminal value	(24,000)		0.092	(2,208)
	Total Net Present Value Cost:				$2,391,737
	Uniform Annual Cost:			$2,391,737/9.077 =	$ 263,494

Alternative 2 - Retrofit cathodic protection on existing line.

Cost of installation of cathodic protection on existing line	$38,000
Cost of annual maintenance:	$ 3,500
Major rehabilitation:	$12,000

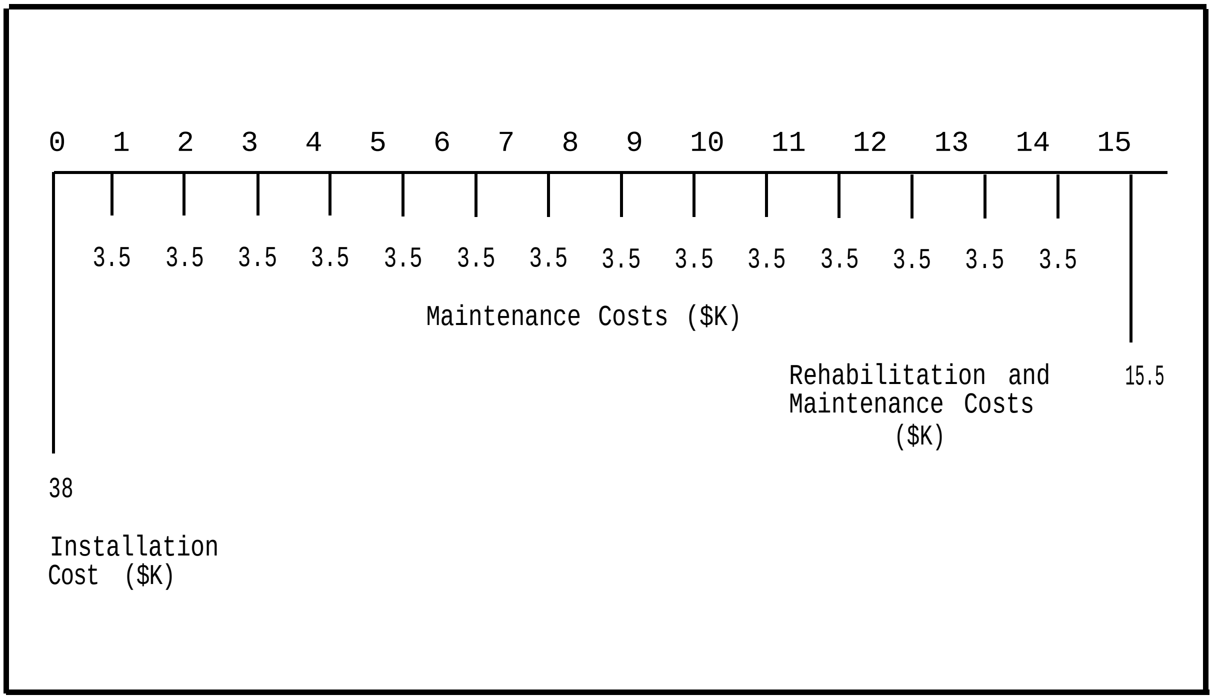


Figure 5-3
Cash Flow Diagram - Retrofit Cathodic Protection on Existing Line

Alternative 2 (economic life - 15 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Installation	$38,000		1.000	$38,000
1-15	Maintenance		$3,500	7.606	26,621
15	Rehabilitation	12,000		0.239	2,868
		Total Net Present Value Cost:			$67,489
		Uniform Annual Cost $67,489/7.606 =			$ 8,873

Alternative 3 - Replace existing line

Cost of installation of steel line:	$960,000
Cost to repair leaks at:	$ 25,000 each (number of leaks increase exponentially)
Terminal value:	$ 24,000

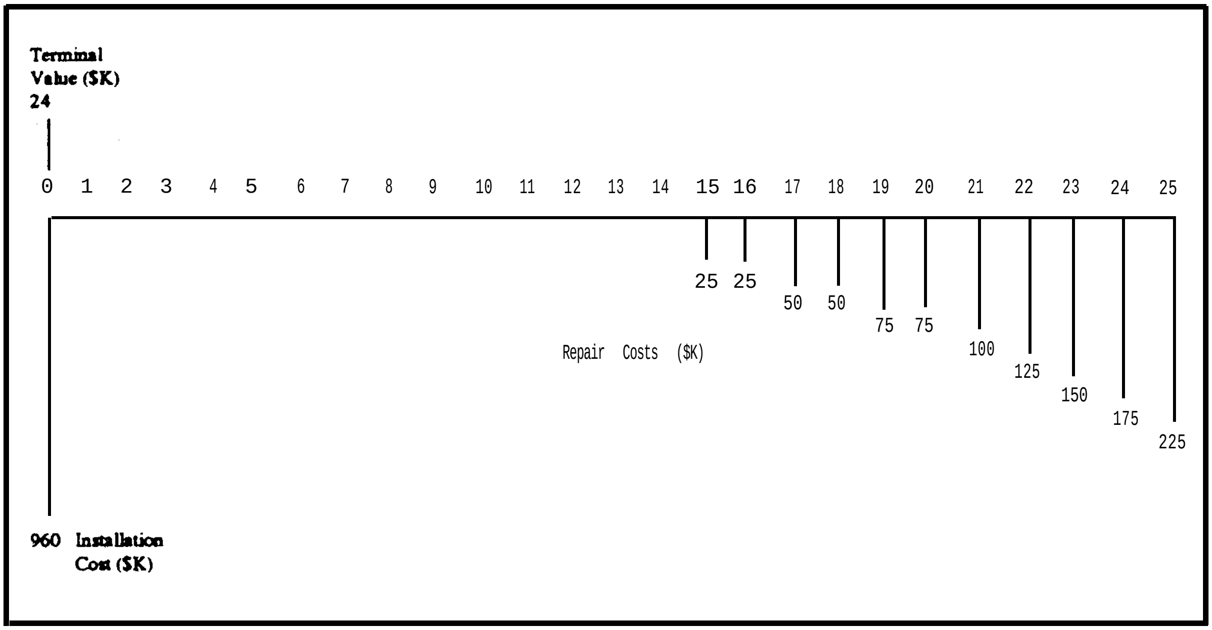


Figure 3-4
Cash Flow Diagram - Replacement of Existing Line

Alternative 3 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Installation	$960,000		1.000	$960,000
0	Terminal value	(24,000)		1.000	(24,000)
1-14	None				
15	Repair leaks	25,000		0.239	5,975
16	Repair leaks	25,000		0.218	5,450
17	Repair leaks	50,000		0.198	9,900
18	Repair leaks	50,000		0.180	9,000
19	Repair leaks	75,000		0.164	12,300
20	Repair leaks	75,000		0.149	11,175
21	Repair leaks	100,000		0.135	13,500
22	Repair leaks	125,000		0.123	15,375
23	Repair leaks	150,000		0.112	16,800
24	Repair leaks	175,000		0.102	17,850
25	Repair leaks	225,000		0.092	20,700
Total Net Present Value Cost:					$1,074,025
Uniform Annual Cost: $1,074.025/9.077 =					$ 118,324

Compare Costs/Benefits and Rank Alternatives

Alternative 1 - Continue repairs on existing line

Net present value = $2,391,737
Uniform annual cost = $,263,494

Alternative 2 - Retrofit cathodic protection on existing line

Net present value = $ 67,489
Uniform annual cost = $ 8,873

Alternative 3 - Replace existing line

Net present value = $1,074,025
Uniform annual cost = $ 118,324

A comparison of the uniform annual costs suggests that Alternative 2, retrofit cathodic protection on existing line, is the life cycle cost proposal with the least associated cost.

Sensitivity Analysis. The economic analysis suggests that Alternative 2 is the life cycle cost proposal with the least associated cost. This comparison, however, involves estimates of future expenditures and assumptions made about future events. Therefore, some degree of uncertainty is present. A sensitivity analysis is performed to evaluate this uncertainty and determine its effect on the ranking of alternatives.

The sensitivity analysis establishes if and when the ranking of alternatives change as the dominant cost factors are varied. First, the dominant cost factors are determined for each alternative. The dominant cost factors are those estimates and assumptions that have the greatest influence on the net present value cost of an alternative. Second, different methods of sensitivity analysis are applied to the dominant cost factors. There are different methods available for performing sensitivity analysis. The methods are chosen depending on the structure of the analysis and the uncertainty of the data. Third, the sensitivity analysis results are compared with the original ranking of alternatives. This comparison tests the reliability of the original analysis results.

1. Determine the Dominant Cost Factors. The dominant cost factors are determined in Figures 3-5 (Alternative 1), 3-6 (Alternative 2), and 3-7 (Alternative 3). Each figure graphs the changes in the net present value cost of the alternative as the following estimates and assumptions are varied: installation costs, economic life, and repair cost (per leak).

The dominant cost factors for each alternative are represented by the steepest curve. These are as follows:

Alternative 1 - Repair Costs

Alternative 2 - Installation Cost

Alternative 3 - Installation Cost

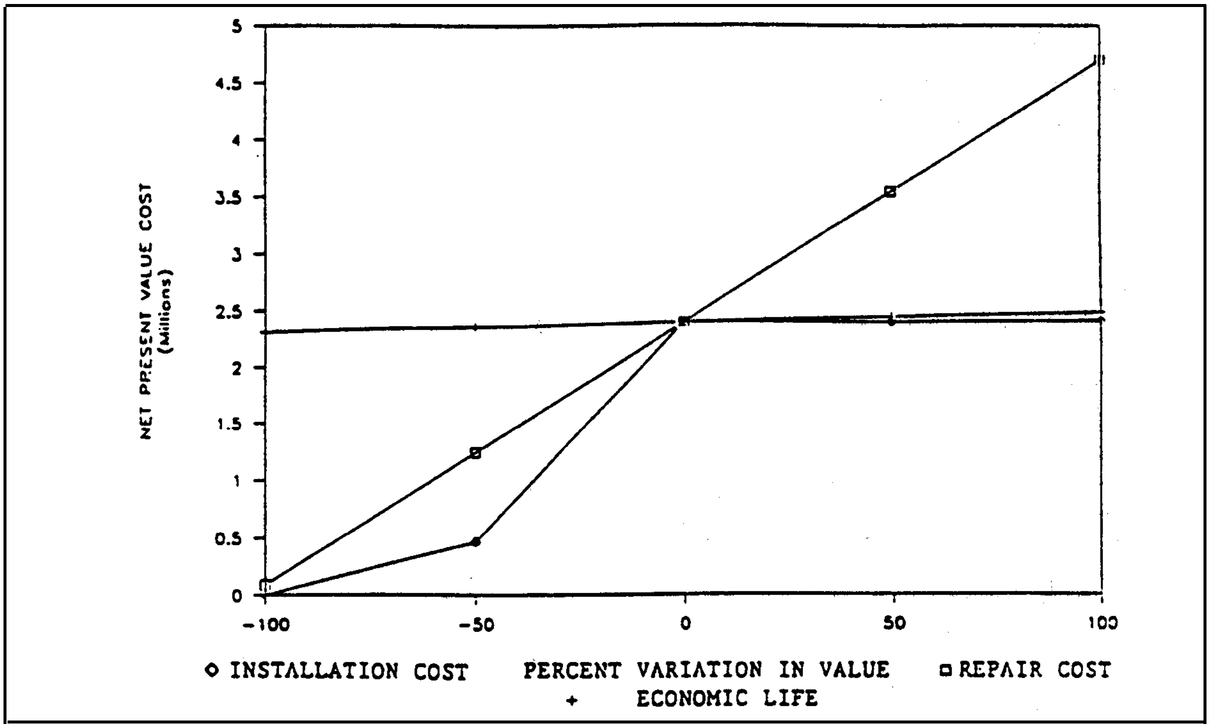


Figure 3-5
Determination of the Dominant Cost Factor
Alternative 1 - Continue Repairs

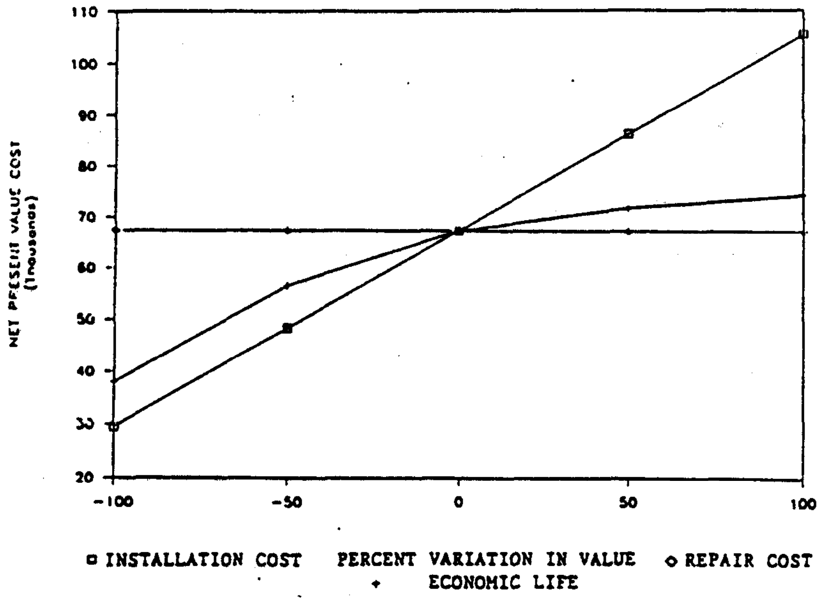


Figure 3-6
Determination of the Dominant Cost Factor
Alternative 2 - Cathodic Protection

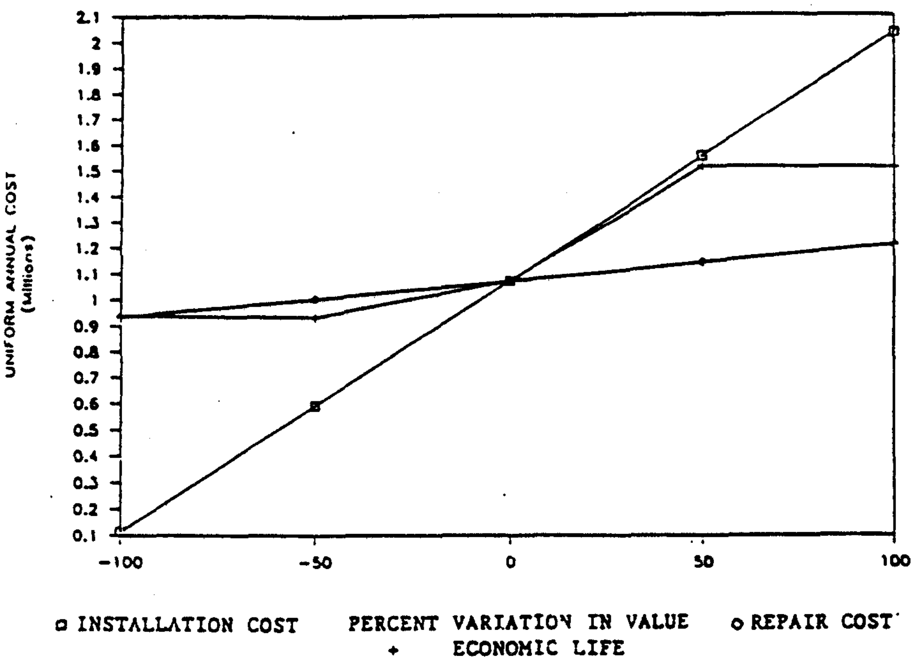


Figure 3-7
Determination of the Dominant Cost Factor
Alternative 3 - Replacement

2. Apply Sensitivity Analysis to the Dominant Cost Factors

This sensitivity analysis is applied in two stages. The first stage tests the result of varying repair costs. The second stage tests the result of varying the installation cost of cathodic protection.

- **First Stage:** Repair cost is the dominant cost factor for Alternative 1, as illustrated in Figure 3-5. A method of sensitivity analysis is applied by varying the cost of repairs and determining if this variation changes the ranking of alternatives. The first stage compares the uniform annual costs of Alternative 1 and Alternative 3 with the uniform annual cost of Alternative 2 as the repair costs are varied. It is tested to see if and when lowering the repair costs will result in equal uniform annual costs of Alternative 1 or Alternative 3 with those of Alternative 2. Figure 3-8 graphs the uniform annual cost of each alternative as the repair cost is varied. The uniform annual cost is used because the three alternatives have differing economic lives. As the repair cost is varied from $0 to $50,000. Alternative 2 remains the economic choice. Varying the repair cost changes the ranking of Alternatives 1 and 3 only when the repair cost falls below $9,803. This suggests that the ranking of alternatives is insensitive to variation in the repair cost.

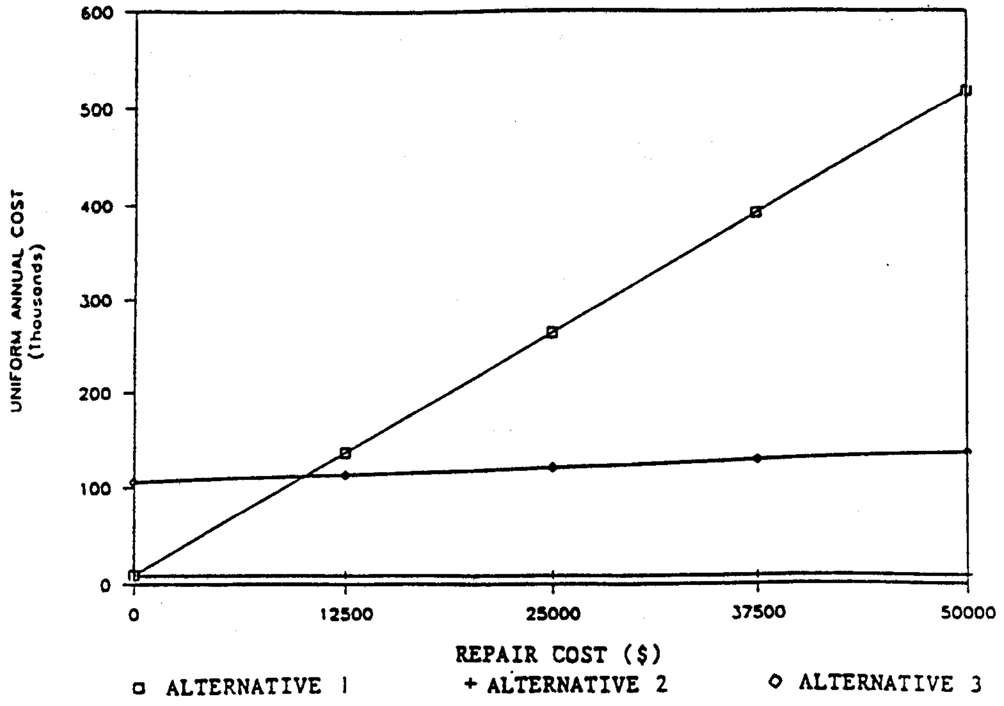


Figure 3-8
Sensitivity Analysis
Vary Repair Costs - All Alternatives

- **Second Stage.** Installation cost is the dominant cost factor for Alternatives 2 as illustrated in Figure 3-6. To test the sensitivity of varying the installation cost of cathodic protection on the existing line, a break-even analysis is used. The variable X is substituted into the equations that were originally used to estimate the uniform annual costs of Alternatives 1 and 3. X represents the installation cost of cathodic protection on the existing line. These equations are set equal to the uniform annual cost of the least costly alternative (Alternative 2). Solving the equations for X determines the minimum installation cost of cathodic protection required for the uniform annual cost of Alternative 2 to be equivalent with Alternatives 1 and 3. At a higher cost than X, Alternative 2 will no longer be the most economical alternative. The following example illustrates this process:

Uniform Annual Cost (UAC) of Alternative 2 =

(X + ($3,500 x 7.606) + ($12,000 x 0.239)) / 7.606

where:

X = Cost of installation of cathodic protection on existing line
$3,500 = Cost of annual maintenance
$12,000 = Cost of rehabilitation of the system

Uniform Annual Cost (UAC) of Alternative 1 = $263,494
Uniform Annual Cost (UAC) of Alternative 3 = $118,324

Set:

UAC of Alternative 1 = UAC of Alternative 2
$263,494 = (X + ($3,500 x 7.606) + ($12,000 x 0.239)) / 7.606
$263,494 = (X + $26,621 + $2,868) / 7.606
$263,494 = (X + $29,489) / 7.606
$263,494 x 7.606 = X + $29,489
$2,004,135 = X + $29,489
$2,004,135 - $29,489 = X
$1,974,646 = X

Set:

UAC of Alternative 3 = UAC of Alternative 2
$118,324 = (X + ($3,500 x 7.606) + ($12,000 x 0.239)) / 7.606

$\$118{,}324 = (X + \$26{,}621 + \$2{,}868) / 7.606$
$\$118{,}324 = (X + \$29{,}489) / 7.606$
$\$118{,}324 \times 7.606 = X + \$29{,}489$
$\$899{,}972 = X + \$29{,}489$
$\$899{,}972 - \$29{,}489 = X$
$\$870{,}483 = X$

The cost of installing cathodic protection on the existing line is estimated to be \$38,000. If the actual installation cost of cathodic protection amounts to more than \$870,483 then Alternative 3 is cost justified when compared with Alternative 2. If the actual installation cost of cathodic protection amounts to more than \$1,974,646 then both Alternatives 1 and 3 are cost justified when compared with Alternative 2. The actual installation cost of cathodic protection must be significantly higher than the original estimate of \$38,000 to change the ranking of Alternative 2 as the least cost proposal. This suggests that the ranking of alternatives is insensitive to variation in the installation cost of cathodic protection.

3. Comparison of the Sensitivity Analysis Results. The first stage of the sensitivity analysis determined that the ranking of alternatives is insensitive to a variation in the repair costs. The second stage determined that the ranking of alternatives is insensitive to a variation in the installation cost of cathodic protection. This suggests that the original analysis results are reliable and Alternative 2 is the most attractive alternative.

3.5 CORROSION PREVENTION AND CONTROL FOR WATER STORAGE TANKS

Example 2 - Interior of a Water Storage Tank

Objective: Provide corrosion control for the interior of an existing 100,000-gallon (steel) elevated water storage tank. The tank was constructed and originally coated 7 years ago.

Alternatives

1. Continue repairs and coatings of existing tank/no cathodic protection.

2. Continue repairs and coatings of existing tank/retrofitting cathodic protection.

This list is not exhaustive. All feasible alternatives should be examined that will meet the objective. For clarity of demonstration, only two alternatives will be considered in this example.

Assumptions

1. The maximum economic life of an elevated water storage tank is 25 years. It is assumed that a salvage value of $45,000 will be remitted when the tank is replaced.

2. The predicted frequency of coating repairs required on the existing water storage tank without cathodic protection is once every 2 years. The predicted frequency of coating replacement is once every 6 years. The tank will be replaced in the 18th year of the analysis, when it is 25 years old. These predictions are based on historical data and technical expertise.

3. The predicted frequency of coating repairs required on the existing water storage tank retrofitted with cathodic protection is once every 7 years. Continued maintenance and protection is assumed. Thus, coating and tank replacement is not required during the analysis period. This prediction is based on historical data and technical expertise.

4. To compute present values, a 10% discount rate is assumed.

5. Labor and materials costs increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1 - Continue repairs and coatings of existing tank/no cathodic protection.

Cost of coating repairs:	$15,000 each (every 2 years/between coatings)
Cost of coating:	$70,000 each (every 6 years)
Cost of new installation:	
Water storage tank:	$650,000
Initial coating:	+ 70,000
	$720,000
Terminal value:	$45,000 (18th year of the analysis)

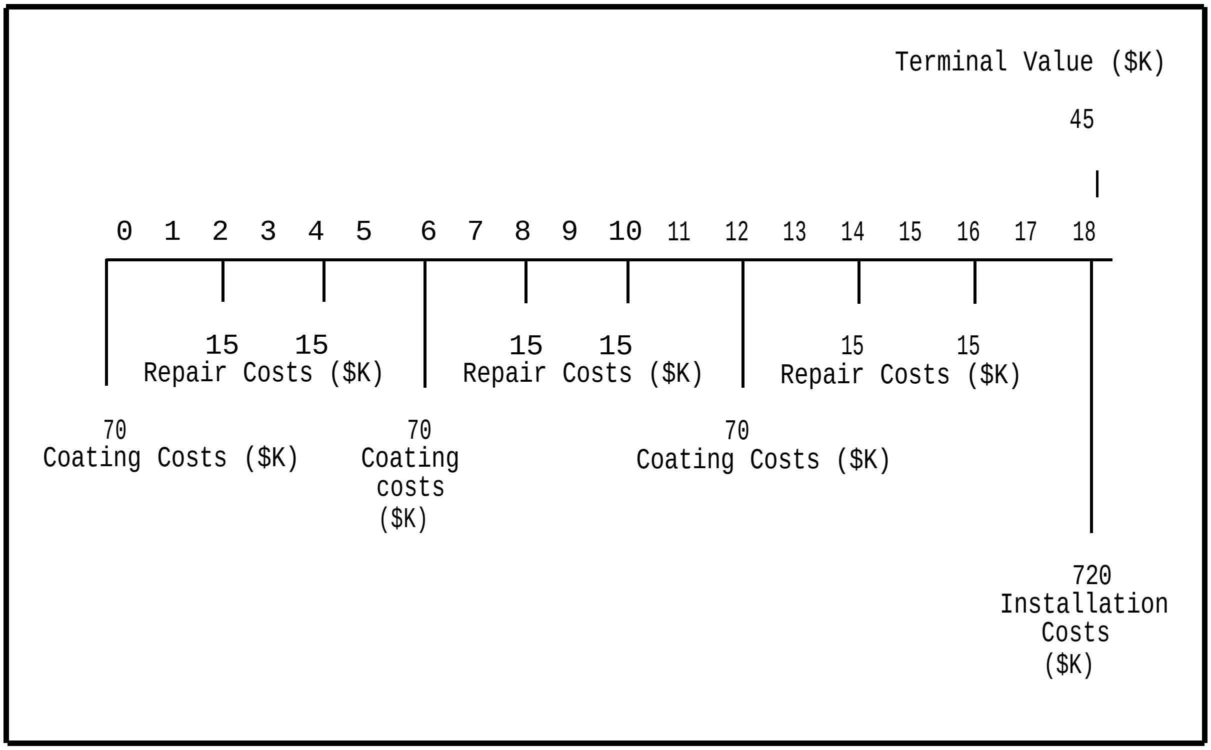


Figure 3-9
Cash Flow Diagram - Continue Repairs and Coatings of
Existing Tank/No Cathodic Protection

Alternative 1 (economic life - 18 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$ 70,000		1.000	$ 70,000
2	Repair	15,000		0.826	12,390
4	Repair	15,000		0.683	10,245
6	Coating	70,000		0.564	39,480
8	Repair	15,000		0.467	7,005
10	Repair	15,000		0.386	5,790
12	Coating	70,000		0.319	22,330
14	Repair	15,000		0.263	3,945
16	Repair	15,000		0.218	3,270
18	Installation	720,000		0.180	129,600
18	Terminal Value	(45,000)		0.180	(8,100)

Total Net Present Cost: $295,955
Uniform Annual Cost : $295,955/8.201 = $ 36,088

Alternative 2: Continue repairs and coatings of existing tank/retrofitting cathodic protection

Cost of Repairs:	$15,000 each (every 7 years)
Cost of Coating:	$70,000 (base year of the analysis)
Annual Cost of Cathodic Protection System Maintenance:	$7,000
Cost of Retrofitting Cathodic Protection	$65,000 (base year of the analysis)

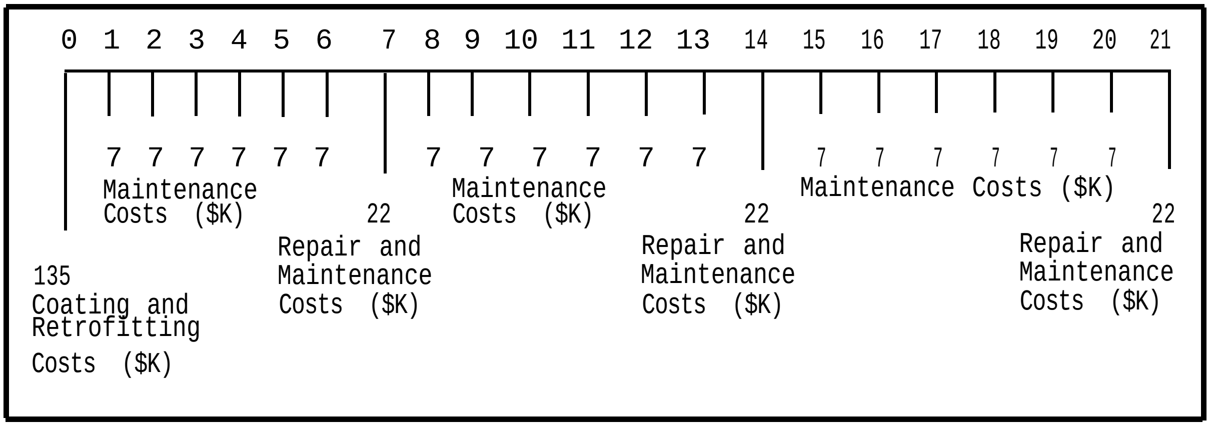


Figure 3-10
Cash Flow Diagram - Continue Repairs and Coatings of Existing Tank/Retrofitting Cathodic Protection

Alternative 2 (economic life - 21 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$70,000		1.000	$ 70,000
0	Retrofit	65,000		1.000	65,000
1-21	Maintenance		7,000	8.649	60,543
7	Repair	15,000		0.513	7,695
14	Repair	15,000		0.263	3,945
21	Repair	15,000		0.135	2,025
Total Net Present Value Cost:					$209,208
Uniform Annual Cost:				: $209,208/8.649 =	$ 24,189

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Continue repairs and coatings of existing tank/no protection

Net present value :	$295,955
Uniform annual cost:	$36,088

Alternative 2. Continue repairs and coatings of existing tank/retrofitting cathodic protection

Net present value :	$209,208
Uniform annual cost:	$24,189

A comparison of the uniform annual costs suggest that Alternative 2, retrofitting cathodic protection on the existing tank, is the life cycle cost proposal with the least associated cost.

Example 3. Exterior of a Water Storage Tank

Objective: To provide corrosion control for the 100,000 ft^2 exterior steel surface of a water storage tank. This water storage tank is located on the Pacific Coast.

Alternatives

1. Continue applying a three-coat alkyd coating system.

2. Continue applying a three-coat epoxy coating system.

This list is not exhaustive. All feasible alternatives should be examined that will meet the objective. For clarity of demonstration, only two alternatives will be considered in this example.

Assumptions

1. Although the physical life of an elevated water storage tank is 40 years, due to constraints of discounting factors, a maximum economic life of 25 years will be assumed. In reality, it may take longer than 40 years for the tank to be replaced. Thus, replacement is not included in this analysis. To facilitate the analysis process, the economic lives used are 24 years for the alkyd coating system and 20 years for the epoxy coating system. This allows the ending year of the final coating application of each alternative to match the ending analysis year.

2. The predicted frequency for recoating required for a three-coat alkyd coating system, is once every 6 years. This prediction is based on historical data and technical expertise.

3. The predicted frequency for recoating required for a three-coat epoxy coating system, is once every 10 years. This prediction is based on historical data and technical expertise.

4. To compute present values, a 10% discount rate is assumed.

5. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Continue applying a three-coat alkyd coating system

Cost of applying a three-coat alkyd coating system:

Surface preparation (commercial blast):	$\$\ 0.60/\text{ft}^2$ or	$ 60,000
Paint material:	$+0.08/\text{ft}^2$ or	+ 8,000
Paint application:	$+0.45/\text{ft}^2$ or	+45,000
Total	$\$\ 1.13/\text{ft}^2$ or	$113,000

Maintenance paint cost (10% repainting):

Labor, equipment, related costs:	$\$0.225/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$2,250
Material costs:	$0.08/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	+ 800
	Total:	$3,050

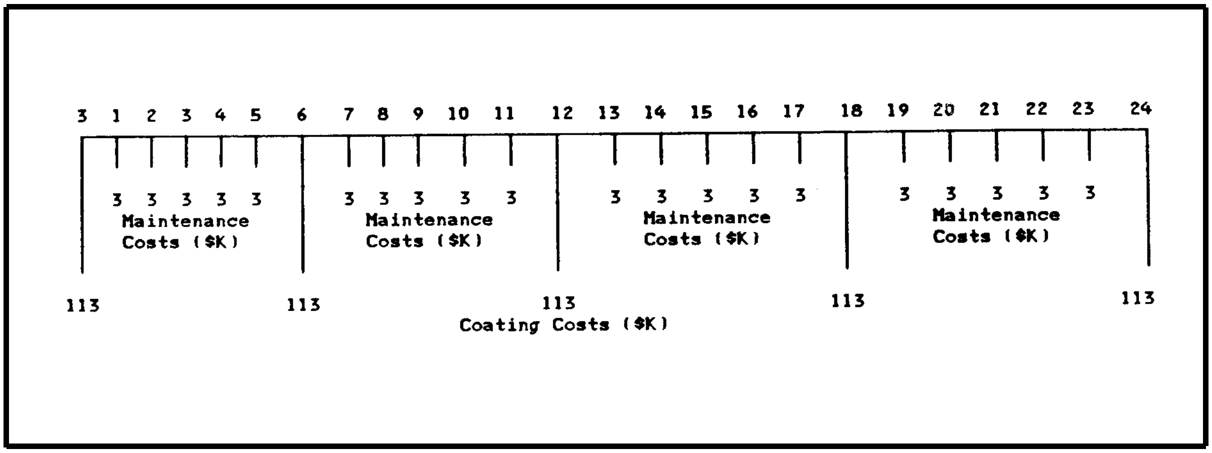


Figure 3-11

Cash Flow Diagram - Continue Applying a Three-Coat Alkyd Coating System

Alternative 1 (economic life - 24 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$113,000		1.000	$113,000
0-24	Maintenance		$3,050	8.985	27,404
6	Coating	113,000		0.564	63,732
12	Coating	113,000		0.319	36,047
18	Coating	113,000		0.180	20,340
24	Coating	113,000		0.102	11,526
	Total Net Present Value Cost:				$272,049
	Uniform Annual Cost:			$272,049/8.985 =	$ 30,278

Alternative 2 - Continue applying an epoxy coating system

Cost of applying a three-coat epoxy coating system (at 10-year intervals):

Surface preparation (near white blast):	$\$\ 0.80/\text{ft}^2$	or	$ 80,000
Paint material:	$+\ 0.11/\text{ft}^2$	or	+ 11,000
Paint application:	$+0.60/\text{ft}^2$	or	+60,000
Total:	$\$\ 1.51/\text{ft}^2$	or	$151,000

Maintenance paint cost (10% repainting):

Labor, equipment, related costs:	$\$0.225/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$2,250
Material costs:	$0.110/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	+ 1,100
Total:		$3,350

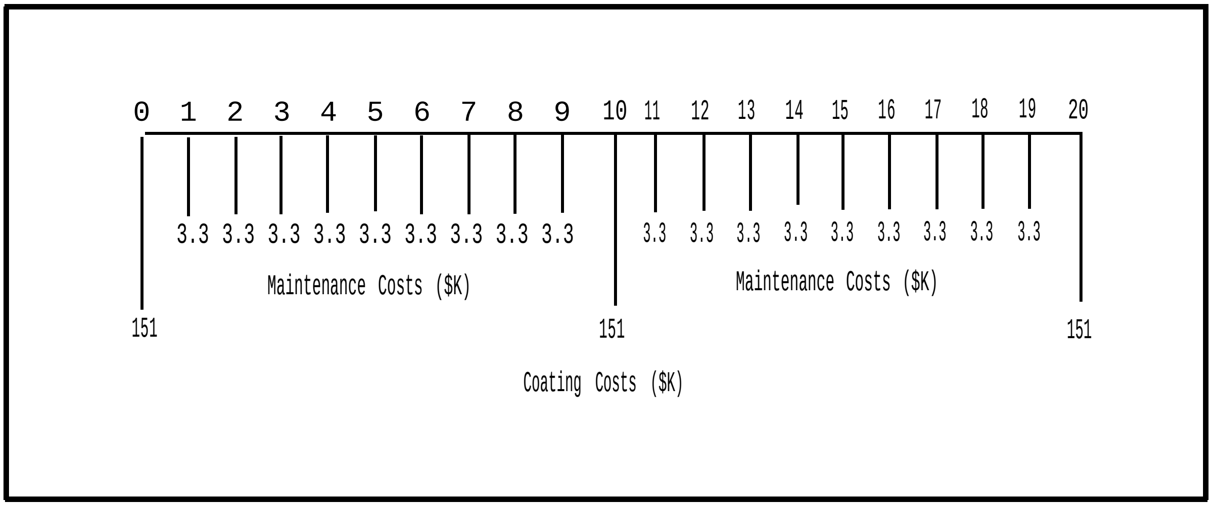


Figure 3-12
Cash Flow Diagram - Continue Applying an Epoxy Coating System

Alternative 2 (economic life - 20 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$151,000		1.000	$151,000
0-20	Maintenance		$3,350	8.514	28,522
10	Coating	151,000		0.386	58,286
20	Coating	151,000		0.149	22,499
	Total Net Present Value Cost:				$260,307
	Uniform Annual Cost:			$260,307/8.985 =	$ 28,971

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Continue applying a three-coat alkyd coating system

Net present value : $272,049
Uniform annual cost: $30,278

Alternative 2. Continue applying a three-coat epoxy coating system

Net present value : $260,307
Uniform annual cost: $28,971

A comparison of the uniform annual costs suggests that Alternative 1 is the life cycle cost proposal with least associated cost. It is, however, concluded that the three-coat alkyd and three-coat epoxy coating systems are close economic substitutes and that the use of either coating system is recommended.

Example 4. Exterior of a Water Storage Tank (abrasive blasting prevented by local restrictions)

Objective: To provide corrosion control for the 100,000 ft^2 exterior steel surface of a water storage tank. The tanks cannot be abrasively blasted because of local restrictions, and it will be necessary to prepare the steel surface for painting by power wire brushing. Using wire brushing to prepare the surface shortens the service lives of the coating systems. The service lives of the alkyd and epoxy systems are expected to be 5 and 6 years, respectively.

Alternatives

1. Continue applying a three-coat alkyd coating system.

2. Continue applying a three-coat epoxy coating system.

This list is not exhaustive. All feasible alternatives should be examined that will meet the objective. For clarity of demonstration, only two alternatives will be considered in this example.

Assumptions

1. The physical life of an elevated water storage tank is 25 years. To facilitate the analysis process, the economic lives used are 25 years for this alkyd coating system and 24 years for the epoxy coating system. This allows the ending year of the final coating application of each alternative to match the ending analysis year.

2. The predicted frequency for recoating required for a three-coat alkyd coating system, is once every 5 years. This prediction is based on historical data and technical expertise.

3. The predicted frequency for recoating required for an epoxy coating system is once every 6 years. This prediction is based on historical data and technical expertise.

4. To compute present values, a 10% discount rate is assumed.

5. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Continue applying a three-coat alkyd coating system

Cost of applying a three-coat alkyd coating system:

Surface preparation (power wire brushing):	\$ 0.50/ft^2 or \$ 50,000
Paint material:	+ 0.08/ft^2 or + 8,000
Paint application:	+0.45/ft^2 or +45,000
Total:	\$ 1.03/ft^2 or \$ 103,000

Maintenance paint cost (10% repainting):

Labor, equipment, related costs:	$\$0.225/\text{ft}^2 \times 10,000\ \text{ft}^2 =$	$2,250
Material costs:	$0.080/\text{ft}^2 \times 10,000\ \text{ft}^2 =$	+800
	Total:	$3,050

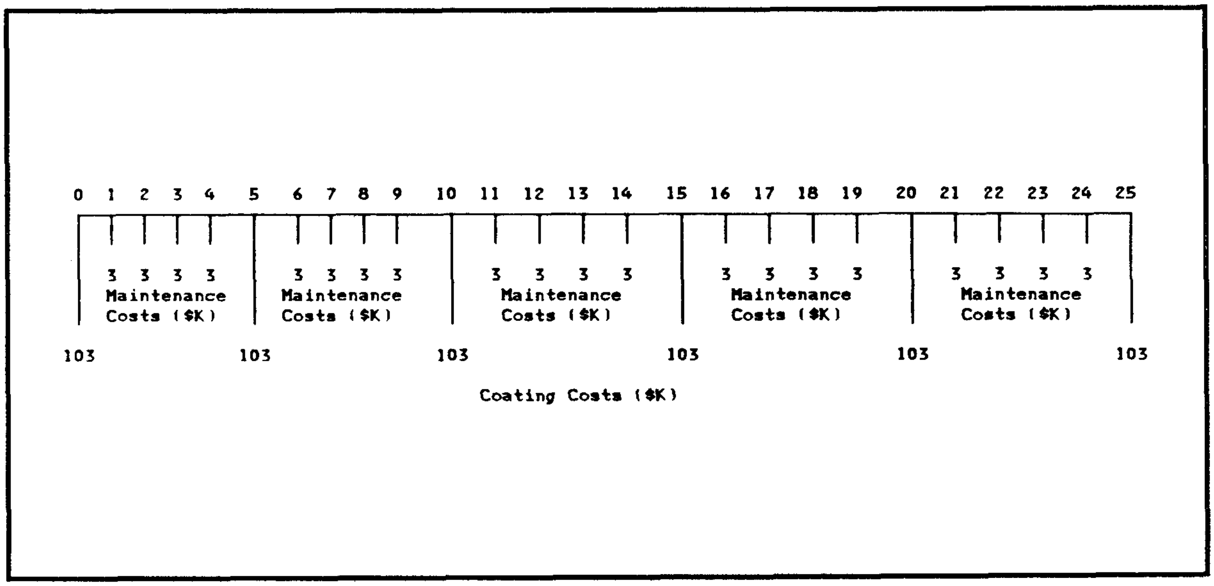


Figure 3-13

Cash Flow Diagram - Continue Applying a Three-Coat Alkyd Coating System

Alternative 1 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$103,000		1.000	$103,000
0-25	Maintenance		$3,050	9.077	27,685
5	Coating	103,000		0.621	63,963
10	Coating	103,000		0.386	39,758
20	Coating	103,000		0.149	15,347
25	Coating	103,000		0.092	9,476
	Total Net Present Value Cost:				$283,846
	Uniform Annual Cost:			$283,846/9.077 =	$ 31,271

Alternative 2. Continue applying a three-coat epoxy coating system.

Cost of applying a three-coat epoxy coating system:

Surface preparation (power wire brushing):	\$ 0.50/ft^2 or	\$50,000
Paint material:	+0.11/ft^2 or	+ 11,000
Paint application:	+0.60/ft^2 or	+ 60,000
Total:	\$1.21/ft^2 or	\$121,000

Maintenance paint cost (10% repainting):

Labor, equipment, related costs:	\$0.225/ft^2 x 10,000 ft^2 =	\$2,250
Material costs:	0.110/ft^2 x 10,000 ft^2 =	+ 1,100
	Total	\$3,350

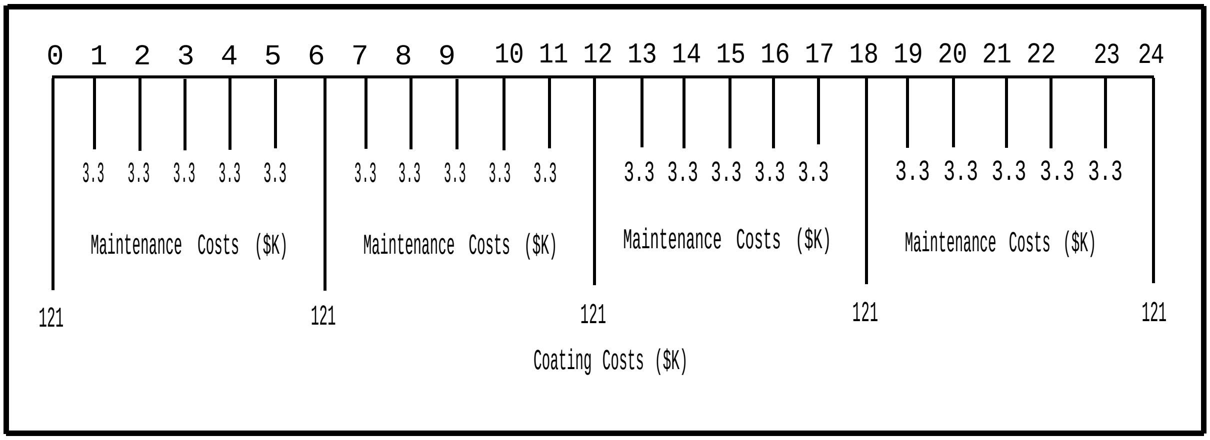


Figure 3-14

Cash Flow Diagram - Continue Applying a Three-Coat Epoxy Coating System

Alternative 2 (economic life - 24 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	\$121,000		1.000	\$121,000
0-24	Maintenance		\$3,350	8.985	30,100
6	Coating	121,000		0.564	68,244
12	Coating	121,000		0.319	38,599
18	Coating	121,000		0.180	21,780
24	Coating	121,000		0.102	12,342
Total Net Present Value Cost:					\$292,065
Uniform Annual Cost:				\$292,065/9.077 =	\$ 32,506

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Continue applying a three-coat alkyd coating system

Net present value: $283,846
Uniform annual cost: $ 31,271

Alternative 2. Continue applying a three-coat epoxy coating system

Net present value: $292,065
Uniform annual cost: $32,506

A comparison of the uniform annual costs suggest that Alternative 1 is the life cycle cost proposal with the least associated cost.

3.6 CORROSION PREVENTION AND CONTROL FOR HIGH STEEL ANTENNA TOWERS

Example 5. High Steel Antenna Tower

Objective: Provide corrosion control for a high steel antenna tower constructed at a remote location on the Pacific Coast. The tower has a surface area of 10,000 ft^2.

Alternatives

1. Coat at the site after the tower is erected (inorganic zinc primer.)
2. Coat at the site after the tower is erected (zinc rich epoxy primer).
3. Coat at the site before the tower is erected (inorganic zinc primer).
4. Coat in a shop before the tower is erected (inorganic zinc primer).

This list is not exhaustive. All feasible alternatives should be examined that will meet the objective. For clarity of demonstration, only four alternatives will be considered in this example.

Assumptions

1. The maintenance painting requirement and economic life of the coating system varies depending on the alternative selected.

Maintenance Painting Required	Economic Life
Alternative 1: 7 years	Alternative 1: 12 years
Alternative 2: 9 years	Alternative 2: 15 years
Alternative 3: 9 years	Alternative 3: 15 years
Alternative 4: 10 years	Alternative 4: 16 years

2. Maintenance painting will be performed when required and that the tower will be coated again at the end of the economic life of the coating system.

3. Environmental regulations require that abrasive from blasting be disposed of as hazardous waste. It is assumed that the disposal of abrasive at the site increases the total cost of coating and maintenance painting by a factor of two. This is a conservative estimate.

4. The disposal of abrasive from blasting in the shop increases the total cost of coating and maintenance painting by a factor of 1-1/4. The cost is less than abrasive disposal at the site because an enclosed system is used and the abrasive is recycled several times before final disposal.

5. To compute present values, a 10% discount rate is assumed.

6. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Coat at the site after the tower is erected (inorganic zinc primer).

The surface is prepared with conventional abrasive blasting and coated with an inorganic zinc primer, an intermediate coat of epoxy-polyamide, and a finish coat of aliphatic polyurethane.

Cost to coat at the site after the tower is erected:

Surface preparation (conventional blasting)

Labor, equipment, related costs $\$1.20/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 = \$12{,}000$

Primer (inorganic zinc)		
Labor, equipment, related costs	$\$0.60/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 = \$6{,}000$	
Material costs	$\$0.11/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 = \$1{,}100$	
Intermediate coat (epoxy-polyamide)		
Labor, equipment, related costs	$\$0.30/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 = \$3{,}000$	
Material costs	$\$0.09/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 = \$\ 900$	
Finish coat (aliphatic polyurethane)		
Labor, equipment, related costs	$\$0.40/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	\$4,000
Material costs	$\underline{\$0.07/\text{ft}^2} \text{ x } 10{,}000\ \text{ft}^2 =$	+ 700
	$\$2.77/\text{ft}^2$	\$27,700
Collection and disposal of Abrasive (increases cost by a factor of 2)		x 2
	Total cost to coat:	\$55,400
Maintenance painting cost (10% repainting):		
Labor, equipment, related costs	$\$3.00/\text{ft}^2 \text{ x } 1{,}000\ \text{ft}^2 =$	\$3,000
Material costs	$\underline{\$0.11/\text{ft}^2} \text{ x } 1{,}000\ \text{ft}^2 =$	+ 110
	$\$3.11/\text{ft}^2$	\$3,110
Collection and disposal of Abrasive (increases cost by a factor of 2)		x 2
	Total maintenance cost	\$6,220

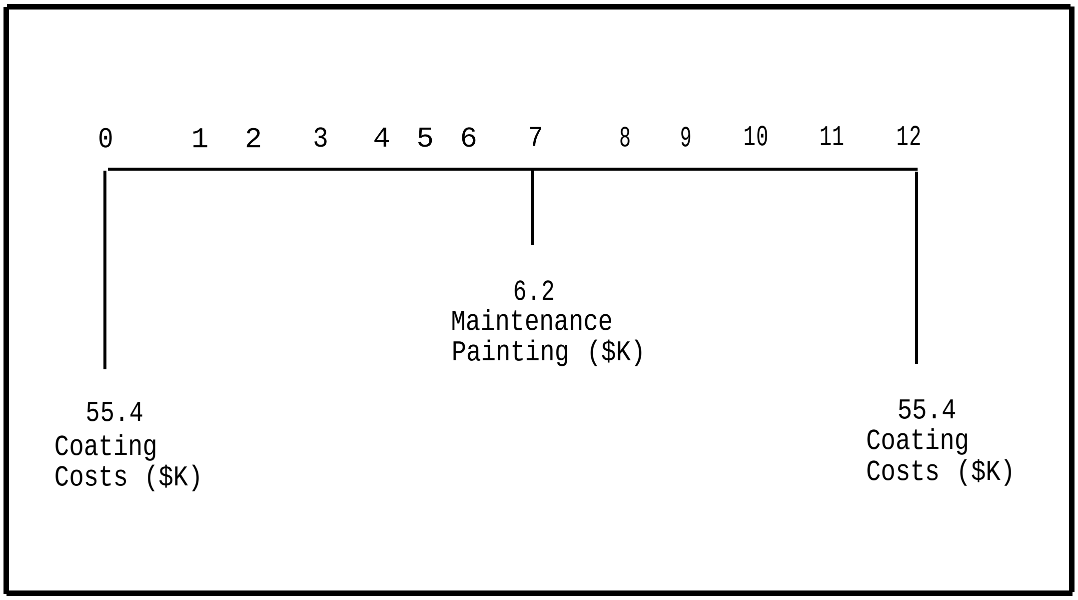


Figure 3-13
Cash Flow Diagram - Coated at the Site After the
Tower is Erected (inorganic zinc primer)

Alternative 1 (economic life - 12 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$55,400		1.000	$55,400
7	Maintenance	6,220		0.513	3,191
12	Coating	55,400		0.319	17,673
	Total Net Present Value Cost:				$76,264
	Uniform Annual Cost:			$76,264/6.814 =	$11,192

Alternative 2. Coated at the site after the tower is erected (zinc rich epoxy primer).

The surface is prepared with conventional abrasive blasting and coated with a zinc rich epoxy primer, an intermediate coat of epoxy-polyamide, and a finish coat of aliphatic polyurethane.

Cost to coat at the site after the tower is erected:

Surface preparation (conventional blasting)		
Labor, equipment, related costs	\$ 1.20/ft^2 x 10,000 ft^2	= \$12,000
Primer (zinc rich epoxy)		
Labor, equipment, related costs	\$0.60/ft^2 x 10,000 ft^2	= \$ 6,000
Material costs	\$0.15/ft^2 x 10,000 ft^2	= \$ 1,500
Intermediate coat (epoxy-polyamide)		
Labor, equipment, related costs	\$0.30/ft^2 x 10,000 ft^2	= \$3,000
Material costs	\$0.09/ft^2 x 10,000 ft^2	= \$ 900
Finish coat (aliphatic polyurethane)		
Labor, equipment, related costs	\$0.40/ft^2 x 10,000 ft^2	= \$ 4,000
Material costs	\$0.07/ft^2 x 10,000 ft^2	= + 700
	\$2.81/ft^2	\$28,100
Collection and disposal of Abrasive (increases cost by a factor of 2)		x 2
Total cost to coat:		\$56,200

Maintenance painting cost (10% repainting):

Labor, equipment, related costs	\$3.00/ft^2 x 1,000 ft^2	= \$3,000
Material costs	\$0.15/ft^2 x 1,000 ft^2	= \$ 150
	\$3.15/ft^2	\$3,150
Collection and disposal of Abrasive (increases cost by a factor of 2)		x 2
Total maintenance cost:		\$ 6,300

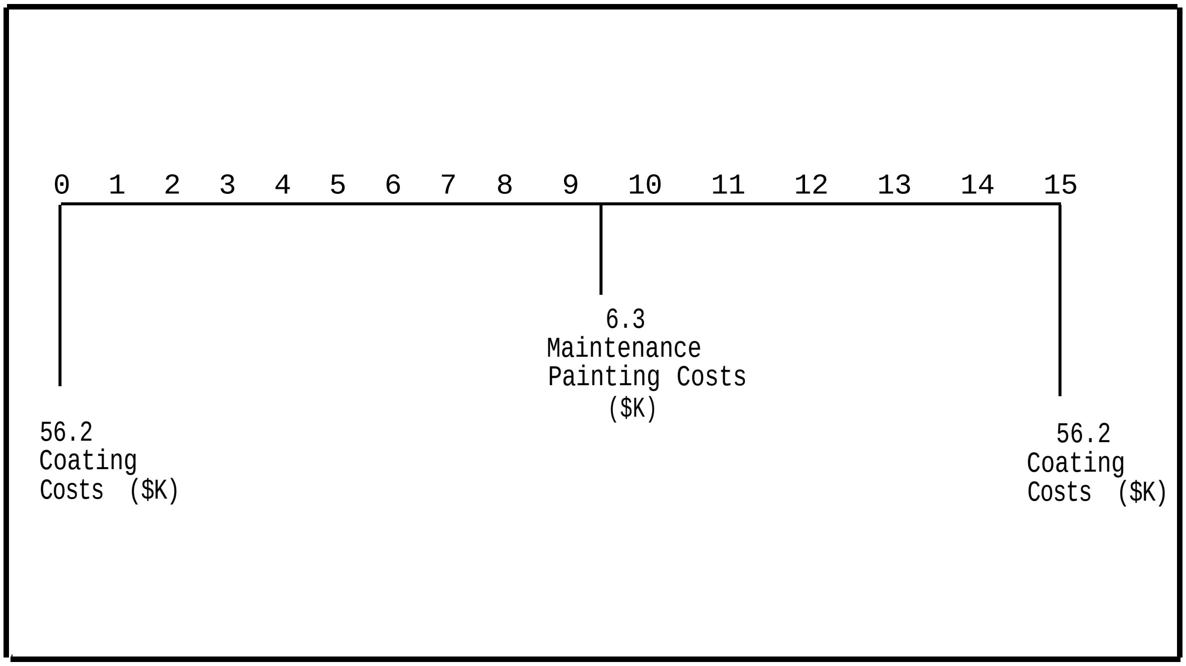


Figure 3-16
Cash Flow Diagram - Coated at the Site After the Tower is Erected (zinc rich epoxy primer)

Alternative 2 (economic life - 15 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$56,200		1.000	$56,200
9	Maintenance	6,300		0.424	2,671
15	Coating	56,200		0.239	13,432
Total Net Present Value Cost:					$72,303
Uniform Annual Cost:				$72,303/7.606 =	$ 9,506

Alternative 3. Coated at the site before the tower is erected (inorganic zinc primer).

The surface is prepared with conventional abrasive blasting and coated with an inorganic zinc primer, an intermediate coat of epoxy-polyamide, and a finish coat of aliphatic polyurethane.

Cost to coat at the site before the tower is erected:

Surface preparation (conventional blasting)		
Labor, equipment, related costs	$\$0.60/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	$6,000
Primer (inorganic zinc)		
Labor, equipment, related costs	$\$0.30/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	$3,000
Material costs	$\$0.11/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	$ 1,100
Intermediate coat (epoxy-polyamide)		
Labor, equipment, related costs	$\$0.15/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	$ 1,500
Material costs	$\$0.09/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	$ 900
Finish coat (aliphatic polyurethane)		
Labor, equipment, related costs	$\$0.20/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	$2,000
Material costs	$\$0.07/\text{ft}^2 \text{ x } 10{,}000\ \text{ft}^2 =$	$ 700
	$1.52/ft	$15,200
Collection and disposal of abrasive (increases cost by a factor of 2)		x 2
	Total cost to coat	$30,400
Maintenance painting cost (10% repainting):		
Labor, equipment, related costs	$\$3.00/\text{ft}^2 \text{ x } 1{,}000\ \text{ft}^2 =$	$3,000
Material costs	$\$0.11/\text{ft}^2 \text{ x } 1{,}000\ \text{ft}^2 =$	+ 110
	$\$3.11/\text{ft}^2$	$3,110
Collection and disposal of abrasive (increases cost by a factor of 2)		x 2
	Total maintenance cost	$6,220

Cost to recoat at the site after the tower is erected:

Surface preparation (conventional blasting)		
Labor, equipment, related costs	$\$1.20/\text{ft}^2$ x 10,000 ft^2 =	\$12,000
Primer (inorganic zinc)		
Labor, equipment, related costs	$\$0.60/\text{ft}^2$ x 10,000 ft^2 =	\$6,000
Material costs	$\$0.11/\text{ft}^2$ x 10,000 ft^2 =	\$ 1,100
Intermediate coat (epoxy-polyamide)		
Labor, equipment, related costs	$\$0.30/\text{ft}^2$ x 10,000 ft^2 =	\$3,000
Material costs	$\$0.09/\text{ft}^2$ x 10,000 ft^2 =	\$ 900
Finish coat (aliphatic polyurethane)		
Labor, equipment, related costs	$\$0.40/\text{ft}^2$ x 10,000 ft^2 =	\$4,000
Material costs	$\$0.07/\text{ft}^2$ x 10,000 ft^2 =	\$ 700
	$\$2.77/\text{ft}^2$	\$27,700
Collection and disposal of abrasive (increases cost by a factor of 2)		x 2
	Total cost to recoat	\$55,400

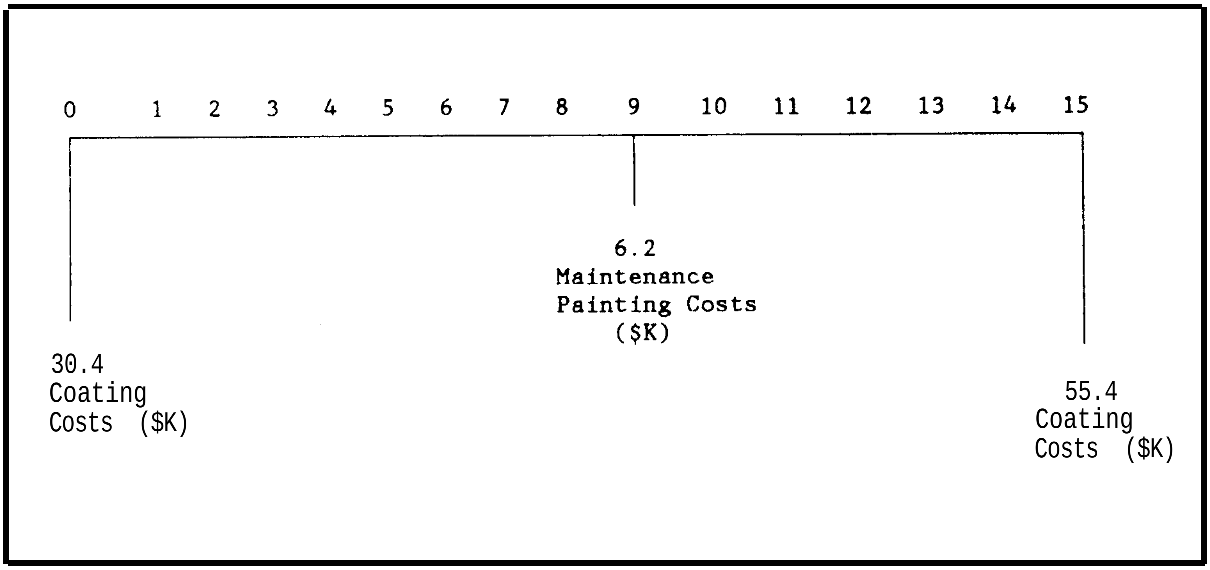


Figure 3-17
Cash Flow Diagram - Coated at the Site Before the Tower is Erected (inorganic zinc primer)

Alternative 3 (economic life - 15 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$30,400		1.000	$30,400
9	Maintenance	6,220		0.424	2,637
15	Coating	55,400		0.239	13,241
Total Net Present Value Cost:					$46,278
Uniform Annual Cost:				$46,278/7.606 =	$ 6,084

Alternative 4. Coat in a shop before the tower is erected (inorganic zinc primer).

The surface is prepared with centrifugal abrasive blasting and coated with an inorganic zinc primer, an intermediate coat of epoxy-polyamide, and a finish coat of aliphatic polyurethane.

Cost to coat:

Surface preparation (white metal blasting)		
Labor, equipment, related costs	$0.50/ft^2 x 10,000 ft^2 =	$5,000
Primer (inorganic zinc)		
Labor, equipment, related costs	$0.16/ft^2 x 10,000 ft^2 =	$ 1,600
Material costs	$0.11/ft^2 x 10,000 ft^2 =	$ 1,100
Intermediate coat (epoxy-polyamide)		
Labor, equipment, related costs	$0.06/ft^2 x 10,000 ft^2 =	$ 600
Material costs	$0.09/ft^2 x 10,000 ft^2 =	$ 900
Finish coat (aliphatic polyurethane)		
Labor, equipment, related costs	$0.12/ft^2 x 10,000 ft^2 =	$ 1,200
Material costs	$0.07/ft^2 x 10,000 ft^2 =	$ 700
	$1.11/ft^2	$11,100
Collection and disposal of abrasive in the shop (increases cost by a factor of 1.25)		x 1.25
Total cost to coat		$13,875

Maintenance painting cost (10% repainting):

Labor, equipment, related costs	$\$3.00/\text{ft}^2 \times 1{,}000\ \text{ft}^2 =$	$3,000
Material costs	$\underline{\$0.11/\text{ft}}^2 \times 1{,}000\ \text{ft}^2 =$	+ 110
	$\$3.11/\text{ft}^2$	$3,110
Collection and disposal of abrasive (increases cost by a factor of 2)		x 2
	Total maintenance cost	$ 6,220

Cost to recoat at the site after the tower is erected:

Surface preparation (conventional blasting)		
Labor, equipment, related costs	$\$1.20/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$12,000
Primer (inorganic zinc)		
Labor, equipment, related costs	$\$0.60/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$6,000
Material costs	$\$0.11/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$ 1,100
Intermediate coat (epoxy-polyamide)		
Labor, equipment, related costs	$\$0.30/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$3,000
Material costs	$\$0.09/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$ 900
Finish coat (aliphatic polyurethane)		
Labor, equipment, related costs	$\$0.40/\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$4,000
Material costs	$\underline{\$0.07/}\text{ft}^2 \times 10{,}000\ \text{ft}^2 =$	$ 700
	$\$2.77/\text{ft}^2$	$27,700
Collection and disposal of abrasive (increases cost by a factor of 2)		x 2
	Total cost to recoat	$55,400

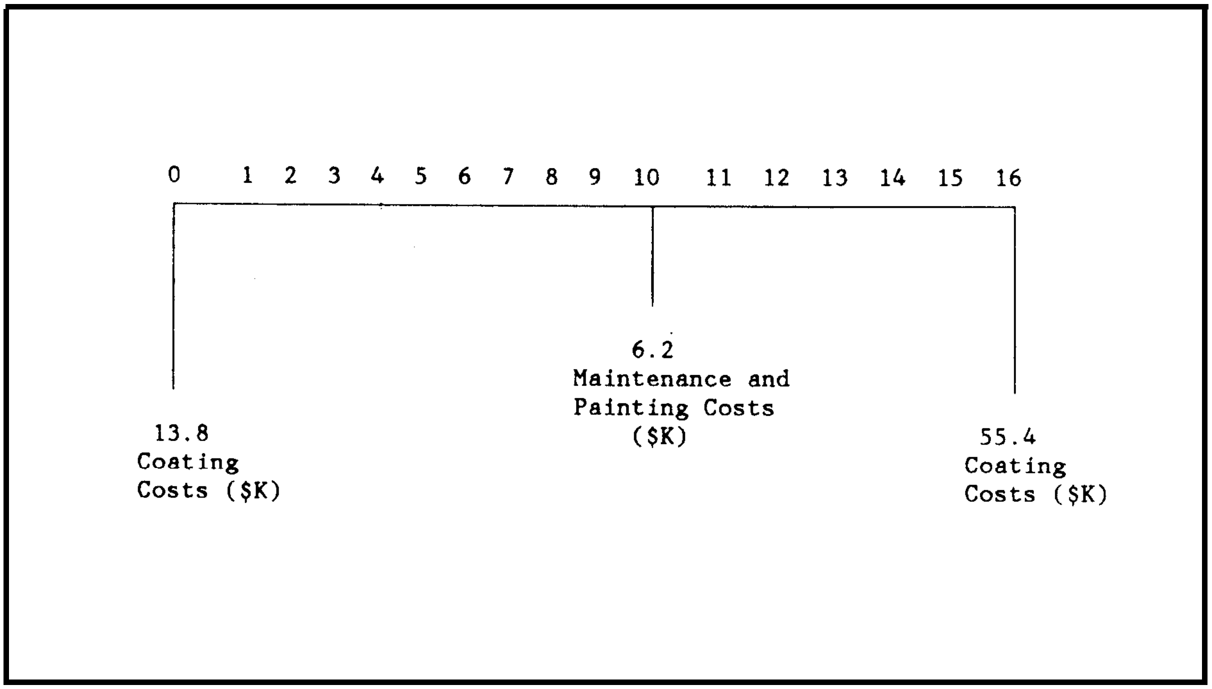


Figure 3-18
Cash Flow Diagram - Coated in a Shop Before the
Tower is Erected (inorganic zinc primer)

Alternative 4 (economic life - 16 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$13,875		1.000	$13,875
10	Maintenance	6,220		0.386	2,401
16	Coating	55,400		0.218	12,077
Total Net Present Value Cost:					$28,353
Uniform Annual Cost:				$20,353/7.824 =	$ 3,624

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Coat at the site after the tower is erected (inorganic zinc primer)

Net present value = $76,264
Uniform annual cost = $11,192

Alternative 2. Coat at the site after the tower is erected (zinc rich epoxy primer)

Net present value = $72,303
Uniform annual cost = $9,506

Alternative 3. Coat at the site before the tower is erected (inorganic zinc primer)

Net present value = $46,278
Uniform annual cost = $ 6,084

Alternative 4. Coat in a shop before the tower is erected (inorganic zinc primer)

Net present value = $28,353
Uniform annual cost = $ 3,624

A comparison of the uniform annual costs suggest that Alternative 4 is the life cycle cost proposal with the least associated cost.

3.7 CORROSION PREVENTION AND CONTROL FOR STEEL PIPING UNDER A PIER

Example 6. Steel Piping Under a Pier.

Objective: Provide corrosion control for the steel piping located under a Pacific coast pier. The piping is 3 inches in diameter and 1,200 feet long (surface area = 942 ft^2).

Alternatives

1. Blast cleaning and applying an epoxy polymer coating.

2. Application of petroleum paste and tape.

This list is not exhaustive. All feasible alternatives should be examined that will meet the objective. For clarity of demonstration, only two alternatives will be considered in this example.

Assumptions

1. The maintenance painting requirement and economic life of the steel piping varies depending on the alternative selected.

Maintenance Painting Required	Economic Life
Alternative 1: 2 years	Alternative 1: 4 years
Alternative 2: 3 years	Alternative 2: 9 years

2. Steel piping will be replaced at the end of its economic life.

3. Environmental regulations require that abrasive from blasting be disposed of as hazardous waste. It is assumed that the disposal of abrasive at the site increases the total cost of coating and maintenance painting by a factor of two. This is a conservative estimate.

4. To compute present values, a 10% discount rate is assumed.

5. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Blast cleaning and applying an epoxy polymer coating

Cost to Coat:

Surface preparation (conventional blasting)		
Labor, equipment, related costs	$\$1.050/ft^2$ x 942 ft^2 =	$ 989
Coating (epoxy polymer)		
Labor, equipment, related costs	$\$0.525/ft^2$ x 94.2 ft^2 =	$ 495
Material costs	$\$.090/ft^2$ x 94.2 ft^2 =	$ 85
	$\$1.665/ft^2$	$1,569
Collection and disposal of abrasive (increases cost by a factor of 2)		x 2
Total coating cost:		$3,138

Maintenance coating cost (10% recoating):

Coating Touch Up

Labor, equipment, related costs	$\$2.625/\text{ft}^2$ x 942 ft^2 =	\$ 247
Material costs	$\$0.090/\text{ft}^2$ x 942 ft^2 =	\$ 8
	$\$2.715/\text{ft}^2$	\$ 255

Collection and disposal of abrasive

(increases cost by a factor of 2)	x 2
Total maintenance cost	\$ 510

Replacement Cost

Cost to install new steel piping:

Labor, equipment, related costs	\$7.00/ft x 1,200 ft	= \$8,400
Material costs	\$1.00/ft x 1,200 ft	= \$1,200

Cost to remove existing steel piping:

Labor, equipment, related costs	\$5.00/ft x 1,200 ft	= \$6,000
Salvage value		= - 800
Total replacement cost		= \$14,800

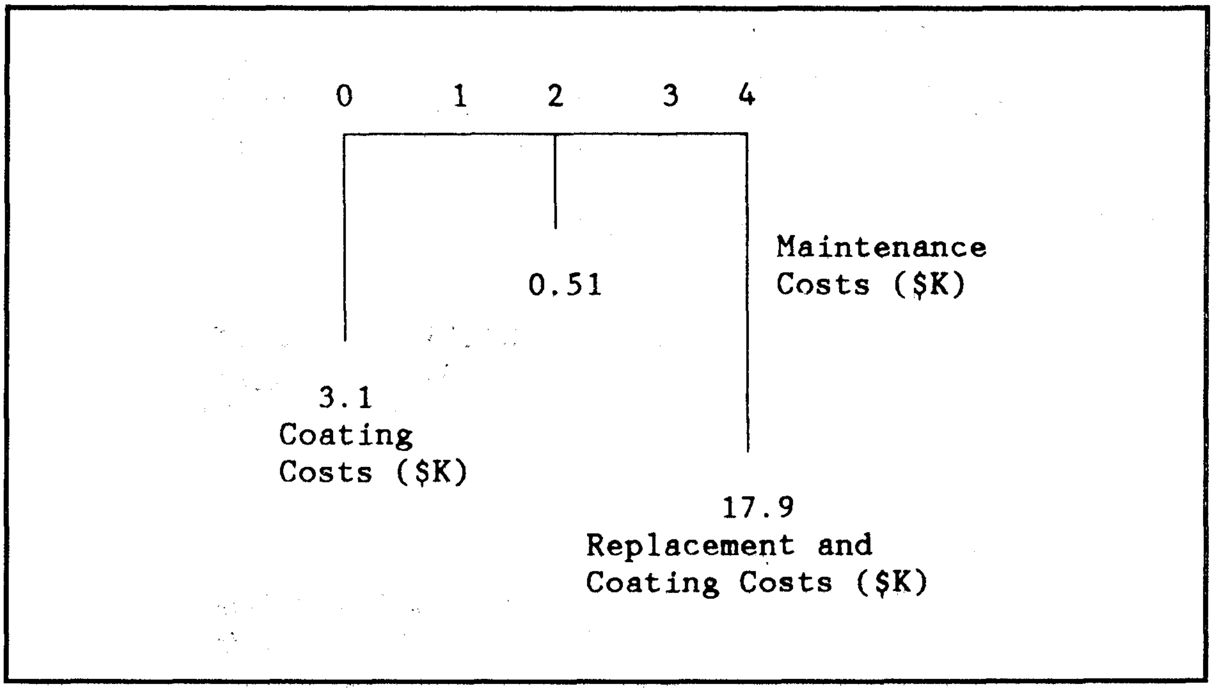


Figure 3-19
Cash Flow Diagram - Blast Cleaning and Application of an Epoxy Polymer Coating

Alternative 1 (economic life - 4 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$ 3,138		1.000	$ 3,138
2	Maintenance	510		0.826	421
4	Coating	14,800		0.683	10,108
4	Coating	3,138		0.683	2,143
	Total Net Present Value Cost:				$15,810
	Uniform Annual Cost:			$15,810/3.170 =	$ 4,987

Alternative 2. Application of petroleum paste and tape.

Cost to Coat:

Surface preparation (wire brushing)

Labor, equipment, related costs	$\$0.70/\text{ft}^2 \text{ x } 942\ \text{ft}^2 =$	$ 659

Application of petroleum paste and tape

Labor, equipment, related costs	$\$1.00/\text{ft}^2 \text{ x } 942\ \text{ft}^2 =$	$ 942
Material costs	$\$2.20/\text{ft}^2 \text{ x } 942\ \text{ft}^2 =$	$2.072
Total coating cost:		$3,673

Maintenance Coating Cost (10% recoating):

Coating touch up

Labor, equipment, related costs	$\$1.35/\text{ft}^2 \text{ x } 94.2\ \text{ft}^2 =$	$ 127
Material costs	$\$2.20/\text{ft}^2 \text{ x } 94.2\ \text{ft}^2 =$	$ 207
Total maintenance cost:		$ 334

Replacement Cost:

Cost to install new steel piping:

Labor, equipment, related costs	$7.00/ft x 1,200 ft =	$8,400
Material costs	$1.00/ft x 1,200 ft =	$ 1,200

Cost to remove existing steel piping:

Labor, equipment, related costs	$5.00/ft x 1,200 ft =	$ 6,000
Salvage value	=	- 800
Total replacement cost:	=	$14,800

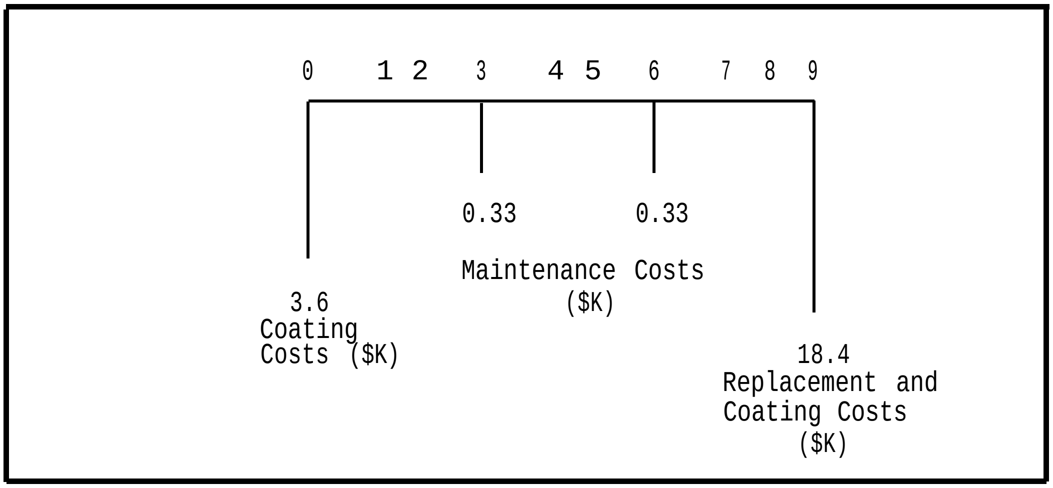


Figure 3-20
Cash Flow Diagram - Tape and Application
of a Petroleum Paste

Alternative 2 (economic life - 9 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Coating	$ 3,673		1.000	$ 3,673
3	Maintenance	334		0.751	251
6	Maintenance	334		0.564	188
9	Replacement	14,800		0.424	6,275
9	Coating	3,673		0.424	1,557
	Total Net Present Value Cost:				$11,944
	Uniform Annual Cost:				$11,944/5.759 = $ 2,074

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Blast cleaning and applying an epoxy polymer coating

Net present value = $15,810
Uniform annual cost = $4,987

Alternative 2. Application of petroleum paste and tape

Net present value = $11,944
Uniform annual cost = $2,074

A comparison of the uniform annual costs suggest that Alternative 2 is the life cycle cost proposal with the least associated cost.

3.8 CORROSION PREVENTION AND CONTROL FOR SEAWALLS.

Example 7 - Construct a Seawall.

Objective: Provide corrosion control for a seawall that will be constructed with sheet steel piling (1,000 feet long).

Alternatives

1. Provide no corrosion prevention or control.

2. Coat the seawall.

3. Provide cathodic protection and coat the seawall.

This list is not exhaustive. All feasible alternatives should be examined that will meet the objective. For clarity of demonstration, only three alternatives will be considered in this example.

Assumptions

1. The economic life of the seawall varies depending on the alternative selected:

    a. Alternative 1 (no corrosion prevention or control): 15 years

    b. Alternative 2 (coated): 20 years

    c. Alternative 3 (cathodic protected and coated): 25 + years

2. A salvage value of $20/ft or $20,000 will be remitted when the seawall is replaced at the end of its economic life.

3. The seawall will require replacement at the end of its economic life when cathodic protection is not applied.

4. The seawall will not require replacement at the end of its economic life when cathodic protection is applied. Continued maintenance and protection is assumed.

5. To compute present values, a 10% discount rate is assumed.

6. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Provide no corrosion prevention or control

Cost of new installation:	$375/ft x 1,000 ft = $375,000
Cost of replacement:	$375/ft x 1,000 ft = $375,000
Terminal value (year 15):	
Salvage value	$20/ft x 1,000 ft = $20,000
Cost to' remove existing seawall:	$8/ft x 1,000 ft = -8,000
Terminal value:	$12,000

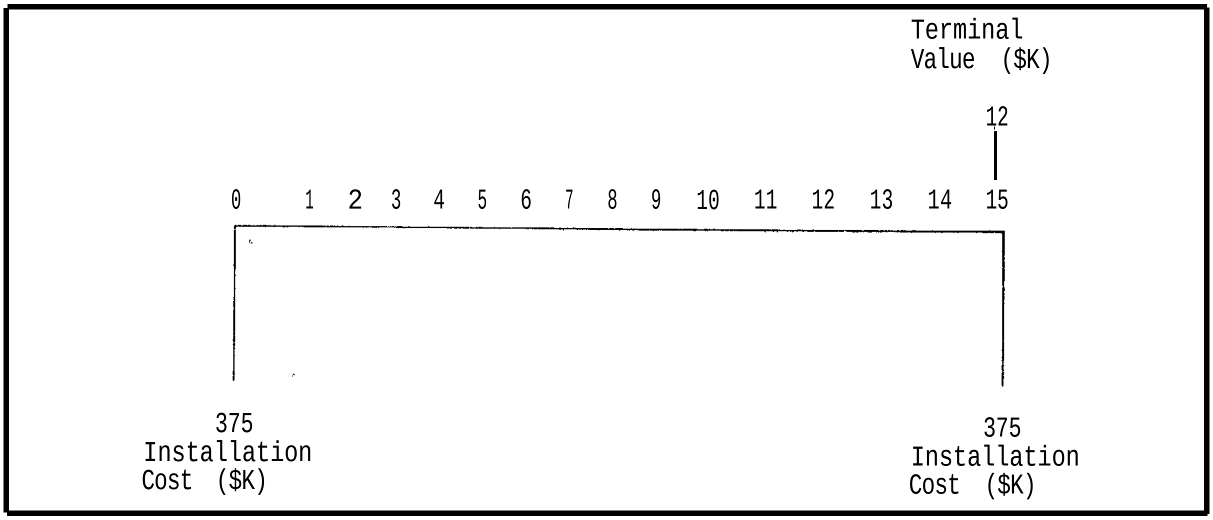


Figure 3-21
Cash Flow Diagram - Provide No Corrosion
Prevention or Control

Alternative 1 (economic life - 15 years)

Project Year(s)	Cost Element	Amount		Discount Factor	**Discounted Cost**
		One-Time	Recurring		
0	Installation	$375,000		1.000	**$375,000**
15	Replacement	375,000		0.239	**89,625**
15	Terminal	(12,000)		0.239	**(2,868)**
	Total Net Present Value Cost:				**$461,757**
	Uniform Annual Cost:			**$461,757/7.606 =**	**$ 60,710**

Alternative 2. Coat the Seawall

Cost of new installation:
Cost of seawall: $375/ft x 1,000 ft = $375,000
Cost of coating: $50/ft x 1,000 ft = $50,000
$425/ft $425,000

Cost of replacement:
Cost of seawall: $375/ft x 1,000 ft = $375,000
Cost of coating: $50/ft x 1,000 ft = $50,000
$425/ft $425,000

Terminal value (year 20):
Salvage value: $20/ft x 1,000 ft = $20,000
Cost to remove existing seawall: $ 8/ft x 1,000 ft = -8,000
$12,000

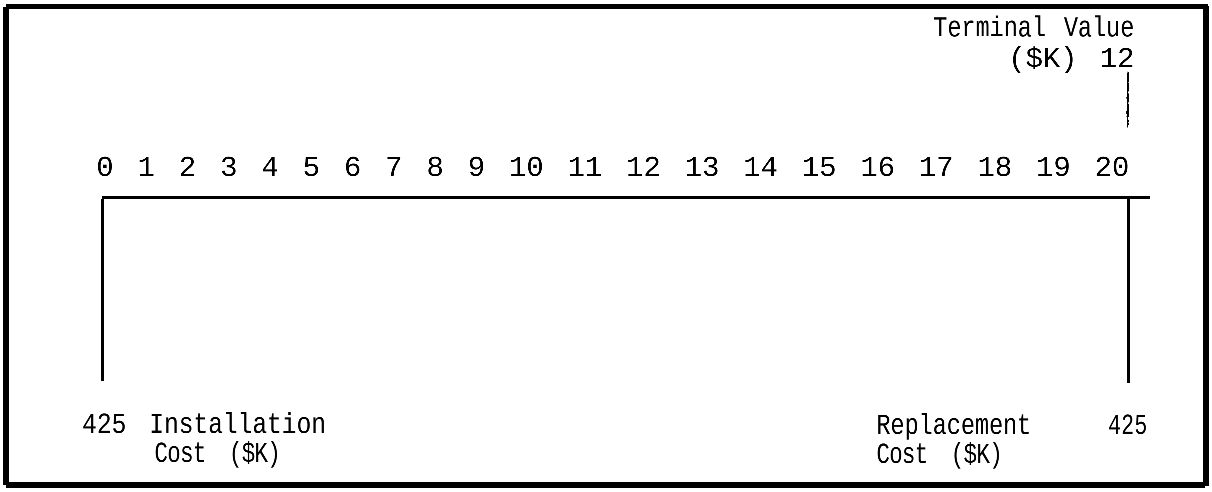


Figure 3-22
Cash Flow Diagram - Coat the Seawall

Alternative 2 (economic life - 20 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Installation	$425,000		1.000	$425,000
20	Replacement	425,000		0.149	63,325
20	Salvage	(12,000)		0.149	(1,788)

Total Net Present Value Cost: $486,537
Uniform Annual Cost: $486,537/8.514 = $ 57,145

Alternative 3 - Provide cathodic protection and coat the seawall.

Cost of new installation:

Cost of seawall	$375/ft x 1,000 ft =	$375,000
Cost of cathodic protection and coating:	$ 80/ft x 1,000 ft =	$ 80,000
	$455/ft	$455,000

Cost of annual cathodic protection maintenance	$5/ft x 1,000 ft =	$ 5,000

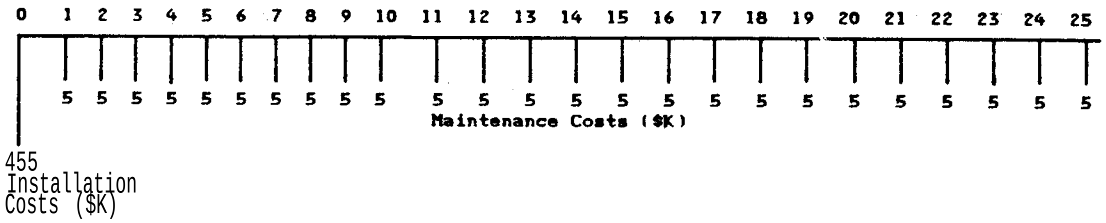


Figure 3-23
Cash Flow Diagram - Provide Cathodic Protection
and Coat the Seawall

Alternative 3 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Installation	$455,000		1.000	$455,000
1-25	Maintenance		5,000	9.077	45,385
Total Net Present Value Cost:					$500,385
Uniform Annual Cost:				$500,385/9.077 =	$ 55,127

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Provide no corrosion prevention or control.

Net present value = $461,757
Uniform annual cost = $ 60,710

Alternative 2. Coat the seawall

Net present value = $486,537
Uniform annual cost = $ 57,145

Alternative 3. Provide cathodic protection and coat the seawall

Net present value = $500,385
Uniform annual cost = $ 55,127

A comparison of the uniform annual costs suggests that Alternative 3 is the life cycle cost proposal with the least associated cost. However, the cost comparisons imply that the alternatives are close economic substitutes.

Example 8. Existing Seawall.

Objective: Provide corrosion control for an existing sheet steel piling seawall, 1,000 feet long. The seawall is 20 years old and extensive repairs or replacement is necessary.

Alternatives

1. Mechanical repair of existing seawall (no corrosion prevention or control).

2. Mechanical repair of existing seawall (coat only).

3. Mechanical repair of existing seawall (coat and cathodic protection).

4. Replace the seawall (no corrosion prevention or control).

5. Replace the seawall (apply coat only).

6. Replace the seawall (apply coat and cathodic protection).

Assumptions

1. The economic life of the seawall varies depending on the alternative selected:

    a. Alternative 1 (no corrosion prevention or control): 10 years
    b. Alternative 2 (coat only): 15 years
    c. Alternative 3 (coat and cathodic protection): 25 + years
    d. Alternative 4 (replacement/no corrosion prevention or control): 15 years
    e. Alternative 5 (replacement/coat only): 20 years
    f. Alternative 6 (replacement/coat and cathodic protection): 25 + years

2. A salvage value of $20/ft or $20,000 will be remitted when the seawall is replaced.

3. Mechanical repair of the existing seawall will extend the economic life 10 years. Replacement will then be necessary.

4. Mechanical repair of the existing seawall and intertidal coating will extend the economic life 15 years. Replacement will then be necessary.

5. Mechanical repair of the existing seawall, intertidal coatings, and installing cathodic protection will extend the economic life indefinitely.

6. To compute present values, a 10% discount rate is assumed.

7. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Mechanical repair of the existing seawall (no corrosion prevention or control)

Cost to repair: $ 65/ft x 1,000 ft = $ 65,000
Cost of replacement: $375/ft x 1,000 ft = $375,000

Terminal value (year 10):
Salvage value: $20/ft x 1,000 ft = $20,000
Cost to remove existing seawall: -8 ft x 1,000 ft = - 8,000
$12/ft $12,000

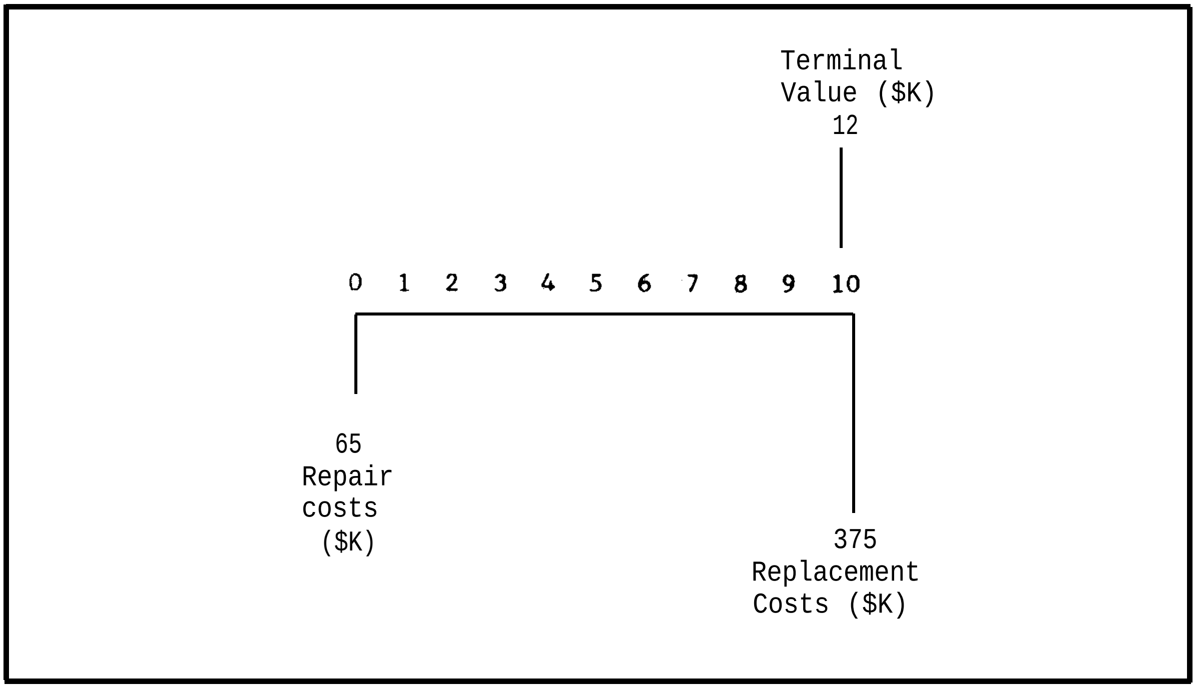


Figure 3-24
Cash Flow Diagram - Mechanical Repair of Existing Seawall
(no corrosion prevention or control)

Alternative 1 (economic life - 10 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Mechanical Repair	$ 65,000		1.000	$ 65,000
10	Replacement	375,000		0.386	144,750
10	Terminal Value	(12,000)		0.386	(4,632)
Total Net Present Value Cost:					$205,118
Uniform Annual Cost:				$205,118/6.145 =	$ 33,380

Alternative 2. Mechanical repair of existing seawall (coat only)

Cost to repair: $65/ft x 1,000 ft = $65,000
Cost to coat intertidal: $ 15/ft x 1,000 ft = $ 15,000
Cost of replacement:

Cost of seawall: $375/ft x 1,000 ft = $375,000
Cost of coating: +50/ft x 1,000 ft = + 50,000
$425/ft $425,000

Terminal value (year 15):
Salvage value: $20/ft x 1,000 ft = $20,000
Cost to remove existing seawall: -8/ft x 1,000 ft = -8,000
$12/ft $12,000

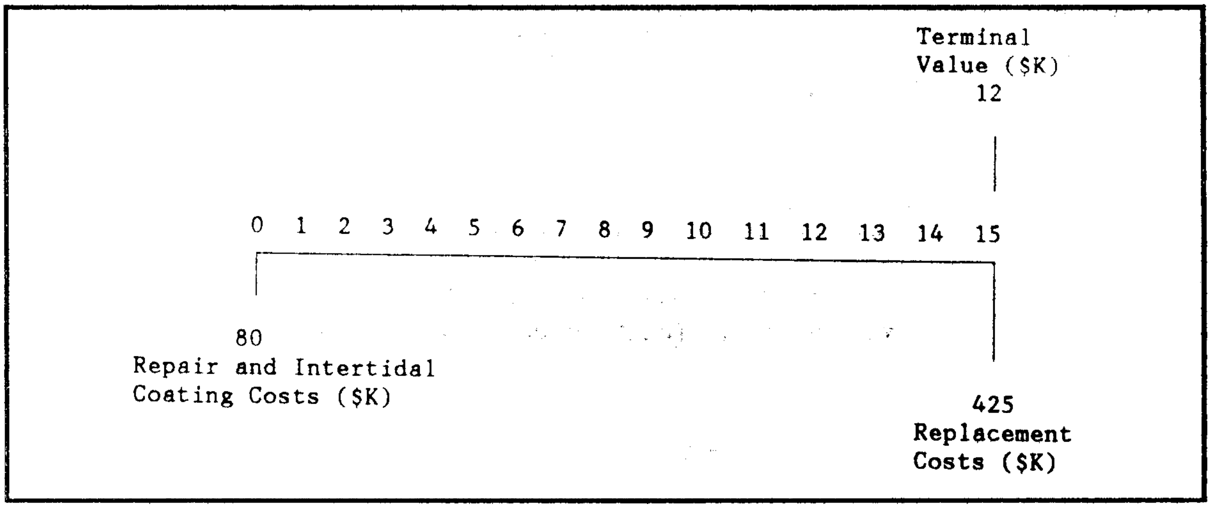


Figure 3-25
Cash Flow Diagram - Mechanical Repair of Existing Seawall (coat only)

Alternative 2 (economic life - 15 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Mechanical Repair	$ 65,000		1.000	$ 65,000
0	Intertidal Coating	15,000		1.000	15,000
15	Replacement	425,000		0.239	101,575
15	Terminal Value	(12,000)		0.239	(2,868)
	Total Net Present Value Cost:				$178,707
	Uniform Annual Cost:			$178,707/7.606 =	$ 23,495

Alternative 3. Mechanical repair of existing seawall (coat and cathodic protection).

Cost to repair: $65/ft x 1,000 ft = $65,000
Cost to coat intertidal: $15/ft x 1,000 ft = $15,000
Cost of retrofitting cathodic protection on the seawall: $30/ft x 1,000 ft = $15,000
Cost of annual maintenance (cathodic protection): $5/ft x 1,000 ft = $5,000

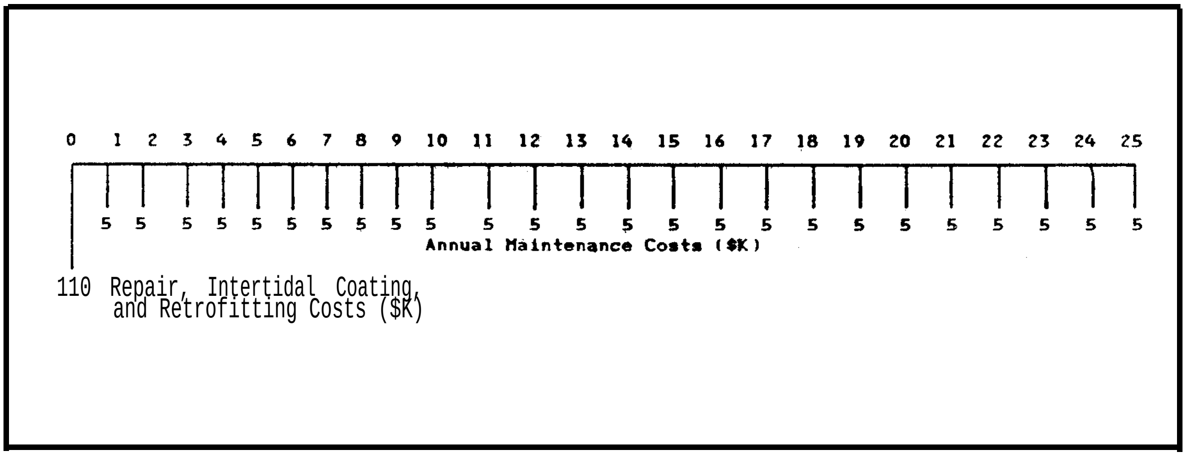


Figure 3-26
Cash Flow Diagram - Mechanical Repair of Existing Seawall (coat and cathodic protection)

Alternative 3 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Mechanical Repair	$ 65,000		1.000	$ 65,000
0	Intertidal Coating	15,000		1.000	15,000
0	Retrofit	30,000		1.000	30,000
l-25	Maintenance		5,000	9.077	45,385
Total Net Present Value Cost:					$155,385
Uniform Annual Cost:				$155,385/9.077 =	$ 17,118

Alternative 4. Replace the seawall (no corrosion prevention or control)

Cost of replacement: $375,000

Terminal value (year 15):
Salvage value: $20/ft x 1,000 ft = $20,000
Cost to remove existing seawall: - 8/ft x 1,000 ft = - 8,000
$12/ft $12,000

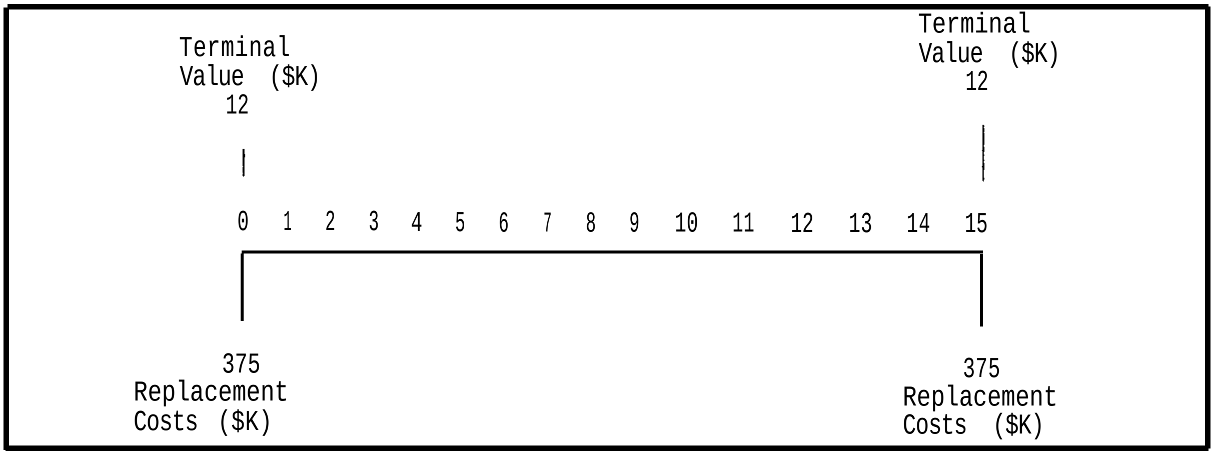


Figure 3-27
Cash Flow Diagram - Replace the Seawall
(no corrosion prevention or control)

Alternative 4 (economic life - 15 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$375,000		1.000	$375,000
0	Terminal Value	(12,000)		1.000	(12,000)
15	Replacement	375,000		0.239	89,625
15	Terminal Value	(12,000		0.239	(12,000)

Total Net Present Value Cost: $449,757
Uniform Annual Cost: $449,757/7.606 = $ 59,132

Alternative 5. Replace the seawall (coat only)

Cost of replacement:

Cost of seawall: $375/ft x 1,000 ft = $375,000
Cost of coating: $ 50/ft x 1,000 ft = +50,000
$425/ft $425,000

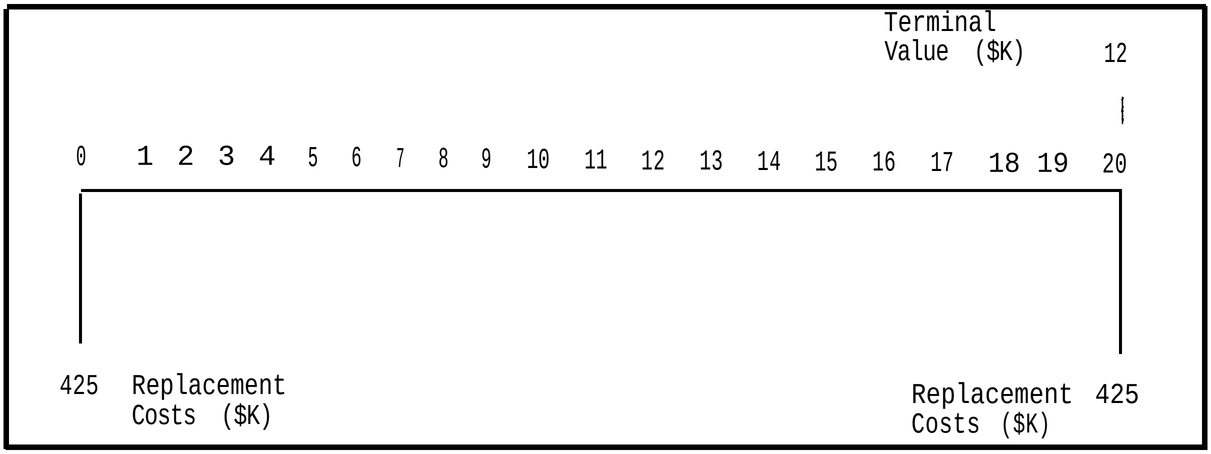


Figure 3-28
Cash Flow Diagram - Replace the Seawall (coat only)

Alternative 5 (economic life - 20 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0 0 20 20	Replacement Terminal Value Replacement Terminal Value	$425,000 (12,000) 425,000 (12,000)		1.000 1.000 0.149 0.149	$425,000 (12,000) 63,325 (1,788)
	Total Net Present Value Cost:				$474,537
	Uniform Annual Cost:			$474,537/8.514 =	$ 55,736

Alternative 6. Replace the seawall (coat and cathodic protection).

Cost of replacement:
Cost of seawall: **$375/ft x 1,000 ft = $375,000**
Cost of cathodic protection:
and coating **+80/ft x 1,000 ft = +80,000**
$455/ft $455,000

Terminal value (year 20):
Salvage value: $20/ft x 1,000 ft = $20,000
Cost to remove existing seawall: -$8/ft x 1,000 ft =-$ 8,000
$12/ft $12,000

Cost of annual maintenance (cathodic -
protection: $5/ft x 1,000 ft = $5,000

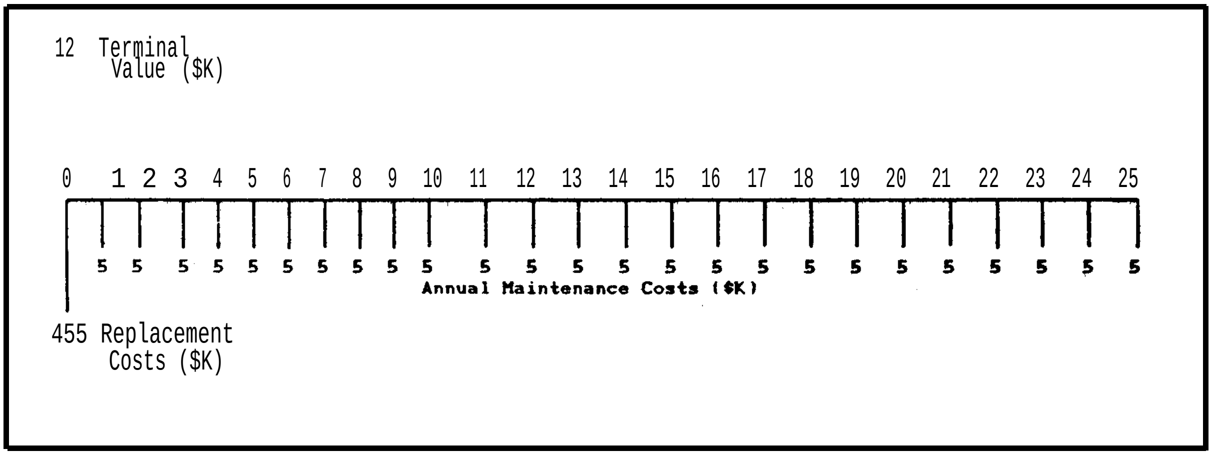


Figure 3-29
Cash Flow Diagram - Replace the Seawall
(coat and cathodic protection)

Alternative 6 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$455,000		1.000	$455,000
0	Terminal Value	(12,000)			(12,000)
1-25	Maintenance		5,000	9.077	45,385
Total Net Present Value Cost:					$488,385
Uniform Annual Cost:				$488,385/9.077 =	$ 53,805

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Mechanical repair of existing seawall (no corrosion prevention or control)

Net present value = $205,118
Uniform annual cost = $ 33,380

Alternative 2. Mechanical repair of existing seawall (coat only)

Net present value = $178,707
Uniform annual cost = $ 23,495

Alternative 3. Mechanical repair of existing seawall (coat and cathodic protection)

Net present value = $155,385
Uniform annual cost = $ 17,118

Alternative 4. Replace the seawall (no corrosion prevention or control)

Net present value = $449,757
Uniform annual cost = $ 59,132

Alternative 5. Replace the seawall (coat only)

Net present value = $474,537
Uniform annual cost = $ 55,736

Alternative 6. Replace the seawall (coat and cathodic protection)

Net present value = $488,385
Uniform annual cost = $ 53,805

A comparison of the uniform annual costs suggest that Alternative 3 is the life cycle cost proposal with the least associated cost.

3.9 CORROSION PREVENTION AND CONTROL WITH COMPOSITE MATERIALS

Example 9. Exterior Doors of a Marine Barracks.

Objective: Provide corrosion control for the exterior doors of a marine barracks for the least life cycle cost. This requires replacing the doors periodically.

Alternatives

1. Hollow core wood interior with steel exterior doors.

2. Fiberglass gelcoat balsa wood core exterior doors.

Assumptions

1. The physical life of the doors vary depending on the material used and also determines the required number of doors to be replaced annually.

   a. Hollow core wood interior steel exterior - 5 years
   Doors to be replaced annually = 75

   b. Fiberglass gelcoat balsa wood core - 8 years
   Doors to be replaced annually = 47

2. At the end of its physical life, the door will be replaced.

3. The analysis period covers 25 years (economic life of the building - 25 years).

4. Replacing the doors produces no salvage value.

5. To compute present values, a 10% discount rate is assumed.

6. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1. Hollow core wood interior with steel exterior doors

Doors to be replaced annually = 75 doors	
Cost of installation (per door):	
Materials (per door)	
(a) Door	$ 300.00
(b) Frame	+ 100.00
	$ 400.00
Cost of labor (per door):	
(a) Hourly salary	$ 26.41/hr
(b) Hours required (replace):	x 9 hrs
	$ 237.69
Cost to paint (refinishing):	
Materials (per door)	$ 4.00
Cost of labor (per door):	
(a) Hourly salary	$ 26.41/hr
(b) Hours required (replace)	x 2hrs
	$ 52.82
Cost for additional welder:	
Materials (per door)	$ 4.00
Cost of labor (per door):	
(a) Hourly salary	$ 26.41/hr
(b) Hours required (replace)	x 1 hr
	$ 26.41
Total cost per door:	$ 724.92

Number of doors in barracks: 339

Total cost per door:	$ 724.92
Annually (replace 75 doors):	x 75
Annual cost to replace 75 doors:	$54,369.00

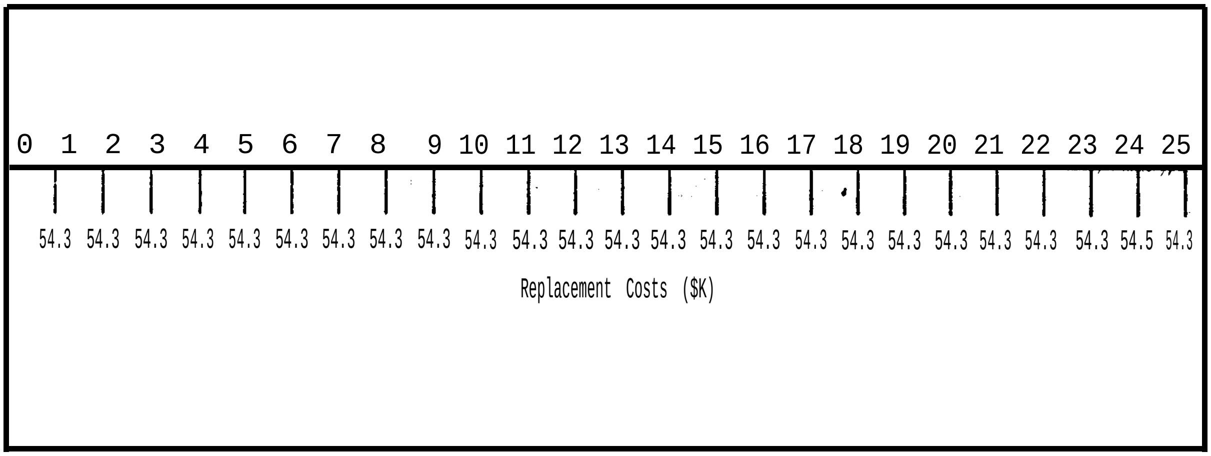


Figure 3-30
Cash Flow Diagram - Hollow Core Wood Interior,
Steel Exterior Doors

Alternative 1 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
1-25	Replacement		$54,369	9.077	$493,507
Total Net Present Value Cost:					$493,507
Uniform Annual Cost:				$493,507/9.077 =	$ 54,369

Alternative 2. Fiberglass gelcoat balsa wood core exterior doors.

Doors to be replaced annually: 47
Cost of installation (per door):

Materials (per door):

(a) Door	$ 300.00
(b) Frame	+125.00
	$ 425.00

Cost of labor (per door):

(a) Hourly salary	$ 26.41/hr

(b) Hours required (replace) x 9 hrs

$ 237.69

Cost to paint (refinishing): Not required

Cost for additional welder: Not required

Total cost per door: $ 662.69

Number of doors in barracks: 339

Total cost per door: $ 662.69

Annually (replace 47 doors): x 47

Annual cost to replace 47 doors: $31,146.00

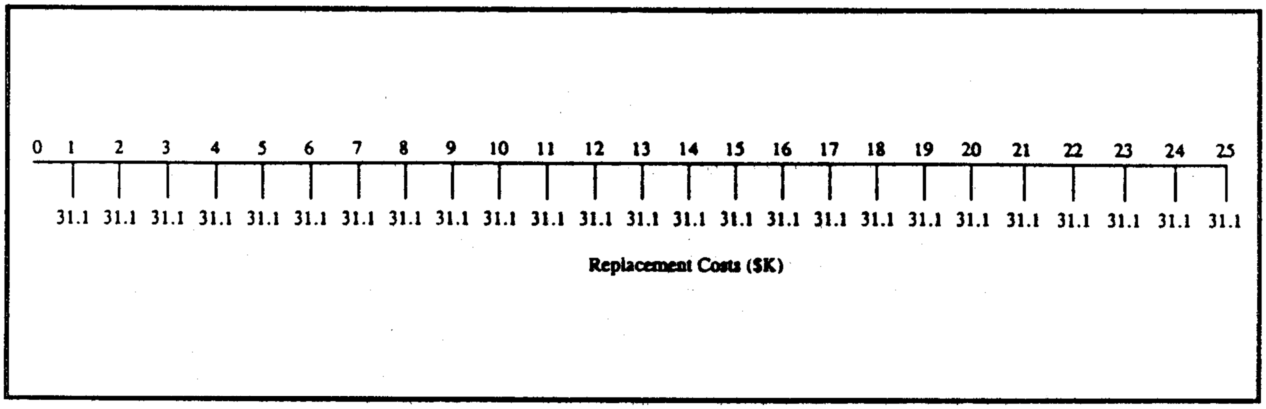


Figure 3-31
Cash Flow Diagram - Fiberglass Gelcoat Balsa
Wooden Core Exterior Doors

Alternative 2

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
1-25	Replacement		$31,146	9.077	$282,712
Total Net Present Value Cost: $282,712 Uniform Annual Cost: $282,712/9.077 = $ 31,146					

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Hollow core wood interior with steel exterior doors

Net present value = $493,507
Uniform annual cost = $ 54,369

Alternative 2. Fiberglass gelcoat balsa wood core exterior doors

Net present value = $282,712
Uniform annual cost = $ 31,146

A comparison of the net present value and uniform annual costs suggest that Alternative 2 is the life cycle cost proposal with the least associated cost. Over an economic life of 25 years, choosing Alternative 2 will result in an overall net present value savings of $210,795 ($493,507 - $282,712 = $210,795).

Navy Wide Savings

Determining the projected savings Navy-wide is prepared using the values derived in the individual economic analysis. It is assumed that Alternative 2, fiberglass gelcoat balsa wood core doors, will be adopted throughout the Navy and produce multiple savings. It is also assumed that all marine barracks have similar site conditions (e.g., 339 doors per site).

To project Navy-wide savings, an average estimate of the number of marine barracks is required. A rough estimate of the average number of Marine barracks is calculated as:

Estimated number of Marine barracks doors Navy wide:	100,000
Number of Marine barracks doors at San Diego:	339
Average number of Marine barracks: 100,000/339 =	295

The average number of marine barracks is then multiplied by the net present value savings calculated, over an economic life of 25 years, for Alternative 2 in the individual project analysis.

Net present value savings (Alt 2):	$ 210,795
Average number of Marine barracks:	x 295
Navy-wide net present value savings:	$ 62,184,525

The analysis results in a projection of $62,184,525 Navy-wide net present value savings if Alternative 2, fiberglass gelcoat balsa wood core doors, is adopted Navy-wide. Note that this is a very rough estimate of expected savings. Marine barracks differ in size and site conditions. There is also no guarantee that Alternative 2 will be adopted at all barracks. The estimate is best used as an approximation of the size of savings expected if Alternative 2 is adopted Navy-wide.

Example 10. Rain Gutters for Navy Housing

Objective: To replace the rain gutters of 100 Navy houses for the least life cycle cost. Each house requires 70 feet of guttering.

Alternatives

1. Galvanized steel rain gutters.
2. Plastic rain gutters.
3. Aluminum rain gutters.

Assumptions

1. The economic life of the rain gutter varies depending on the material chosen.

    a. Alternative 1 (galvanized steel rain gutters): 8 years
    b. Alternative 2 (plastic rain gutters): 12 years
    c. Alternative 3 (aluminum rain gutters): 10 years

2. At the end of the economic life, the rain gutter will be replaced.

3. There is no salvage value and removal costs are minimal.

4. Periodic maintenance painting will be performed every 2 years on the galvanized steel rain gutters. The plastic and aluminum rain gutters do not require maintenance painting.

5. To compute present values, a 10% discount rate is assumed.

6. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

Alternative 1 - Galvanized steel rain gutters

Cost to replace rain gutters (includes downspouts):
Installation costs: $0.70/ft x 70 ft x 100 houses = $ 4,900
Material costs: $1.30/ft x 70 ft x 100 houses = + 9,100
$2.00/ft $ 14,000

Cost of maintenance painting: $30/house x 100 houses = $3,000

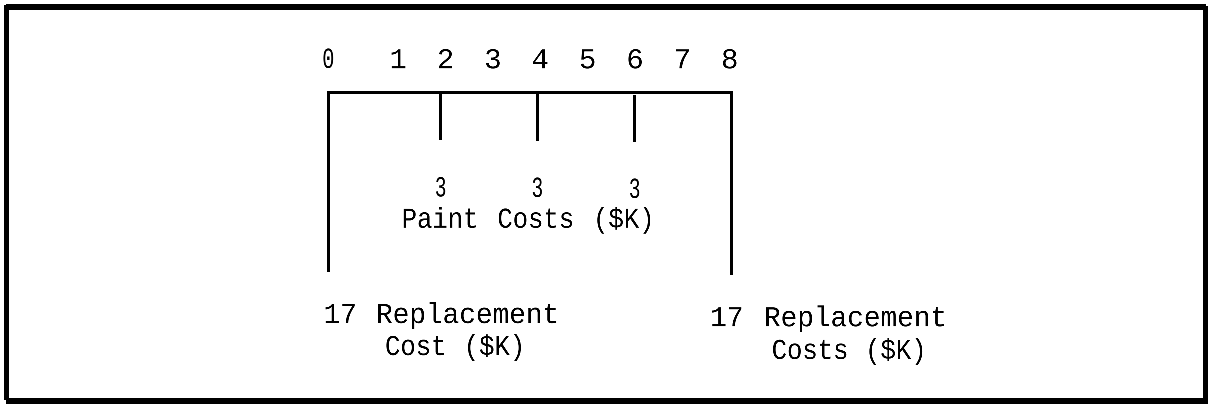


Figure 3-32
Cash Flow Diagram - Galvanized Steel Rain Gutters

Alternative 1 (economic life - 8 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$14,000		1.000	$14,000
0	Paint	3,000		1.000	3,000
2	Paint	3,000		0.826	2,478
4	Paint	3,000		0.683	2,049
6	Paint	3,000		0.564	1,692
8	Replacement	14,000		0.467	6,538
8	Paint	3,000		0.467	1,401
	Total Net Present Value Cost:				$31,158
	Uniform Annual Cost:			$31,158/5.335 =	$ 5,840

Alternative 2 - Plastic rain gutters.

Cost to replace rain gutters (includes downspouts):

Installation costs: $0.70/ft x 70 ft x 100 houses = $4,900
Material costs: +1.70/ft x 70 ft x 100 houses = + 11,900
$2.40/ft $16,800

Cost of maintenance painting: Not required.

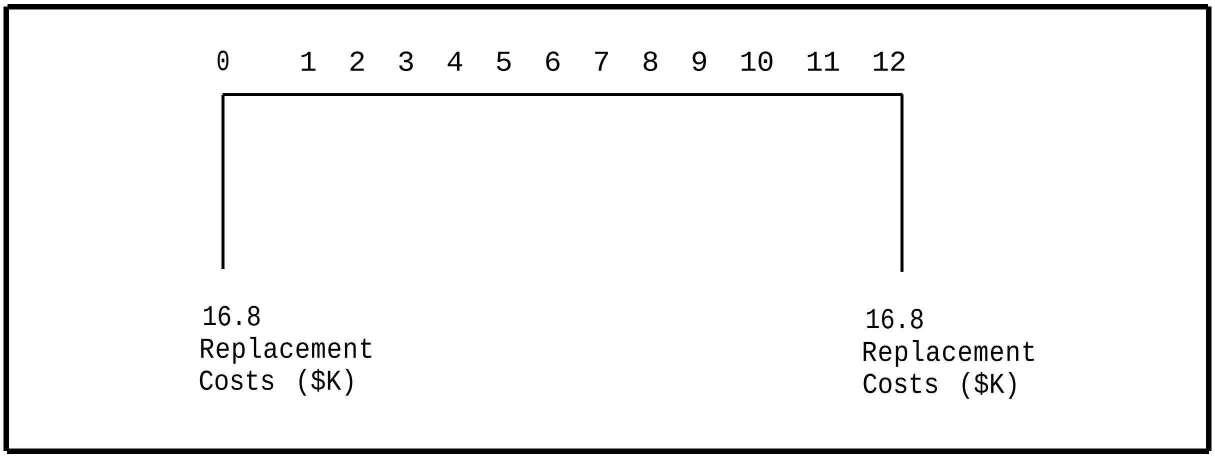


Figure 3-33
Cash Flow Diagram - Plastic Rain Gutters

Alternative 2 (economic life - 12 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0 12	Replacement Replacement	$16,800 16,800		1.000 0.319	$16,800 5,359
Total Net Present Value Cost:					$22,159
Uniform Annual Cost:				$22,159/6.814 =	$ 3,252

Alternative 3 - Aluminum rain gutters.

Cost to replace rain gutters (includes downspouts):
Installation costs: $0.70/ft x 70 ft x 100 houses = $ 4,900
Material costs: +1.90/ft x 70 ft x 100 houses = +13,300
$2.60/ft $ 18,200

Cost of maintenance painting: Not required.

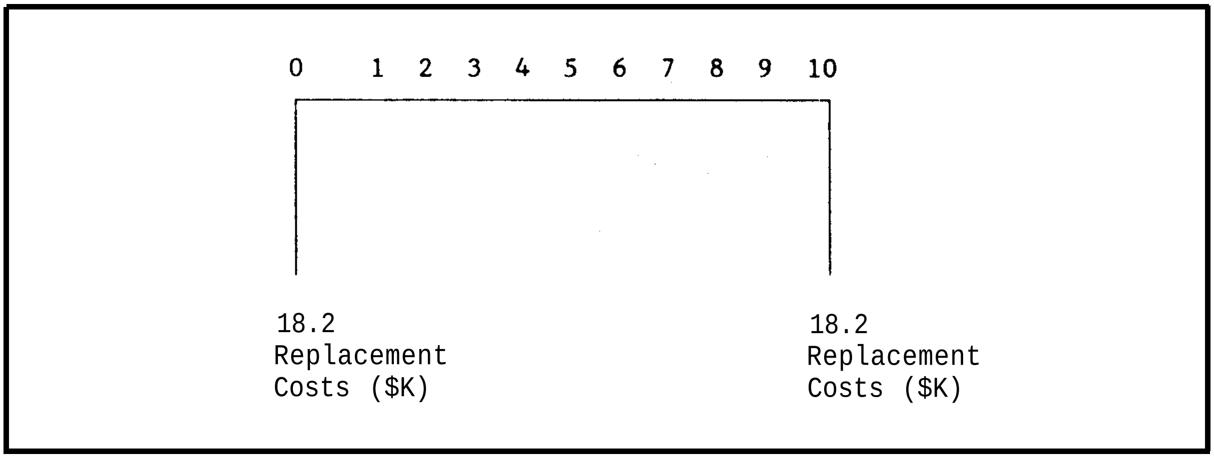


Figure 3-34
Cash Flow Diagram - Aluminum Rain Gutters

Alternative 3 (economic life - 10 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$18,200		1.000	$18,200
10	Replacement	18,200		0.386	7,025
Total Net Present Value Cost:					$25,225
Uniform Annual Cost:				$25,225/6.145 =	$ 4,105

Compare Costs/Benefits and Rank Alternatives

Alternative 1. Galvanized steel rain gutters

Net present value = $31,158
Uniform annual cost = $ 5,840

Alternative 2. Plastic rain gutters

Net present value = $22,159
Uniform annual cost = $ 3,252

Alternative 3. Aluminum rain gutters

Net present value = $25,225
Uniform annual cost = $ 4,105

A comparison of the uniform annual costs suggests that Alternative 2 is the life cycle cost proposal with the least associated cost.

3.10 CORROSION PREVENTION AND CONTROL FOR CHAIN LINK FENCES

Example 11. Chain Link Security Fences (different environments).

Objective: To install security fences, each 1,200 feet long.

Alternatives

1. Galvanized steel chain link fence.
2. Vinyl-coated steel chain link fence.

Assumptions

1. The economic life of the chain link security fence varies depending on the environment:

   a. Tropical Marine Environment

      (1) Galvanized steel: 3 years
      (2) Vinyl-coated: 6 years

b. Temperate Marine Environment

(1) Galvanized steel: 7 years
(2) Vinyl-coated: 10 years

c. Rural (non-marine) Environment

(1) Galvanized steel: 15 years
(2) Vinyl-coated: 25 years

2. At the end of the economic life, the entire fence will be replaced.

3. When the existing fence is replaced, there is a removal cost of $0.15/ft x 1,200 ft = $180 fence and that the removal produces no salvage value.

4. To compute present values, a 10% discount rate is assumed.

5. Costs of labor and materials increase (or decrease) with the general inflation rate. This analysis requires no special treatment of inflation.

Cost/Benefit Analysis

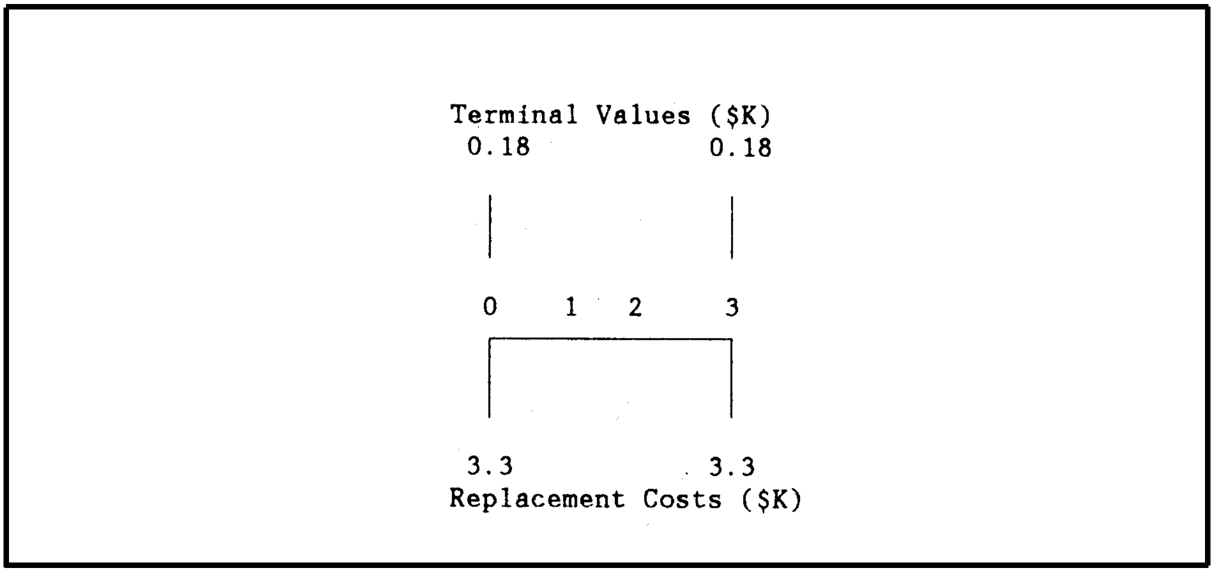
Alternative 1. Galvanized steel chain link fence in a tropical marine environment.

Cost to replace fence:

Installation costs $1.25/ft x 1,200 ft = $1,500
Material costs $1.50/ft x 1,200 ft = $1,800
$2.75/ft $3,300

Terminal value (cost): Salvage value $ 0

Cost to remove fence $180:
$180



Cash Flow Diagram - Galvanized Steel
Chain Link Fence (tropical marine environment)

Alternative 1 (economic life - 3 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$3,300		1.000	$3,300
0	Terminal Value	180		1.000	180
3	Replacement	3,300		0.751	2,478
3	Terminal Value	180		0.751	135
Total Net Present Value Cost:					$6,093
Uniform Annual Cost:				$6,093/2.487 =	$2,450

Alternative 2. Vinyl-coated steel chain link fence in a tropical marine environment.

Cost to replace fence:

Installation costs	$1.25/ft x 1,200 ft =	$1,500
Material costs	$1.85/ft x 1,200 ft =	$2,220
	$3.10/ft	$3,720

Terminal value (cost):	Salvage value	$ 0
	Cost to remove fence	$180
		$180

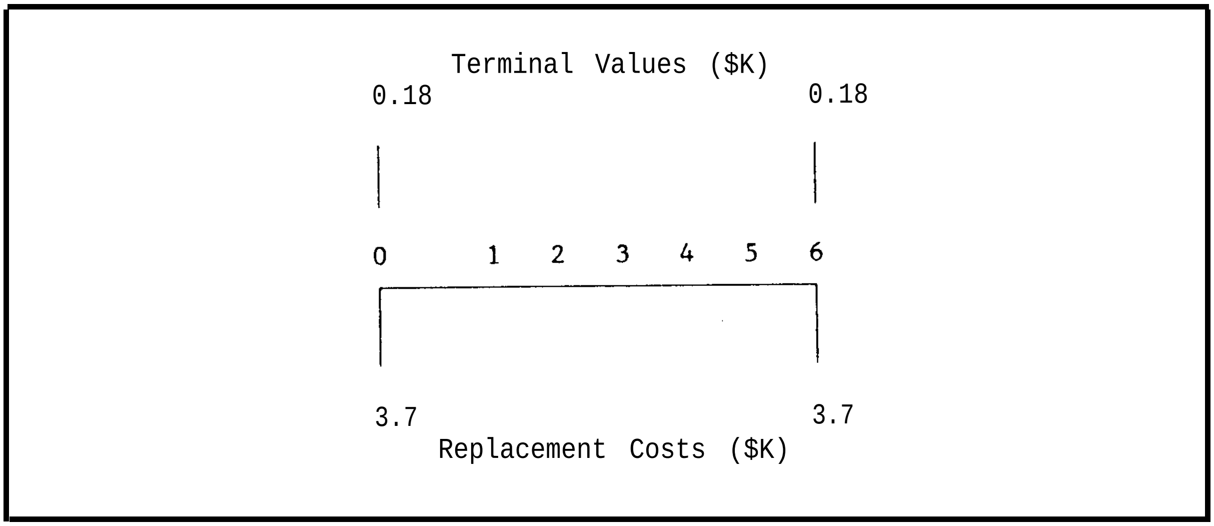


Figure 3-36
Cash Flow Diagram - Vinyl-Coated Steel
Chain Link Fence (tropical marine environment)

Alternative 2 (economic life - 6 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$3,720		1.000	$3,720
0	Terminal Value	180		1.000	180
3	Replacement	3,720		0.564	2,098
3	Terminal Value	180		0.564	101
	Total Net Present Value Cost:				$6,099
	Uniform Annual Cost:			$6,099/4.355 =	$1,400

Alternative 1. Galvanized steel chain link fence in a temperate marine environment.

Cost to replace fence:

Installation costs	$1.25/ft x 1,200 ft =	$1,500
Material costs	$1.50/ft x 1,200 ft =	$1,800
	$2.75/ft	$3,300

Terminal value (cost):	Salvage value	$ 0
	Cost to remove fence	$ 180
		$180

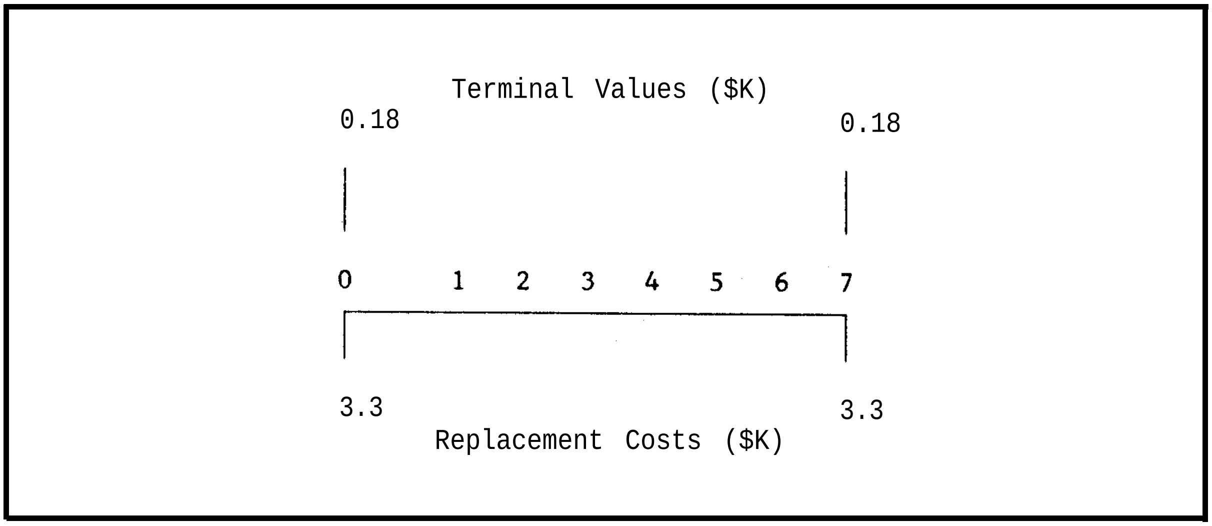


Figure 3-37
Cash Flow Diagram - Galvanized Steel
Chain Link Fence (temperate marine environment)

Alternative 1 (economic life - 7 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$3,300		1.000	$3,300
0	Terminal Value	180		1.000	180
7	Replacement	3,300		0.513	1,693
7	Terminal Value	180		0.513	92
	Total Net Present Value Cost:				$5,265
	Uniform Annual Cost:			$5,265/4.868 =	$1,082

Alternative 2. Vinyl-coated steel chain link fence in a temperate marine environment.

Cost to replace fence:

Installation costs $1.25/ft x 1,200 ft = $1,500
Material costs $1.85/ft x 1,200 ft = $2,220
$3.10/ft $3,720

Terminal value (cost): Salvage value $ 0
Cost to remove fence $ 180
$ 180

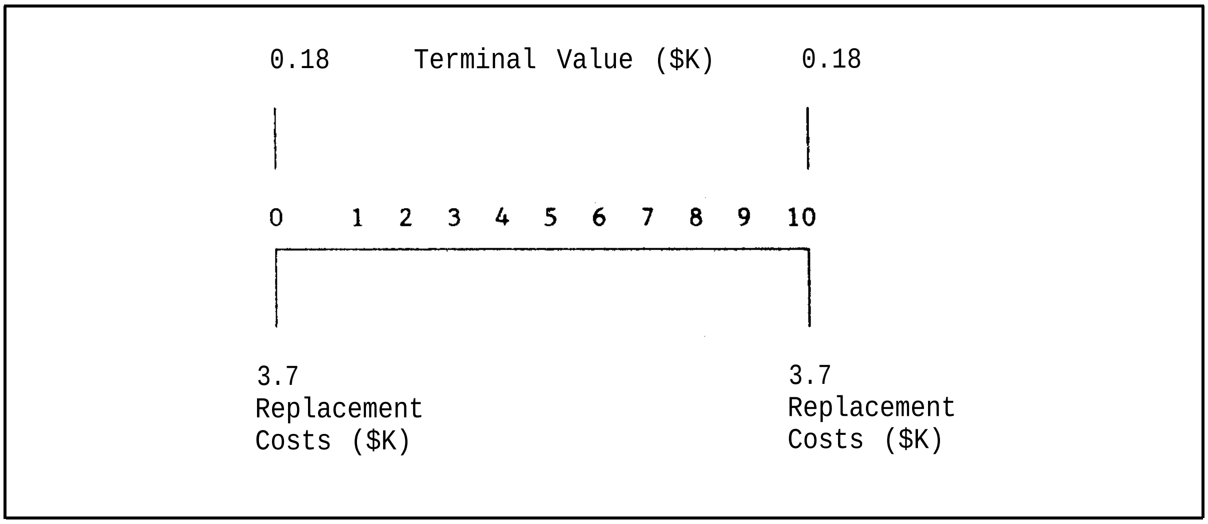


Figure 3-38
Cash Flow Diagram - Vinyl-Coated Steel
Chain Link Fence (temperate marine environment)

Alternative 2 (economic life - 10 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$3,720		1.000	$3,720
0	Terminal Value	180		1.000	180
10	Replacement	3,720		0.386	1,436
10	Terminal Value	180		0.386	69
	Total Net Present Value Cost:				$5,405
	Uniform Annual Cost:			$5,405/6.145 =	$ 880

Alternative 1. Galvanized steel chain link fence in a rural (non-marine) environment.

Cost to replace fence:

Installation costs $1.25/ft x 1,200 ft = $1,500
Material costs $1.50/ft x 1,200 ft = $1,800
$2.75/ft $3,300

Terminal value (cost): Salvage value $ 0
Cost to remove fence $ 180
$ 180

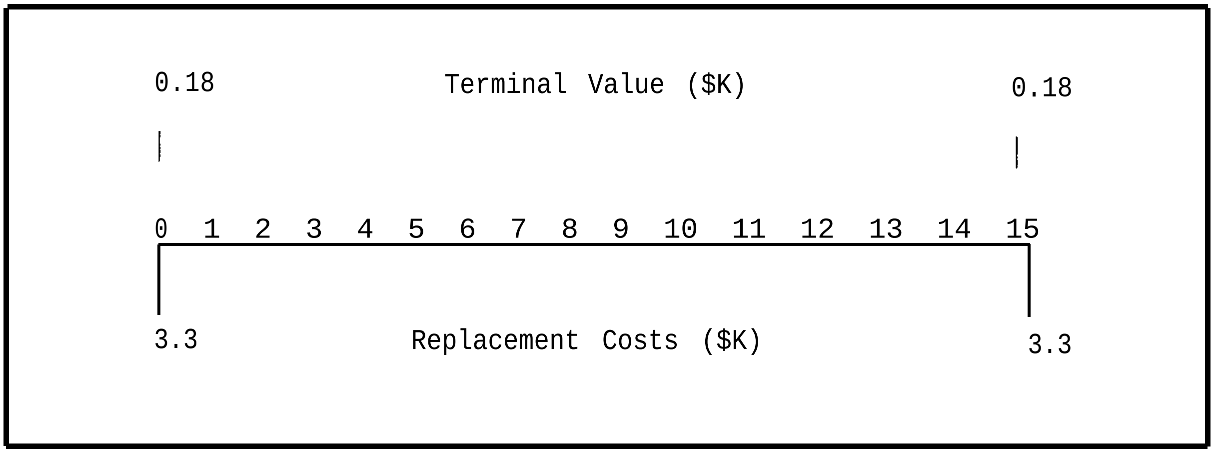


Figure 3-39
Cash Flow Diagram - Galvanized Steel Chain Link Fence in a Rural (non-marine) Environment

Alternative 1 (economic life - 15 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$3,300		1.000	$3,300
0	Terminal Value	180		1.000	180
15	Replacement	3,300		0.239	789
15	Terminal Value	180		0.239	43
	Total Net Present Value Cost:				$4,312
	Uniform Annual Cost:			$4,312/7.606 =	$ 567

Alternative 2. Vinyl-coated steel chain link fence in a rural (non-marine) environment

Cost to replace fence:

Installation costs $1.25/ft x 1,200 ft = $1,500
Material costs $1.85/ft x 1,200 ft = $2,220
$3.10/ft $3,720

Terminal value (cost): Salvage value $ 0
Cost to remove fence $ 180
$ 180

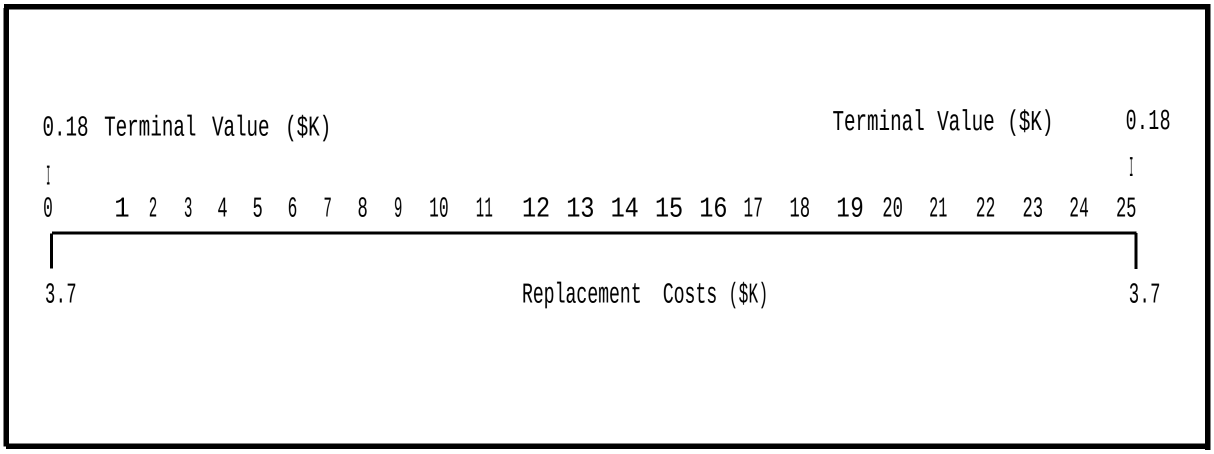


Figure 3-40
Cash Flow Diagram - Vinyl-Coated Chain Link Fence in a Rural (non-marine) Environment

Alternative 2 (economic life - 25 years)

Project Year(s)	Cost Element	Amount		Discount Factor	Discounted Cost
		One-Time	Recurring		
0	Replacement	$3,720		1.000	$3,720
0	Terminal Value	180		1.000	180
25	Replacement	3,720		0.092	342
25	Terminal Value	180		0.092	17
	Total Net Present Value Cost:				$4,259
	Uniform Annual Cost:			$4,259/9.077 =	$ 469

Compare Costs/Benefits and Rank Alternatives

Tropical Marine Environment:

Alternative 1. Net present value: $6,093
Uniform annual cost: $2,450

Alternative 2. Net present value: $6,099
Uniform annual cost: $1,400

Temperate Marine Environment:

Alternative 1. Net present value: $5,265
Uniform annual cost: $1,082

Alternative 2. Net present value: $5,405
Uniform annual cost: $ 880

Rural (non-marine) Environment:

Alternative 1. Net present value: $4,312
Uniform annual cost: $ 567

Alternative 2. Net present value: $4,259
Uniform annual cost: $ 469

In all three environments, a comparison of the uniform annual costs suggest that Alternative 2 is the life cycle cost proposal with the least associated cost. However, for the rural environment, Alternatives 1 and 2 are close economic substitutes.

3.11 ADDITIONAL COMMENTS. The goal of the economic process is to provide quantitative information in an unbiased manner and to provide the decision maker with relevant information. The preceding examples give a baseline from which to start. Actual case analyses will be more complex. Adherence to the six-step economic process, will provide guidance and assure that the goal will be met.

CHAPTER 4. FORMS AND MECHANISMS OF CORROSION

4.1 DRIVING FORCE FOR CORROSION. Most metals used in the construction of facilities are subject to corrosion. This is due to the high energy content of the elements in metallic form. In nature, most metals are found in chemical combination with other elements. These metallic ores are refined by man and formed into metals and alloys. As the energy content of the metals and alloys is higher than that of their ores, chemical re-combination of the metals to form ore like compounds is a natural process.

4.2 FUNDAMENTAL MECHANISM OF ATTACK. Corrosion of metals takes place through the action of electrochemical cells. Although this single mechanism is responsible, the corrosion can take many forms. Through an understanding of the electrochemical cell and how it can act to cause the various forms of corrosion, the natural tendency of metals to corrode can be overcome and equipment that is resistant to failure by corrosion can be designed.

4.2.1 The Electrochemical Cell. As in all chemical reactions, corrosion reactions occur through an exchange of electrons. However, in electrochemical reactions, the electrons are produced by a chemical reaction in one area, travel through a metallic path and are consumed through a different chemical reaction in another area. In some cases, such as the common dry cell battery, electrochemical reactions can be used to supply useful amounts of electrical current. In marine corrosion, however, the most common result is the transformation of complex and expensive equipment to useless junk.

Components. In order for electrochemical reactions to occur, four components must be present and active. As shown in Figure 4-1, these components are the anode, cathode, electron path, and electrolyte.

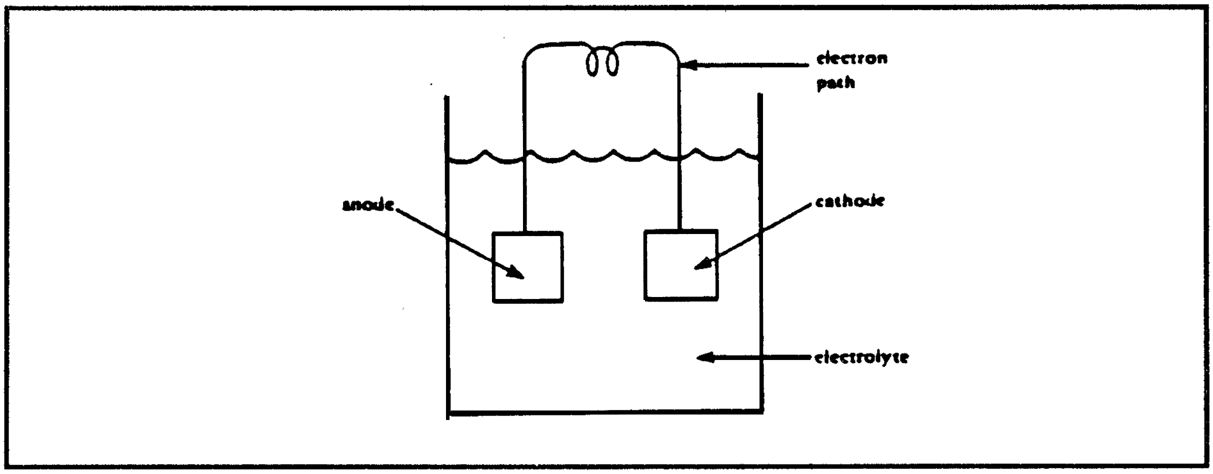


Figure 4-1
Electrochemical Cell

Anode. In an electrochemical cell, the anode is the site where electrons are produced through the chemical activity of the metal. The anode is the area where metal loss occurs. The metal loses electrons and migrates from the metal surface through the environment. The electrons remain in the metal but are free to move about in response to voltage gradients.

Cathode. The cathode in an electrochemical cell is the site where electrons are consumed. For each electron that is produced at an anodic site, an electron must be consumed at a cathodic site. No metal loss occurs at sites that are totally cathodic.

Electron Path. In order for electrons to flow from the anodic sites to cathodic sites, the electrons migrate through a metallic path. This migration occurs due to a voltage difference between the anodic and cathodic reactions. Electrons can move easily only through metals and some non-metals such as graphite. Electrons from electrochemical reactions cannot move through insulating materials such as most plastics nor can they directly enter water or air. In some cases, the electron path is the corroding metal itself, in other cases, the electron path is through an external electrical path.

Electrolyte. Electrolytes are solutions that can conduct electrical currents through the movement of charged chemical constituents called ions. Positive and negative ions are present in equal amounts. Positive ions tend to migrate away from anodic areas and toward cathodic areas. Negative ions tend to migrate away from cathodic areas and towards anodic areas.

Anodic Reactions. Metal loss at anodic sites in an electrochemical cell occurs when the metal atoms give up one or more electrons and move into the electrolyte as positively charged ions.

Typical Reactions. The generic chemical formula for this metal loss at anodic sites is:

$$M^{o} \longrightarrow M^{+} + e^{-}$$

where: M^{o} = uncharged metal atom at the metal surface

M^{+} = positively charged metal ion in the electrolyte

$\mathbf{e}^{-}$ = electron that remains in the metal

This type of chemical reaction is called oxidation even though it does not directly involve oxygen but only results in an increase in positive charge on the atom undergoing oxidation.

More than one electron can be lost in the reaction as in the case for iron where the most common anodic reaction is:

$$Fe^{o} \longrightarrow Fe^{++} + 2e^{-}$$

where: Fe^{o} = metallic iron

Fe^{++} = ferrous ion that carries a double negative charge

Correlation Between Current Flow and Weight Loss. For each specific anodic reaction a characteristic number of electrons are produced in the reaction of one metal ions. Thus, all other things being equal, the metal loss is proportional to the number of electrons that are produced. As the electrons produced migrate to cathodic areas through the electron path, the metal loss is proportional to the current flow. In cases where more positively charged ions are produced, more electrons flow for a given number of corroding metal atoms but the current flow remains proportional to the metal loss.

Cathodic Reactions. The electrons that are produced at anodic sites are consumed at cathodic sites. The type of chemical reactions that consume electrons are called reduction and have the generic chemical formula:

$$R^{+} + e^{-} \longrightarrow R^{o}$$

where: R^{+} = a positive ion in solution

e^{-} = an electron in the metal

R^{o} = the reduced chemical

In reduction, the chemical being reduced gains electrons and its charge is made more negative. In some cases, the where the ion in solution has a multiple positive charge, the total positive charge on the ion may not be neutralized. In other cases, the chemical which is reduced may not be a positive ion but is a neutral chemical which then becomes a negatively charged ion in solution in a reaction such as:

$$R^{o} + e^{-} \longrightarrow R^{-}$$

Reactions in Acidic Solutions. The simplest cathodic reactions occur in acidic solutions. In acids where there are large numbers of hydrogen ions, the reduction of hydrogen is the most common cathodic reaction. The formula for this reaction is:

$$H^{+} + e^{-} \longrightarrow H^{o}$$

Where: H^{+} = positive hydrogen ion in solution

e^{-} = electron

H^{o} = hydrogen atom

In most cases, the hydrogen atoms combine in pairs to form hydrogen gas (H_2), which is often visible as bubbles on the metal surface.

Reactions in Neutral and Alkaline Solutions. In alkaline solutions, there are few hydrogen ions. In such solutions, other cathodic reactions predominate. The most common cathodic reaction in such solutions is the reduction of water. The formula for this reaction is:

$$2\ H_2O + O_2 + 4e^{-} \longrightarrow 4\ OH^{-}$$

In this reaction, two water molecules combine with one oxygen molecule and four electrons to form four hydroxyl (OH^{-}) ions. This reaction requires oxygen and proceeds rapidly when the oxygen content of the environment is high. The production of hydroxyl ions makes the solution in the area of the cathodes more alkaline. Although this is the most common cathodic reaction in seawater or other alkaline environments, other reactions can and will occur, particularly if the amount of dissolved oxygen is reduced.

Overall Reactions. The generic formula for the overall electrochemical reaction is:

$$M^{o} + R^{+} \longrightarrow M^{+} + R^{o}$$

In this formula, the electrons, which are exchanged in equal amounts, are not noted.

Reaction Rates. Most metals tend to corrode in any environment where moisture is present. However, the rate of corrosion can often be controlled to acceptable levels. As electrochemical reactions depend on electron production at the anode, electron conduction through the electron path and electron combination at the cathode, the rate of reaction can be controlled by controlling the reactions at either the anodes or cathodes or by increasing the resistance to the flow of electrons through the electron path.

The site where the electrochemical activity is most limited controls the overall reaction rate.

Polarization. In electrochemical reactions, chemical activity at or near the metal surface can have a significant effect on the reaction rates. These reactions often limit the flow of current in the reactions and result in polarization, or resistance to flow of current across the metal-electrolyte interface.

Formation of Films. The buildup of reaction products is a common cause of polarization. Metal ions buildup at anodic sites and make the formation of more metal ions more difficult. Similar buildup of reaction products, such as hydrogen gas or hydroxyl ions, at cathodic areas inhibit further reactions there. This reduction of reaction rates due to the buildup of reaction products is common in many chemical reactions and is called “the law of mass action.” The law of mass action states that in a generic reaction such as:

$$M^{o} \longrightarrow M^{+} + e^{-}$$

That an excess of materials, which appear on the left of the arrow, will increase the reaction rate whereas an excess of the materials on the right will decrease the reaction rate.

In many environments, polarization at the cathode due to the buildup of hydroxyl ions is a common limiting factor in the rate of corrosion. Under flow conditions, polarization if commonly reduced as the materials causing polarization are rapidly carried away.

Passivity. In some cases the surface of a metal is naturally covered by a film of reaction products. Stainless steels and titanium alloys are resistant to corrosion in many environments due to the presence of such passive films. In the case of stainless steel and titanium, these films are oxides and are naturally formed during the manufacture of the materials. This film causes a high level of polarization and can result in excellent resistance to corrosion. In some environments, however, these passive films can break down and result in localized attack.

Supply of Reactants. Polarization can also be caused by limiting the amount of materials required for reactions that are available at the metal surface. An example of this type of polarization occurs in the typical cathodic reaction in alkaline or neutral solutions:

$$2\ H_2O + O_2 + 4\ e^{-} \longrightarrow 4\ OH^{-}$$

In this case, the availability of oxygen can limit the reaction rate. The availability of oxygen can be affected by both the amount of oxygen dissolved in the electrolyte and by the velocity of flow that provides a continuous source of water that is rich in oxygen.

Seawater as an Electrolyte. Seawater is an excellent electrolyte. The presence of a large amount of dissolved salts, sodium chloride (NaCl), that are ionized make it an excellent conductor. The chloride ions is particularly aggressive as it causes a breakdown of passivity. The chloride ion is also particularly aggressive as most chloride compounds are highly soluble, which limits the formation of polarizing anodic films. Seawater also usually contains enough dissolved oxygen for reducing water to be the prevalent cathodic reaction in most cases.

4.3 FORMS OF CORROSION. Although there is only one fundamental mechanism of corrosion, the electrochemical cell, there are several forms of attack that can occur. Each form of attack has a specific arrangement of anodes and cathodes and the corrosion which occurs has a specific location and pattern. Each form of corrosion can be effectively controlled during design if it is anticipated. By understanding the various forms of corrosion, the conditions under which they occur, and how they are quantified, they can each be addressed and controlled.

4.3.1 Immunity. The first form of corrosion described is the lack of attack, or immunity. This can result from the action of two basic mechanism. Corrosion test measurements that are used to measure very low corrosion rates must be used to validate that corrosion activity is completely absent.

Definition. Immunity is the lack of measurable attack on a metal when exposed to operational environments.

Mechanism. Immunity can result from two basic mechanisms. In the first case, the energy content of the metal is lower (more stable) than any of the corrosion products that could possibly form. Such metals are commonly found in nature as metals that indicates the stability of the metallic state for these elements. Corrosion of such metals where an increase of energy is required will not take place naturally just as a ball will not roll uphill unless pushed. In the second case, there is an energy tendency for the metal to corrode, but corrosion activity is prevented by the presence of a highly stable passive film. Not only must this film be stable in the environment, but it must be able to repair itself by reaction with the environment if it is damaged.

Examples. Gold and platinum are examples of metals that are normally immune in a wide variety of environments due to the low energy content of their metallic state. Titanium and some highly alloyed materials, such as the complex nickel-chromium-molybdenum alloy Hastelloy C-276, have an extremely stable passive film that will repair itself when damaged.

Appearance. A metal that is immune to corrosion in a given environment will not show any change due to corrosion after exposure.

Significant Measurements. Metals that do not corrode are unchanged by exposure to their environment. Their strength, weight, size, shape, and surface finish are unaffected by exposure. To measure very low rates of corrosion, weight loss and other material property measurements may not be sufficiently sensitive. In these cases, the metal is exposed to a small quantity of the electrolyte and the electrolyte is analyzed for the presence of metal atoms from the corrosion process.

4.3.2 Uniform Corrosion. If a metal is not immune to attack and corrosion cannot be completely eliminated, uniform corrosion is considered the form of corrosion that can be tolerated in marine structures and equipment. It is also relatively easy to control uniform corrosion to acceptable levels through judicious selection of materials, the application of corrosion control measures, and to allow for any corrosion which does occur.

Definition. Uniform corrosion is the attack of a metal at essentially the same at all exposed areas of its surface. At no point is the penetration of the metal by corrosion twice as great as the average rate.

Mechanism. Uniform corrosion occurs when there are local anodic and cathodic sites on the surface of the metal. Due to polarization effects, these locations shift from time to time and a given area on a metal will be act as both an anode and as a cathode over any extended period of time. The averaging effect of these shifting local action cells results in a rather uniform attack and general loss of material and roughening of the surface.

Examples. Rusting steel in the atmosphere and the corrosion of copper alloys in seawater are common examples where uniform corrosion is usually encountered. Steel submerged in seawater can also corrode uniformly but can also suffer from non-uniform attack under some circumstances.

Appearance. In uniform corrosion, the metal loss occurs at essentially the same rate over the entire metal surface. Smooth surfaces are usually roughened during uniform corrosion. This form of corrosion is characterized by the lack of any significant non-uniform attack such as pitting or crevice corrosion, which will be described later. Corrosion products commonly remain on uniformly corroding surfaces but these can be removed by velocity, by mechanical action or by other mechanisms.

Significant Measurements. Weight loss is the most commonly used method of measuring the corrosion rate of metals when uniform corrosion occurs. In this method, a test sample is cleaned, weighed, and its surface area is measured. It is then exposed for a specific period of time, re-cleaned and re-weighed. The amount of metal loss as measured by the weight loss is used to calculate the loss in thickness of the metal assuming that the corrosion was absolutely uniform. In some cases this is further verified by thickness measurements. These results are commonly expressed in "Mils per Year" or "Microns per Year." It must be remembered that these rates are usually calculated from weight loss rather than thickness loss and are only valid if the attack was uniform. The maximum error of this measurement is theoretically a factor of two if the rule that attack can be no greater than twice the average rate at any given point is properly applied.

4.3.3 Galvanic Corrosion. When two different metals are electrically connected in an electrolyte, the electrochemical cell formed is called a galvanic cell. This is one of the original forms of electrochemical cell that was discovered and was used to produce direct current electricity in a battery. The dry cell batteries in common use today use the galvanic corrosion of zinc as an anode in conjunction with graphite as a cathode to produce useful electric current. Galvanic corrosion is a similar but undesirable for of electrochemical action.

Definition. Galvanic corrosion is corrosion that is caused or accelerated through the electrical coupling of two or more dissimilar metals that are both immersed in an electrolyte.

Mechanism. As shown in Figure 4-2, galvanic corrosion is caused by classical electrochemical activity. The more active metal acts as an anode. The less active metal acts as a cathode. The rate of attack on the anode is usually controlled by the activity of the cathode or the resistance of the external circuit.

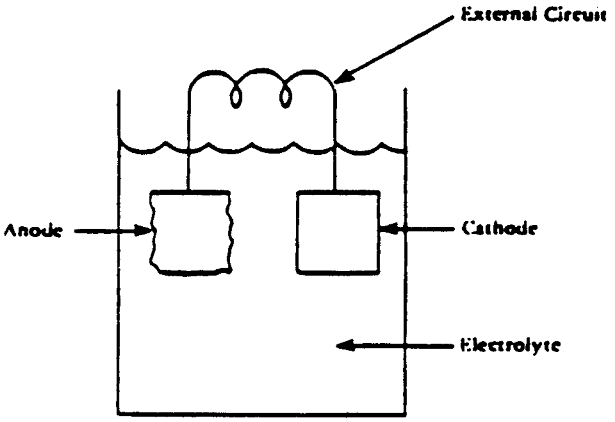


Figure 4-2
Galvanic Cell

The Galvanic Series. The activity of most metals and alloys has been determined both experimentally and through practical experience. In a galvanic series, the metals are listed in order of their activity, usually with the most active metals listed higher in the series. A galvanic series for common metals in seawater is given in Table 4-1. In this series, when coupled with a metal lower in the series, a metal will suffer accelerated attack. The ordering of materials in the galvanic series for a wide variety of environments such as fresh water and soils closely follows their ordering in the galvanic series for seawater.

Galvanic Corrosion Rates. The rate at which galvanic corrosion proceeds can be controlled by the rate of activity at either the anode or the cathode or by electrical resistance of the electron path. The driving force for the reaction is the potential difference between the anode and cathode. This is a function of their separation in the galvanic series. Metals that are close to each other in the galvanic series will suffer less attack than widely separated metals, all other factors remain equal.

In common situations in many environments the limiting factor is the activity at the cathode. Corrosion at the anode will usually occur as fast as the reaction as the cathode can consume the electrons produced at the anode. The relative exposed areas of anodic and cathodic metals in a galvanic cell is a very important factor in the rate at which galvanic corrosion will attack the anodic material. If, as in Figure 4-3, the exposed anodic area is large with respect to the exposed cathodic area, the attack at the anode is limited by the ability of the electrons produced at the anode to be consumed at the small cathode. However, if as in Figure 4-4, the exposed cathodic area is large with respect to the exposed anodic area, the electrons produced in the anodic reaction are easily consumed over the large cathode and the activity is concentrated in a small anodic area. Thus, when the anode is small with respect to the cathode, the most severe attack will occur. The application of protective coatings can affect the effective areas of metals in galvanic cells. If the anode is coated and the cathode is left bare, the effective cathode/anode areas are large and rapid attack can occur at the anode.

Examples. When two or more dissimilar metals are electrically connected and immersed in an electrolyte, galvanic corrosion will occur. As nearly every structure or piece of equipment is constructed of more than one metal, galvanic corrosion is likely to occur. Ships hulls are severely affected by the electrical coupling with their bronze propellers unless corrective action is taken. Aluminum alloys are particularly susceptible to galvanic attack due to their high activity. If isolated, the performance of many of the aluminum alloys is satisfactory, but galvanic corrosion can cause rapid attack, particularly when adverse area ratios are encountered.

Stray electrical currents can also result in what is essentially galvanic corrosion. This is particularly severe where direct currents are involved but can also occur with alternating current. Where the (positive) current leaves the metal and enters the

Table 4-1
Galvanic Series in Seawater

Most Active	Magnesium
	Zinc
	Galvanized Steel (New)
	Aluminum Alloy 7000 Series
	Aluminum Alloy 6000 Series
	Pure Aluminum (99 + %)
	Aluminum Alloy 3000 Series
	Aluminum Alloy 2000 Series
	Aluminum Alloy 5000 Series
	Mild Steel
	Alloy Steel
	Cast Iron
	Monel Alloy 400 (Active)
	Stainless Steel 410 (Active)
	Stainless Steel 430 (Active)
	Solder (60% Pb - 40% Sn)
	Stainless Steel 304 (Active)
	Stainless Steel 316 (Active)
	Stainless Steel Alloy 20-Cb (Active)
	Lead
	Tin
	Muntz Metal
	Manganese Bronze
	Naval Brass
	Nickel (Active)
	Yellow Brass
	Admiralty Brass
	Aluminum Bronze
	Red Brass
	Copper
	Silicon Bronze
	Nickel Silver
	Cupro-Nickel 90-10
	Cupro-Nickel 80-20
	Cupro-Nickel 70-30
	G-Bronze
	M-Bronze
	Nickel (Passive)
	Silver Solder
	Monel (Passive)
	Stainless Steel 410 (Passive)
	Stainless Steel 430 (Passive)
	Stainless Steel 316 (Active)
	Stainless Steel 304 (Passive)
	Stainless Steel Alloy 20-Cb (Passive)
	Silver
	Inconel 625
	Hastelloy C
	Titanium
	Graphite
	Gold
Least Active	Platinum

electrolyte it does so through an anodic reaction. For alternating currents, the current reverses during each cycle. The anodic activity is periodic and partially counteracted while the surfaces are cathodic.

Appearance. Galvanic corrosion can take many forms on the anodic surfaces. It can either be uniform or non-uniform. Very high galvanic corrosion activity can be accompanied with the formation of gas bubbles on both the anodes and the cathodes.

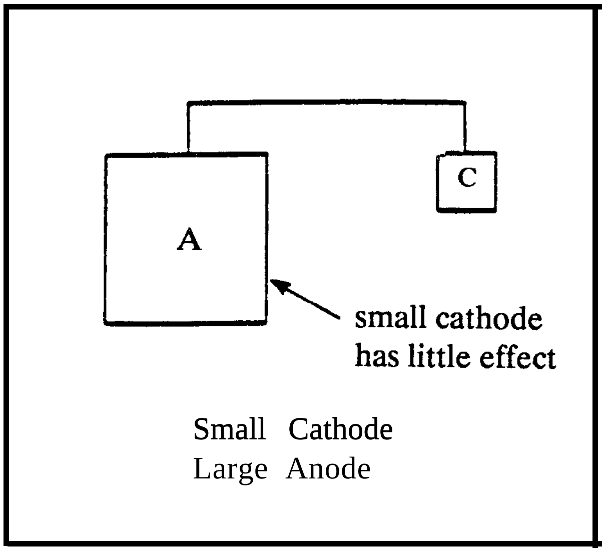


Figure 4-3
Benign Area Relationship

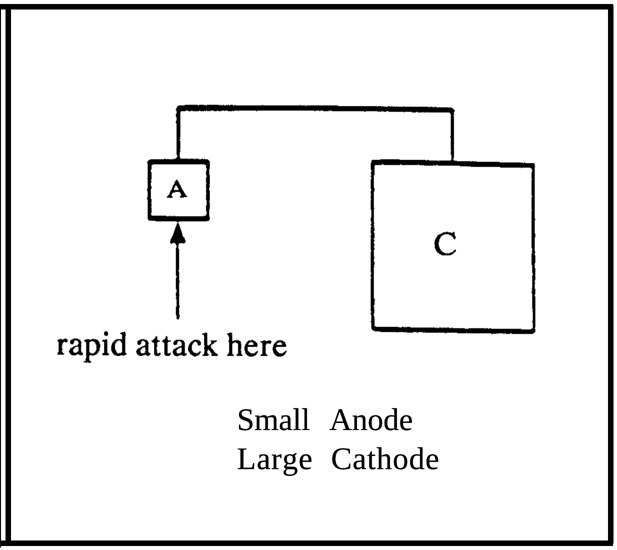


Figure 4-4
Adverse Area Relationship

Significant Measurements. Galvanic corrosion should be measured using a method of measurement appropriate for the distribution of corrosion on the anode. If the attack is uniform, weight loss of coupled metals can be used. If the attack is non-uniform, other methods of measurement must be used. Electrical measurements of galvanic potentials and currents can be used to measure and predict galvanic attack. Relative galvanic potentials can be easily measured using isolated metal specimens. When immersed, the more active metal will have the more negative potential. Absolute potential measurement requires the use of a standard reference electrode which is used to provide a stable potential with which to compare the potential of other metals. Current measurements are made by electrically isolating the metals of concern with the appropriate relative areas and allowing the electrical current to flow through a measuring circuit. Galvanic corrosion rates can then be calculated from the measured current.

4.3.4 **Pitting.** When a metal is susceptible to corrosion and the anodic and cathodic sites on it’s surface tend to remain in the same locations rather than moving frequently as in uniform corrosion, the corrosion tends to be localized in specific areas. This can result in pitting.

Definition. Pitting is the attack of a metal where the corrosion rate is substantially higher at some exposed areas than at others. When the maximum penetration due to corrosion is less than two times the average rate the corrosion is considered to be uniform, when it is greater than two times the average rate, the attack is considered to be pitting.

Mechanism. Pitting is likely to occur whenever anodic and cathodic sites do not move with time. One mechanism which results in pitting is the local breakdown of passive films. As in both stainless steels and aluminum alloys, the metals are covered by a passive oxide film. This film results in the protection of these materials in a wide range of corrosive environments. In marine applications, however, the protective film on many of these alloys will break down and, if damaged, will not be naturally repaired. Where these passive films break down, local anodes will be formed. The surrounding areas are cathodic. In the galvanic series in Table 4-1, this is identified for stainless steels and some other alloys by the (active) and (passive) notations. As can be seen, there is significant difference in potential between the active and passive areas. Also, the area where the passive layers break down is usually a small proportion of the total area and the anode/cathode area ratio is unfavorable. Thus, rapid, localized attack occurs.

Where a difference in environment is found between different areas on a metal, pitting can occur. This is described further under concentration cell corrosion.

Examples. Stainless steels, aluminum alloys, monel, and some copper alloys are susceptible to pitting attack in many environments. Other alloys can exhibit pitting when concentration cells are formed on the metal surface.

Appearance. Pitting can range from broad, shallow cratering where the corrosion rate at the area of deepest penetration is only slightly more than two times average to small deep holes which look as though they have been drilled either mechanically or by a metal eating organism. In many cases, the areas surrounding the pits is essentially unattacked.

Significant Measurements. It cannot be over-emphasized that corrosion rates that are determined by weight loss cannot be used to evaluate pitting. In pitting, the depth of attack is usually much greater than the average corrosion rate. Pitting is normally measured by mechanically measuring the depth of attack. The deepest attack is commonly reported, but the average of the ten deepest pits on a sample is also sometimes reported. The pitting frequency, which is the number of pits per unit area, is also important and should be measured and reported. In some applications, such as an open framework, pitting can be innocuous. In other applications, such as tanks or pressure vessels, the effect of pitting can much more severe than the amount of lost material would indicate.

4.3.5 Concentration Cell Corrosion. As mentioned above, a difference in environment between sites on a single metal can also result in increased electrochemical activity. This difference in environment can be due to non-uniform deposits or fouling on the surface, or, more commonly, built in features which create significant difference in environment. Crevices at joints are the most common cause of these built in environmental differences. This form of concentration cell corrosion called "crevice corrosion" is often the most difficult form of corrosion to avoid in design and also is one of the most common causes of failure of marine equipment.

Definition. Concentration cell corrosion is corrosion that is accelerated by differences in environment between separated areas on a single metal.

Mechanism. Any situation that creates a difference in environment between areas on a single metal can cause concentration cell attack. The basic mechanism is essentially the same as in galvanic corrosion but in the case of concentration cell corrosion the driving force is the difference in potential between a single metal exposed to different environments rather than the difference in potential between two different metals exposed to a single environment. The rates of attack experienced in concentration cell corrosion are affected by relative anode/cathode areas in the same manner as in galvanic corrosion. In crevice corrosion, the resistance of the electrolyte to the flow of ions can also be a significant factor in limiting attack in deep tight crevices.

Oxygen Concentration Cells. Dissolved oxygen has a significant effect on the corrosion of many metals. This is particularly true for alloys such as stainless steels where the corrosion resistance of the alloy is dependent upon abundant oxygen for the stability and self-repair of protective films. Oxygen is also an active participant in the most predominant cathodic reaction in many environments. The oxygen content of the electrolyte inside a crevice is usually low as oxygen is consumed by both corrosion and biological activity and replacement of oxygen inside the crevice is limited. The crevice can be formed by metal-to-metal contact, by contact of a metal with a nonmetal or under deposits of debris or fouling.

For a metal with a passive film, the metal tends to become active within the crevice where the lack of oxygen causes the passive film to be less stable and less easily repaired. The resulting active/passive cell has substantial driving potential as noted on the galvanic series. The anodic area within the crevice is normally small with respect to the cathodic area outside the crevice and with this adverse area ratio, the corrosion inside the crevice can be very rapid. Once initiated, crevice corrosion can also be accelerated by the formation of aggressive chemical compounds within the crevice which further accelerates the attack within the crevice. In the case of stainless steels, the chromium and nickel chlorides which are formed are very acidic and crevice corrosion can be very rapid once initiated.

Oxygen concentration cell corrosion can also occur on metals which do not have passive films. In this case, the difference in oxygen content makes the area with low oxygen content predominantly anodic with respect to more highly oxygenated areas. The reason for this is due to the effect of the law of mass action on the predominant cathodic reaction in neutral and alkaline environments. This reaction is:

$$2\ H_2O + O_2 + 4\ e^- \longrightarrow 4\ OH^-$$

The law of mass action indicates that, where the oxygen content is high, the cathodic reaction will occur more readily than when the oxygen content is low. Thus areas where the oxygen content is low will not be as effective a cathode, anodic reactions will predominate and the area will act as an anode. Where the oxygen content is high, the cathodic reactions will predominate and the area will act as a cathode. Thus, the area inside a crevice will be anodic with respect to the area outside and the same process as described above for active/passive oxygen concentration cells will occur.

Oxygen concentration cell crevice corrosion is particularly insidious. First, many material are susceptible to this form of attack that have otherwise excellent performance in marine environments. Second, the attack often occurs deep inside crevices in sealed areas, in joints, and in fasteners where a very small amount of corrosion can result in a serious failure. Third, as it occurs deep within the crevice, it is difficult to detect. Crevice corrosion of this type often remains hidden until revealed by failure.

Metal Ion Concentration Cells. Differences in concentration of other dissolved materials. In metal ion concentration cells the difference in concentration of metal ions, usually those formed during the corrosion process, cause accelerated corrosion. In crevices or other protected areas, the metal ions produced by corrosion build up to high concentrations. In boldly exposed areas the concentration of these ions is lower due to diffusion and natural flushing of the surfaces. As in the case of oxygen concentration cells, this form of attack is governed by the law of mass action. In this case, it is the anodic reaction that is affected. In the anodic reaction:

$$M^o \longrightarrow M^+ + e^-$$

a buildup of metal ions inhibits the reaction. In areas where the anodic reaction is inhibited, cathodic reactions predominate and those areas become cathodes. In areas where the relative content of metal ions is low, the reaction can proceed freely and those areas tend to become anodic. In metal ion concentration cell attack, it is the areas outside the crevices which are anodic. Thus, in metal ion concentration cell attack, corrosion is concentrated just inside or at the entrance to the crevice. In most configurations, the area outside the crevices is much larger than that inside. Thus the anode/cathode area is more favorable than in oxygen concentration cell attack and the acceleration of attack is less severe.

Other Concentration Cells. Whenever a difference in a factor which affects corrosion occurs between different areas on a metal surface, some form of concentration cell attack can occur. Although less common in marine applications than oxygen and metal ion attack, differences in such factors as temperature, alkalinity and concentration of corrosion inhibitors can result in concentration cells.

Examples. Crevice corrosion of stainless steels in sealed areas, joints and fasteners, and wire rope is perhaps the most common cause of corrosion related failure in marine systems. Most materials are susceptible to concentration cell attack of some kind. Even highly resistant alloys can be affected under certain conditions. Titanium is susceptible to crevice attack in chloride environments at elevated temperatures. Inconel 625 is susceptible if the crevices are tight and deep.

Appearance. Concentration cell attack is usually localized either deep within or at the entrance to crevices. This corrosion often has the appearance of pitting.

Significant Measurements. As in other forms of localized corrosion, weight loss cannot be used to measure concentration cell attack. The severity of environmental differential required to initiate and propagate concentration cell attack is often used to determine the suitability of alloys for particular applications. The tightness and depth of crevices required to allow attack to start is often the factor that is determined. In many cases where crevice attack would result in catastrophic system failure, completely resistant alloys are used. In other cases, as metal ion attack is relatively innocuous, alloys susceptible to metal ion attack are intentionally selected and the design is modified so that the attack that occurs at the entrance to the crevice is not functionally significant.

4.3.6 Dealloying. Most of the commonly used metallic material are alloys formed from mixing two or more metals. Pure metals are usually too soft and weak to be used structurally. In dealloying, corrosion selectively attacks one or more constituent of the alloy mixture.

Definition. Dealloying is the selective corrosive attack of one or more constituent of a metallic alloy.

Mechanism. As can be seen from the galvanic series, constituents of many common alloys have widely separated positions on the galvanic series. In the case of brass, the main constituents are zinc and copper. In the case of cast iron, the main constituents are iron and graphite. When the surface of such alloys is exposed to an electrolyte, galvanic action proceeds with the more anodic material being selectively attacked. In many cases, the cathodic material remains behind and is bound into its original shape by a residue of remaining anodic material and corrosion products. The strength of the remaining material is, however, greatly reduced and will often fail during normal handling. Single phase material, where the alloy constituents are well mixed, are often less susceptible to this form of attack than alloys where phases of largely different composition are present. In many alloys, heat treatments have been developed specifically to make the alloy more homogeneous and less susceptible to dealloying.

Examples. The dezincification of brass and the graphitization of cast iron are common examples of dealloying.

Appearance. In dealloying, the size and shape of the original component is often retained. The remaining constituent is often a different color than the original alloy and the depth and location of attack can be easily identified by this color change. Dealloying can either occur over the entire surface (layering) or localized in pits (plug type).

Significant Measurements. Weight loss is not a significant measurement of the impact of dealloying. The depth of attack must be measured by sectioning and microscopic examination. The impact of dealloying on the strength of the material can be assessed through mechanical testing. In many cases, the depth of attack is self-limiting, particularly in the plug type of attack but the limiting depth is significant, often in the order of 1/4 inch. The fact that there is a limiting depth is significant only for very thick walled sections.

4.3.7 Intergranular Corrosion. Just as most engineering metals are mixtures of one or more metals, they consist of large numbers of individual metal crystals called grains that are joined together at their surfaces or grain boundaries. As there can be differences in composition at or adjacent to these grain boundaries, selective corrosion can occur at these sites.

Definition. Intergranular corrosion is a selective attack of a metal at or adjacent to grain boundaries.

Mechanism. There are three mechanisms that have been identified as causing intergranular corrosion in various situations.

1. The first mechanism is the selective attack of grain boundary material due to its high energy content. Metal crystals form in an ordered arrangement of atoms because this ordered arrangement has a lower energy content than a disordered arrangement. Grain boundaries are highly disordered as they are at the boundaries of crystals which, although they are internally ordered, have random orientation with respect to each other. The disordered grain boundary is often 10 to 100 atoms wide and these atoms have a higher energy than the surrounding atoms. Higher energy material can be more chemically active than lower energy material and thus, the grain boundary material can be anodic with respect to the surrounding grains. When this occurs, the

anodic area is small and the cathodic area is large, thus, rapid attack can occur. The result is that the individual grains are no longer joined with the strong grain boundary "glue" and disintegrate leaving a powdery residue and rough grainy surface.

2. A second mechanism is selective attack of grain boundary material that has a different composition from the surrounding grains. When metals crystallize from the molten state, the crystals tend to be more pure than the molten material. This is because the pure metal crystals are more ordered and have a lower energy content than if they contained large amounts of impurities. In some cases, most of the impurities are concentrated at the grain boundaries. When the composition of this impure material causes it to be more anodic than the surrounding grains, rapid attack can occur with results similar to those described above. When the composition of the impure grain boundary material causes it to be more cathodic than the surrounding grains, the favorable anode/cathode area ratio makes this situation relatively innocuous. Contamination of grain boundaries can sometimes also occur after manufacture. Mercury on aluminum can penetrate and contaminate the grain boundaries and cause subsequent intergranular attack. This is why mercury and mercury compounds are prohibited aboard aluminum ships or on aircraft.

3. A third mechanism is selective attack adjacent to the grain boundaries due to the local depletion of an alloying element. This form of attack can occur in many stainless steels. It is called sensitization. Many stainless steels rely on a combination of nickel and chromium for their corrosion resistance. As both nickel and chromium are expensive, they are added only in amounts necessary to obtain the necessary corrosion resistance. Another element, which is commonly present in ail steels, is carbon. In stainless steels, carbon atoms tend to concentrate at the grain boundaries as an impurity during solidification. Chromium carbides can form adjacent to the grain boundaries during welding and heat treatment. When these compounds form, the chromium is removed from the alloy adjacent to the grain boundaries and the resulting alloy does not have enough chromium content to remain passive. Again, there is a very unfavorable anode/cathode area ratio and rapid attack can occur. Three different methods are used to avoid this type of attack in stainless steels during welding or other heating.

a. The first method to avoid sensitization is through heat treatment. At high temperatures (above 1,800°F), chromium carbides are unstable and will redissolve if they have formed. At low temperatures, (below 1,000°F) the chromium and carbon atoms cannot move and formation of chromium carbides is prevented. Formation of the chromium carbides is a problem primarily in the ranges of 1,100 to 1,600°F. When welding stainless steel, some area adjacent to the weld is likely to reach this temperature range long enough to form amounts of chromium carbides. When this occurs, or when the alloy is otherwise sensitized, it should be heated to temperatures above 1,800°F to redissolve the carbides, then rapidly cooled to below 1,000°F to avoid carbide formation.

b. The second method used to avoid sensitization in stainless steels is to reduce the carbon content of the alloy to very low levels. These low carbon grades (such as 304 L and 316 L; L stands for low carbon) do not have enough carbon to form carbides and is thus resistant to sensitization during welding. Care must be taken, however, to not introduce additional carbon during welding from contamination, such as can be caused by oil or grease.

c. The third method used to avoid sensitization in the stainless steels is to intentionally add an element that will combine with the carbon but is not required for passivity of the alloy. Titanium and niobium have a greater affinity for carbon than chromium. They are added to the alloy during manufacture in amounts to combine with all of the carbon present in the alloy and thus inhibit sensitization. Type 321 stainless steel contains titanium and Type 347 stainless steel contains niobium. These alloys, or the low carbon grades, should be used when welding without heat treatment is required.

Examples. Aluminum alloys are susceptible to intergranular attack, usually the type that is caused by segregation of impurities at the grain boundaries. In addition to the stainless steels, some nickel alloys are also subject to sensitization and subsequent intergranular attack.

Appearance. Intergranular attack caused by high grain boundary energies or impurities at the grain boundaries results in attack with a grainy residue and rough surface. Under high magnification, the individual grains are often visible. Intergranular attack of aluminum alloys is associated with pitting or other localized attack. Sensitization in stainless steels has a similar grainy appearance. When caused by welding it is often localized in narrow bands adjacent to the weld and is sometimes called "knife line attack."

Significant Measurements. Microscopic examination of sectioned samples is often required to verify that intergranular attack has occurred. There are several standardized methods for determining the resistance of stainless steels to sensitization.

4.3.8 Stress Corrosion Cracking. Metals are useful in engineering structures because of their strength, ductility, and durability. Ductility is extremely important as it allows the material to deform in response to loading thus redistributing the stresses. In some cases, however, chemical interactions with the environment can reduce the ductility of metals so that they behave more like brittle materials when subjected to stress.

Definition. Stress corrosion cracking is the intergranular or transgranular cracking of a material due to the combined action of tensile stress and a specific environment.

Mechanism. Even after many years of intensive study, the exact mechanism of stress corrosion cracking remains a matter of extensive disagreement and study. It is commonly attributed to the rupture of protective films at the tips of pits or pre-existing cracks due to the applied stress. In many cases, the materials appear to be totally resistant to corrosion in a given environment until stresses are applied. They then crack catastrophically without any sign of other corrosion attack.

Examples. Many materials, particularly high strength materials, are susceptible to stress corrosion cracking when exposed to a specific environment. For example, cold worked brass, which is found in ammunition cartridges, is susceptible to stress corrosion cracking when exposed to an environment containing ammonia. In chloride containing environments, titanium alloys, aluminum alloys, and high strength stainless steels are susceptible and specific alloys, which are resistant to stress corrosion cracking, should be used. The stresses required to initiate and propagate cracking are often low and many failures occur due to residual stresses rather than applied stress.

Appearance. Stress corrosion cracking must be evaluated using microscopic examination of the cracked sections. The cracking is often branched. Stress corrosion cracking can occur in the presence of other forms of corrosion attack or without the presence of other visible attack.

Significant Measurements. In general, alloys known to be susceptible to stress corrosion cracking should be avoided. In some cases, special heat treatments can minimize the susceptibility to stress corrosion cracking. Many tests have been developed to test the susceptibility of metals to stress corrosion cracking. All of these combine mechanical loading, often in the presence of a pre-existing crack, and exposure to the specific environment of interest. For alloys with limited sensitivity to stress corrosion cracking, critical stresses can be defined below which stress corrosion will not occur. The structural analysis and manufacturing processes required to accommodate these critical stress criteria are often very complex and the use of highly resistant materials is recommended.

4.3.9 Hydrogen Embrittlement. Hydrogen can enter most metals. Due to the small size of the hydrogen atom, it can migrate through the metal structure and cause a loss of ductility similar to that experienced in stress corrosion cracking.

Definition. Hydrogen embrittlement is the severe loss of ductility of a metal when hydrogen has been introduced into the metal structure.

Mechanism. Hydrogen atoms can enter a metal either from hydrogen gas, usually at elevated temperatures, or from atomic hydrogen that is electrolytically formed on its surface. This hydrogen can either reduce the energy required for forming cracks under stress or can accumulate at areas of high stress, such as crack tips, and cause pressure, which directly assists crack propagation. High strength materials in general are the most susceptible to hydrogen embrittlement. Hydrogen can be formed electrolytically during electroplating, during welding when hydrogen is present in the electrode material, in the electrode coating, in the shielding gas, or simply as moisture on the metal surface, or when excessive cathodic protection is applied (potentials more negative than minus 1.2 volts are normally required for significant hydrogen formation by cathodic protection.)

Examples. Ferritic and martensitic (magnetic) steels, particularly those with a yield strength in excess of 130 ksi, are particularly prone to hydrogen embrittlement. Austenitic (non-magnetic) stainless steels are less susceptible. When hydrogen pickup is suspected, such as in electroplating or welding, the hydrogen can be removed by baking at 200 to 300°F. Hydrogen pickup during welding is normally prevented by using low hydrogen electrodes and mild preheating to remove water from the surfaces being welded.

Appearance. Other than catastrophic failure by cracking, there is often no visible evidence of hydrogen embrittlement. In extreme cases, where hydrogen gas bubbles are formed inside the metal, shinny internal blisters are visible at the fracture surface.

Significant Measurements. Analysis of the metal for untrained hydrogen can be used to verify hydrogen embrittlement if heating subsequent to failure has not driven off the hydrogen gas. Due to the difficulty in verifying this form of attack, it is often blamed for other forms of cracking failure, often when simple overload is the actual cause of failure.

4.3.10 **<u>Corrosion Fatigue.</u>** Many materials will exhibit a substantial reduction in fatigue life when exposed to a corrosive environment. In some cases, the reduction is severe, in other cases it is less dramatic, but only a very few materials show a fatigue resistance in a corrosive environments as great as that in dry air.

Definition. Corrosion fatigue is the reduced ability of a metal to withstand repeated stress when exposed to the combined action of stress and a corrosive environment as compared to the effects of stress alone.

Mechanism. Fatigue resistance can be reduced by corrosion activity in many ways. In materials that are susceptible to stress corrosion, fatigue resistance is probably lowered by the rapid propagation of fatigue cracks after they reach the size required for stress corrosion cracking. In materials not susceptible to stress corrosion cracking, corrosion probably enhances crack propagation through direct attack at the crack tips, or by the formation of stress risers such as pits. Corrosion fatigue is usually more severe at low cycling frequency where the longer time to failure allows more corrosion activity to occur.

Examples. High strength steels are susceptible to substantial reduction in fatigue resistance in many environments. The endurance limit (stress below which fatigue failure will not occur) is often reduced by a factor of ten from that measured in air. Cathodic protection can increase the resistance of steels to corrosion fatigue, but care must be taken not to overprotect them as hydrogen embrittlement would then occur. Titanium alloys, which are not subject to stress corrosion cracking, are particularly resistant to corrosion fatigue as are some of the more corrosion resistance nickel alloys, such as Inconel 625 and Inconel 718. Copper alloys and stainless steels are also susceptible to corrosion fatigue with a reduction of one-half in their endurance limit being common.

Appearance. Corrosion fatigue gives a fracture surface similar to ordinary fatigue except that in some cases, corrosion products are present in the outer sections of the cracks.

Significant Measurements. In the simplest corrosion fatigue test, the electrolyte is simply dripped over the surface of a rotating beam fatigue test specimen. In more sophisticated tests, flat specimens are stressed as cantilever beams and only tensile stresses are induced on the surface exposed to the corrosive environment. When cyclic loading is a factor in design, fatigue data from tests that include the corrosive environment must be used.

4.3.11 Erosion Corrosion. When water flows over a metal surface at high velocity, corrosion can be greatly increased over that encountered at low flow velocities.

Definition. Corrosion accelerated by the high velocity flow of a liquid, or a suspension of solid particles in a liquid is known as erosion corrosion.

Mechanism. Flow can increase corrosion in two ways. First, at relatively low velocities, materials, such as oxygen which are required for the corrosion process, are supplied in greater amounts and the metal ions produced are removed from the sites of attack. Thus both the anodic and the cathodic reactions are enhanced and corrosion is increased. Second, at higher velocities, protective films that give many metals their corrosion resistance can be stripped from the surface. This effect is enhanced by the presence of suspended solids in the fluid and by turbulent flow conditions.

Examples. Erosion corrosion is commonly encountered in pipes, pumps, and valves. Conditions that enhance the effect of velocity are sudden changes in the diameter or direction of flow in pipes, a discontinuity such as a poorly fitting gasket or flange in an otherwise smooth surface, or an improperly used valve such as a gate valve used as a throttling valve, which causes localized high velocity and induces turbulence downstream. For materials that are protected by passive films there is often a limiting flow velocity above which the film will be stripped from the surface even under laminar flow conditions and rapid corrosion will occur.

Appearance. Erosion corrosion usually causes characteristic horseshoe shaped pits shaped as shown in Figure 4-5. It is often localized in the areas where turbulence are induced.

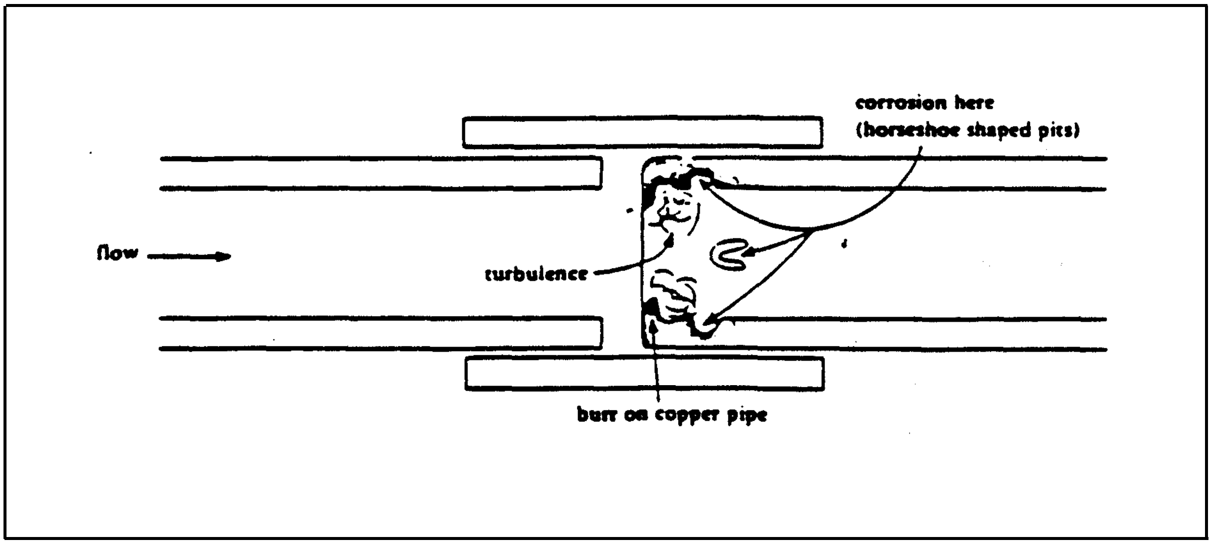


Figure 4-5
Horseshoe-Shaped Pits Created by Erosion Corrosion

Significant Measurements. Limiting flow velocities are often established for common piping materials, primarily based on a combination of experience and testing. For very high velocities such as those experienced in pumps and propellers, impingement tests where a high velocity jet of water impinges on the metal surface have been developed for erosion corrosion testing. In most cases, only those materials that have shown actual experience or actual component tests should be used when high velocity flow is anticipated.

4.3.12 __Cavitation Corrosion.__ Under high velocity flow conditions, particularly when the flow is turbulent, areas of high and low pressure will be induced. In areas of low pressure, gas and vapor bubbles will be produced. When these bubbles move to an area of higher pressure, they collapse and their implosion creates a pressure wave that can remove protective films and cause increased corrosion.

Definition. Cavitation corrosion is corrosion that is enhanced through the formation and collapse of gas or vapor bubbles at or near the metal surface.

Mechanism. As described above, the formation and collapse of gas or vapor bubbles in a liquid can cause localized damage to the films responsible for limiting corrosion. Once this localized corrosion is established, the local roughening can often serve as a new site for further turbulence and more cavitation attack.

Examples. Cavitation is commonly encountered in pumps and in high speed propellers. It is enhanced when entrained air is present in systems with high velocity flow. Cavitation can also occur on or near high intensity sound generators. Stainless steels, some nickel alloys, and titanium alloys are highly resistant to cavitation damage but even these will be attacked under severe conditions.

Appearance. Cavitation corrosion is similar to erosion corrosion and pitting is usually encountered. Cavitation can often be verified by a hydrodynamic analysis that can be used to locate and minimize bubble formation or move the area of bubble collapse to an area where the attack will have a minimal effect.

Significant Measurements. There are no standard tests for cavitation attack. Only through actual full scale tests or from experience can failure due to cavitation be avoided. High velocity flow should be avoided in the design of all systems.

4.3.13 Fretting Corrosion. When surfaces move in relation to each other, this relative motion can result in abrasion. This abrasion can increase the attack at these fraying surfaces.

Definition. Fretting corrosion is an attack that is accelerated by the relative motion of contacting surfaces.

Mechanism. Fretting corrosion is usually a combination of corrosion and abrasive wear. The motion between the surfaces removes protective films and results in accelerated attack. Also, most corrosion products are abrasive and their presence increases the removal of protective films and in direct abrasion of the metal.

Examples. Fretting was common in riveted joints on ships and other riveted structures where cyclic loads were experienced, but this has largely been eliminated through welded construction. Fretting is, however, still encountered in bolted joints and flanges where there is not enough bolt tension to eliminate movement in the joint. Thermal expansion with frequent cycling can also result in fretting attack. Any combination of corrosion and wear will almost always be worse than the action of either one separately.

Appearance. Fretting corrosion usually results in scuffed surfaces in joints or at other wear sites. If inspected soon after the relative motion ceases, the surfaces will often be bright and have corrosion products attached to the surfaces.

Significant Measurements. There are no standard tests for fretting corrosion. When encountered, it is addressed through mechanical design rather than material selection. Where it cannot be eliminated it can sometimes be reduced by using inhibitive caulking compounds in the joints.

CHAPTER 5. METHODS FOR CORROSION CONTROL

5.1 DESCRIPTION OF APPLICABLE CORROSION CONTROL METHODS. There are four basic methods for control of corrosion. They are: (1) Use materials resistant to corrosion, (2) use protective coatings, (3) use cathodic protection, and (4) modify the operating environment.

In most cases, effective corrosion control is obtained by combining two or more of these methods. Corrosion control should be considered at the design stage of a given facility or system. The methods selected must be appropriate for the materials used, for the configurations, and for the types and forms of corrosion which must be controlled.

5.2 USE MATERIALS RESISTANT TO CORROSION. There are no materials that are immune to corrosion in all environments. Materials must be matched to the environment that they will encounter in service. Selecting metallic materials for corrosion resistance is covered in detail in Chapter 8 and selecting non-metallic materials is covered in detail in Chapter 9.

5.3 USE PROTECTIVE COATINGS. Protective coatings are the most widely used corrosion control technique. Essentially, protective coatings are a means for separating the surfaces that are susceptible to corrosion from the factors in the environment which cause corrosion to occur. Remember, however, that protective coatings can never provide 100 percent protection of 100 percent of the surface. If localized corrosion at a coating defect is likely to cause rapid catastrophic failure, additional corrosion control measures must be taken. Coatings are particularly useful when used in combination with other methods of corrosion control such as cathodic protection. The selection and application of protective coatings is covered in detail in Section 7.

5.4 USE CATHODIC PROTECTION. Cathodic protection interferes with the natural action of the electrochemical cells that are responsible for corrosion. Cathodic protection can be effectively applied to control corrosion of surfaces that are immersed in water or exposed to soil. Cathodic protection in its classical form cannot be used to protect surfaces exposed to the atmosphere. The use of anodic metallic coatings such as zinc on steel (galvanizing) is, however, a form of cathodic protection, which is effective in the atmosphere. There are two basic methods of supplying the electrical currents required to interfere with the electrochemical cell action.

The first method uses the corrosion of an active metal, such as magnesium or zinc, to provide the required electrical current. In this method, called sacrificial or galvanic anode cathodic protection, the active metal is consumed in the process of protecting the surfaces where corrosion is controlled and the anodes must be periodically replaced.

In the second method, an alternative source of direct electrical current, usually a rectifier that converts alternating current to direct current, is used to provide the required electrical current. In this system, the electrical circuit is completed through an inert anode material that is not consumed in the process. Section 10 manual covers the application of cathodic protection for corrosion control in detail.

5.5 MODIFY THE OPERATING ENVIRONMENT. Another method of corrosion control often neglected is modifying the operating environment. Using a selective backfill around a buried structure, using corrosion inhibitors in power plant or in engine cooling systems, and modifying structures to provide adequate drainage are all examples of the use of this method of corrosion control. Although best employed during the design stage, in some cases, actions taken to correct corrosion problems through modifying the environment can be taken after a system is built. Careful identification and characterization of corrosion problems will often reveal opportunities for changing the environment to control corrosion. Identification and characterization of corrosion problems is covered in detail in Chapter 11.

CHAPTER 6. COMMON FACILITY CORROSION PROBLEMS AND THEIR REMEDIES

6.1 COMMON CORROSION PROBLEMS. Due to similarities in the missions and locations of many Naval Facilities, many similar corrosion problems are encountered. In this section, these common problems, the mechanisms through which they occur and suggested means for their mitigation are discussed. In all of these cases, the corrosion takes place through the action of the electrochemical cell. In this section, the corrosion problems have been grouped according to the exposure environment.

6.2 ATMOSPHERIC EXPOSURE. A wide variety of structures and equipment are exposed to atmospheric environments at Naval Shore Facilities. Buildings, vehicles, utility systems, fuel storage and distribution systems, and portions of waterfront structures are exposed to atmospheric environments. The atmospheric environment varies drastically with regards to corrosivity depending on the geographical location.

6.2.1 <u>Electrolyte.</u> In atmospheric corrosion, the electrolyte is moisture from precipitation, fog or dew, sea spray, or other sources. The three factors that have the most influence on the corrosivity of the atmosphere at a given site are: (1) the amount of time that exposed surfaces remain wet at the site, (2) the amount of chloride from the sea that reaches the surfaces, and (3) the amount of industrial pollutants (mainly acids) that reach the surfaces. In all atmospheric environments there is an excess of oxygen, thus the corrosion of most metals in atmospheric environments is not limited by the amount of oxygen present and can proceed rapidly when the electrolyte is present.

The corrosivity of the atmosphere varies drastically. The corrosion rate of steel, for example, can vary by a factor of 100. In general, the least corrosive atmospheres are found in dry inland (desert) sites and the most corrosive sites are industrial or industrial-marine sites. Moist tropical locations are very corrosive due both to the time of wetness and the high temperatures experienced. However, local conditions and features of design have an influence on corrosive attack that often exceeds the differences experienced due to geographical conditions. Thus, generalizations regarding specific site corrosivity based on the corrosion of a single metal at a single location at a given site can be misleading. It is not prudent to ignore the possibility of corrosion at a dry inland site nor to consider corrosion inevitable at a marine industrial site. The rates of attack can vary at different sites, but the mechanisms of attack, features that cause accelerated attack and corrective measures that can reduce the attack are similar. Due both to the aggressive nature of moist tropical marine sites and to the large number of Navy activities at such sites, NAVFAC Design Manual DM 11.1, “Tropical Engineering” (Reference 4) gives specific guidance for design and construction of facilities at tropical sites.

6.2.2 <u>Commonly Used Materials</u>. A wide variety of metals are used in atmospheric environments. Steel and aluminum alloys are the most widely used, but stainless steels and copper alloys are also used. In most facilities, several metals are used in combinations. The resultant galvanic corrosion can be significant. As opposed to galvanic corrosion in immersion service, the active area of the galvanic couple in atmospheric exposures is limited to the interface between the coupled metals and the areas just adjacent to the interface, thus the area ratios are roughly equal in most cases.

Protective coatings is the most widely used method of corrosion control in atmospheric environments. If the structure design is proper, protective coatings can give excellent service in most atmospheric environments. Proper design for the successful use of protective coatings includes easy inspection, surface preparation, and coating application as well as avoiding crevices and sharp edges.

Metallic coatings are also used to control corrosion in atmospheric exposures. Hot-dipped zinc coated (galvanized) steel is the most common example of metallic coated metal used in atmospheric exposures.

6.2.3 Structural Features That Lead to Corrosion. Structural features that lead to adverse corrosion in atmospheric exposures are features that trap and hold moisture or debris. Features of this type of corrosion are shown in Figure 6-1 along with suggested alternative designs and corrective modifications.

Features that inhibit the successful use of protective coatings can also cause unnecessary corrosion in atmospheric service.

Galvanic corrosion is usually encountered at joints in atmospheric service and can be due either to coupling of dissimilar metal components, using incompatible fastener materials, or both.

6.2.4 Examples of Corrosion and Means for Control. The following are examples of corrosion problems usually encountered and suggested methods for preventing or avoiding such problems illustrate the various structural features that can lead to attack and offer suggested means for controlling corrosion in atmospheric environments. Table 6-1 contains additional examples of atmospheric corrosion and means for its control.

Galvanic Corrosion. In Figure 6-2, several examples of galvanic corrosion in atmospheric exposures are given. In the uppermost example, two basic problems exist. The first problem is the direct bi-metallic activity between aluminum and brass and between aluminum and steel. The second problem is with the contamination of the aluminum surfaces with corrosion products from the brass that also accelerates the attack of the aluminum. In this case, the problem could have been avoided at the design stage by using aluminum angle iron supports and either a welded joint or by using stainless steel fasteners with a sealant at the interface between the support angle and the aluminum cover. After construction, the problem could be addressed by replacing the brass fasteners with stainless steel, cleaning the brass corrosion products from the aluminum by sandblasting, and applying a sealant between the angle iron and the aluminum cover. It is clear from this example that corrosion is much easier to avoid in the design stage than to correct through modification after construction.

In the middle example a similar problem exists. In this case, either stainless steel or aluminum nails should be used.

Galvanic corrosion of the steel gutter in the bottom example can be controlled by using a material at the joint between the copper and steel. This would exclude moisture from the area where the two metals are adjacent. Either a mastic type coating or sealant would perform adequately provided that the surfaces were properly cleaned. At the design stage, using an all copper system, an all steel (coated) system, or a non-metallic gutter and downspout would have been cost effective.

Effect of Sharp Corners on Paint. Figure 6-3 illustrates how paint draws thin at a sharp corner. Such features can lead to the rapid local failure of protective coatings. Good designs avoid such features, but if they are found after construction, they must be ground to a generous radius and recoated.

6.3 SUBMERGED EXPOSURE. When metals are exposed directly to water or other liquid electrolytes, corrosion is usually more rapid than in atmospheric exposures. The surfaces are continually wet and any electrochemical cells that become active remain active. Galvanic corrosion is often severe in submerged environments as the presence of a bulk electrolyte allows the galvanic currents to affect a large surface area. The effect of adverse anode to cathode area ratios is much more pronounced than in atmospheric environments.

In submerged exposures more methods of corrosion control are applicable than in atmospheric exposures. In addition to using protective coatings, cathodic protection can also be used in many cases.

6.3.1 Electrolyte. Even pure water can serve as an electrolyte and allow corrosion to proceed. In general, electrolytes that are more conductive are more corrosive. Other factors, such as the composition of the dissolved salts in the solution, the acidity or alkalinity of the solution (pH), the types and amounts of dissolved gasses, and the temperature of the environment can also effect corrosion of submerged surfaces. Seawater is an excellent electrical conductor and contains large amounts of chloride ion, which is particularly corrosive.

6.3.2 Commonly Used Materials. Steel, primarily due to its low cost and ease of fabrication, is widely used in submerged service at Navy activities. In nearly all instaces, submerged steel should be protected by protective coatings, cathodic protection, or a combination of coating and cathodic protection.

As the amounts of materials used are often less in submerged service than in atmospheric service, more costly corrosion resistant materials can be considered for submerged service. Stainless steels, copper alloys, and nickel alloys are sometimes used because of their resistance to specific corrosive environments. The properties and selection of such corrosion resistant metals is covered in Chapter 8.

6.3.3 **Structural Features That Lead to Corrosion.** As described above, galvanic corrosion is a greater problem in submerged service than in atmospheric service due to the potential for adverse anode/cathode area ratios.

Concentration cells are also more of a problem in submerged service than in atmospheric exposure. Both oxygen concentration cells and metal ion concentration cells can be active in submerged service.

6.3.4 **Examples of Corrosion and Means for Control.** The following examples of corrosion problems and suggested methods for preventing or avoiding such problems illustrate the various structural and environmental features that can lead to attack. The examples also offer suggestions for controlling corrosion in submerged environments. Table 6-2 lists additional examples of corrosion on submerged surfaces and means for corrosion control.

Galvanic Corrosion. Corrosion of, or around fasteners is a common form of galvanic corrosion in submerged structures. If the fasteners are anodic with respect to the material being joined (steel bolts on a cast iron flange), then rapid corrosion will occur due to the adverse anode/cathode area ratio. If the fasteners are cathodic with respect to the material being joined (Monel bolts on a steel flange), the area ratio is more favorable and the adverse effects of the coupling can be minimal. In the first case, coating the cathodic flanges and piping would reduce the attack. Cathodic protection could also control corrosion of the assembly in both cases.

Concentration Cell Corrosion. Figure 6-4 shows an example of differential aeration corrosion in a sheet steel bulkhead tieback system. This can be prevented by using a sealant in the crevice area and a coating on the tie rod, channel, and piling in the area of the tie rod attachment.

Figure 6-5 shows the distribution of corrosion on steel structures immersed in seawater. The corrosion versus depth profile in the submerged area is due to a differential aeration cell. The high availability of oxygen at the intertidal area makes this zone cathodic with respect to the zone just beneath the mean low tide level where the corrosion is high. A similar but less dramatic effect also occurs at the mud line. To protect steel in waterfront structures, protective coatings can be used in the atmospheric zone and in the intertidal zone. The coating in the intertidal zone will reduce the attack just below low tide by covering the cathodic intertidal zone. Cathodic protection can effectively prevent corrosion in the submerged zone and is particularly effective when used with a factory applied coating on the piling. It is, however, usually more cost effective to cathodically protect an existing bare steel structure in the continually immersed zone than to attempt to coat the structure using expensive underwater coatings.

Figure 6-6 shows a method for repairing a damaged piling. Great care must be taken to insure that the lower seal is completely effective in isolating the inside of the jacketed area from the area outside. Unless complete isolation is achieved, a concentration cell will form and result in accelerated attack of the piling at the bottom of the jacket. A similar effect can occur when a concrete jacket is used for damage repair. In these cases, it is advisable to use the jacket as a means for controlling corrosion in the intertidal zone and to provide protection in the submerged zone. Using cathodic protection will control corrosion in the continuously submerged zone and prevent concentration cell attack at the poorly isolated jackets.

6.4 WATERSIDE (PIPING)

6.4.1 Electrolyte. As described above, water is the most common electrolyte responsible for corrosion. Even pure water can be corrosive. In fuel systems, water can collect a low points in the system and, particularly where microbial action leads to an increase in corrosivity of the water, accelerated corrosion can occur. In some cases, the corrosivity of the liquids in the systems can be reduced by adding corrosion inhibitors.

6.4.2 Commonly Used Materials. Steel is the most common material for piping systems. Cast iron is also used in pipes, valves, and pumps. Copper alloys are used for small diameter piping systems and in heat exchanger tubes.

As the amounts of materials used are often less in submerged service than in atmospheric service, more costly corrosion resistant materials can be considered for submerged service. Stainless steels, copper alloys, and nickel alloys are sometimes selected for their resistance to specific corrosive environments. The properties and selection of such corrosion resistant metals is covered in Chapter 8.

6.4.3 Structural Features That Lead to Corrosion. In piping systems, flow velocity and turbulence can have a significant effect on corrosion. In some cases, such as steel, where the corrosion resistance of the metal is not due to the presence of a passive film, corrosion rates can be roughly proportional to flow rate. In other cases, such as copper piping, where a passive film is responsible for the corrosion resistance of the metal, the corrosion rates are low at low velocity, but if a critical velocity limit is exceeded, the corrosion rate becomes high.

6.4.4 **Examples of Corrosion and Means for Control.** The following are examples of commonly encountered corrosion problems and suggested methods for preventing or avoiding such problems. These examples also illustrate the various structural and environmental features that can lead to attack and offer suggestion for controlling corrosion in piping systems. Table 6-3 contains additional examples of the corrosion of piping systems and means for corrosion control.

Galvanic Corrosion. Figure 6-7 is an example of galvanic corrosion between the copper heating coils and the steel tank that can be prevented by electrically isolating the coils from the tank. While coating the copper coils would improve the anode/cathode area ratio and reduce the amount of attack, copper alloys are difficult to coat and the geometry of the coils would also make coating difficult. The steel tank should not be coated unless the coils are isolated from the tank as the ratio of exposed cathodic copper to the steel exposed at coating defects would be particularly adverse. Cathodic protection using either sacrificial anodes or an impressed current system could also reduce the impact of the galvanic attack in this situation.

Mating steel and copper pipes as shown in Figure 6-8 should be avoided. If the pipe material cannot be changed, then use an isolating flange or non-metallic coupling to prevent the galvanic corrosion that will otherwise cause rapid failure of the steel pipe at the joint.

Concentration Cell Attack. In addition to attack at crevices or flanges, the accumulation of debris corrosion products over an active corrosion site can also create a concentration cell as shown in Figure 6-9. Cleaning and cathodic protection can be used to prevent this type of attack.

Velocity Related Attack. As shown in Figure 6-10, many features can lead to either a high velocity flow in a system or turbulence. These situations should be avoided as high velocities are always undesirable from the stand point of corrosion.

6.5 UNDERGROUND. Corrosion of buried structures is of particular importance at Naval shore activities. The facilities that are buried (utility and fuel systems, etc.) are needed to provide critical Fleet support and in the case of fuel systems, the environmental consequences of failure can be significant. Corrosion of buried structures is often accelerated by stray electrical currents and differential environmental cells. Due to the difficulty in inspecting buried structures many are never inspected until they are removed from service or fail.

Cathodic protection, usually combined with protective coatings, is the most widely used means for controlling underground corrosion. Cathodic protection not only can effectively control corrosion on buried structures, periodic confirmation of the proper operation of the cathodic protection system through electrical inspections can be used to infer the condition of the buried structure.

Table 6-4 contains additional examples of the corrosion of underground systems and means for corrosion control.

6.5.1 Electrolyte. Soils contain mineral matter, organic matter, water, and air. The electrical conductivity of the soil can be affected by many factors but the amount of water and the soluble salts in the mineral and organic matter have the greatest effect. The resistivity of soils is conveniently measured using the four pin method shown in Figure 6-11. In general, a soil with low resistivity will be more corrosive than a soil with high resistivity, but substantial corrosion can still occur in high resistivity soils under certain conditions. High soil resistivity should not be used as the sole criteria for determining the necessity to control corrosion on buried structures.

6.5.2 Commonly Used Materials. Steel is the most commonly used material for buried structures. Cast iron is also used in buried pipes and valves. Aluminum is sometimes used underground for fuel lines where internal corrosion from steel lines would cause unacceptable fuel contamination. Lead is often used as an outer sheath on buried communication lines.

6.5.3 Structural Features That Lead to Corrosion. Stray currents and differential environments are the most common features that cause corrosion of buried structures. As shown in Figures 6-12, 6-13 and 6-14 there can be many causes for the establishment of differential environments on a buried structure. The proper routing of pipelines and using appropriate fill are both important in reducing environmental differences on buried structures. Even when cathodic protection is used, a uniform environment around the buried structure should be provided both to reduce the amount of current needed for protection and to improve the distribution of the protective current and reduce the likelihood of rapid damage if the protective current should be interrupted. Sources of stray currents shown in Figures 6-15, 6-16, and 6-17 can cause rapid corrosion damage if not properly mitigated.

6.5.4 Examples of Underground Corrosion and Means for Control. Cathodic protection is, as described above, the most effective means for controlling underground corrosion. The application of corrosion control to underground structures is covered in detail in Chapter 10.

TABLE 6.1
Structures Exposed to Atmospheric Corrosion

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Automotive Equipment	Failure of coatings because of exposure to atmosphere (salt air and industrial atmosphere).	Iron and steel, small quantities of lead, copper, and magnesium.	Maintain paint coatings and wax film. Store under cover. Grease lead battery fittings with vaseline. Establish a preventive maintenance program.
Buildings, exterior: Roof gutters, corrugated roofing, leader pipes, window frames, and vent flashing.	Exposure to atmosphere (salt air and industrial atmosphere) and trapped moisture.	Steel, aluminum, and copper.	Use galvanized steel, aluminum, or copper. Apply paint coatings. Eliminate moisture traps.
Buildings, interior: Hardware	Exposure to atmosphere or to steam or industrial vapors; handling.	Steel, brass, bronze, and plastic.	Use brass, bronze, or plastic materials. Apply coatings lacquer, paint, or wax).
Piping	Condensation on exterior of pipe (cold water).	Steel, galvanized steel, cast iron, and copper.	Wrap pipe or use copper pipe (with red brass fittings).
Structure Members	Exposure to atmosphere or to other vapors.	Steel	Apply paint coatings; exhaust vapors to outside of building.
Pole Lines and Pole Line Hardware	Exposure to atmosphere (salt air or industrial atmosphere) or dissimilar metal couples.	Steel, copper, aluminum, and brass.	Use galvanized steel, alclad aluminum, copper-clad steel, or other protective coating. Avoid dissimilar metal couples.
Electrical and Radio Gear	Exposure to atmosphere, high relative humidity, flooding, or dissimilar metal couples.	Steel, copper, brass, lead, aluminum, and silver.	Apply paint coatings to steel. Use heaters to keep dry. Drain manholes and vaults. Ventilate and seal enclosures. Avoid dissimilar metal couples.

(Continued)

TABLE 6.1 (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Towers and Cranes	Exposure to atmosphere, trapped moisture, or electrolysis.	Steel	Use galvanized steel. Apply and maintain paint coatings. Eliminate nature moisture traps. Ventilate properly.
Utility Buildings	Exposure to atmosphere or to steam or other vapors, trapped moisture, or inadequate ventilation.	Steel and aluminum.	Use galvanized iron or steel, or aluminum. Apply and maintain paint coatings. Eliminate moisture traps. Ventilate properly.
Electrical Equipment	Exposure to atmosphere, high relative humidity, oxygen in cooling water, flooding in vaults, and electrolysis.	Steel and copper.	Apply and maintain paint coatings on exterior. Use inhibitors in cooling water. Drain vaults and manholes. Use heaters to keep dry. Ground equipment.

TABLE 6.2
Submerged Structures

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Steel Piling	Soil corrosion, different types of soil, different types of waters in estuaries, chemical pollution, differential oxygen content, splash zone, atmospheric corrosion, and stray current.	Steel or steel with concrete capping.	Use a corrosion-resistant jacket in the splash zone that will not create any serious galvanic couple with the piling. Paint piling in the atmospheric zone. Use a bituminous coating on portion of piling encased in concrete capping when capping is in contact with water or soil. Apply cathodic protection under water and under ground portion of piling. Drain stray current if present.
Steel Piles (Cellular)	Soil corrosion, different types of waters in estuaries, chemical pollution, differential oxygen content, splash zone, atmospheric corrosion, and stray current.	Steel or steel with concrete capping.	Paint piers in the splash end atmospheric zones. Apply cathodic protection to structures below water. Use a bituminous coating on portion of piling encased in concrete when capping is in contact with water or soil. Bond all sheet piling to the negative bus to assure complete drainage of cathodic protection currents. Drain stray current if present.
Steel Piers (H-Piling)	Soil corrosion, different types of waters in estuaries, chemical pollution, differential oxygen content, splash zone, atmospheric corrosion, and stray current.	Steel or steel with concrete capping.	Paint piling in the atmospheric zone. Use a corrosion-resistant jacket in the splash zone that will not create any serious galvanic couple with steel piling. Apply cathodic protection to piling below water surface. Drain stray current

(continued)

TABLE 6.2 (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Steel Piers (H-Piling) (cont'd)			if present. Use a bituminous coating on the portion of piling encased in concrete capping when capping is in contact with water or soil. Bond all piling to the negative bus of the cathodic protection system.
Sheet-Piling Bulkheads	Soil corrosion, different types of water is estuaries, chemical pollution, differential oxygen content, splash zone, atmospheric corrosion, and stray current.	Steel or steel with concrete capping.	Paint piling in the atmospheric and splash zones. Apply cathodic protection to portions of the structure below water surface. Use a bituminous coating on the portion of piling encased in concrete capping when capping is in contact with water or soil. Bond all sheet piling to the negative bus of the cathodic protection system. Drain stray current if present.
Barges and Other Floating Structures	Atmospheric and sea water corrosion, splash zone, chemical pollution, differential oxygen content, and dissimilar metals.	Steel, bronze, and brass fittings.	Paint structures in accordance with Chapter 7 of this publication. Apply cathodic protection in conjunction with approved paint system to submerged portion of structure. Avoid dissimilar metals.
Salt Water Intake Lines, Flumes, and Intake Screens	Atmospheric corrosion, chemical pollution, splash and submerged zones, differential oxygen content, and dissimilar metals.	Steel, cast iron, and bronze.	Galvanize all steel and cast iron. Paint structures in accordance with Chapter 7 of this publication. Avoid dissimilar metals. Apply cathodic protect ion.

(continued)

TABLE 6.2 (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Drydocks, Caission Gates, and Lock Gates	Atmospheric corrosion, chemical pollution, splash and submerged zones, differential oxygen content, and dissimilar metals.	Steel, cast iron, and lead.	Paint structures in accordance with Chapter 7 of this publication. Apply cathodic protection to submerged portions of structures. Avoid the use of dissimilar metals without proper precautions.
Intake Flumes and Screens	Oxygen, turbulence, high velocity, and marine organisms.	Steel, cast iron, brass, and copper alloys.	Streamline flow characteristics. Limit velocity. Install cathodic protection. Use heavy galvanized steel or cast iron.
Seadrome Lighting and Harbor Installations	Atmospheric corrosion, chemical pollution, splash and submerged zones, differential oxygen content, and dissimilar metals.	Steel	Paint structures in accordance with Chapter 7 of this publication. Apply cathodic protection to submerged portions of structures. Avoid dissimilar couples.
Ships (Inactive)	Atmospheric corrosion, chemical pollution, splash and submerged zones, differential oxygen content, and dissimilar metals.	Steel, bronze, and brass.	Paint structures in accordance with Chapter 7 of this publication. Apply cathodic protection to submerged portions of ship. Avoid use of dissimilar metal couples.
Ships (Active)	Atmospheric corrosion, chemical pollution, splash and submerged zones, differential oxygen content, and dissimilar metals.	Steel, bronze, and brass.	Paint structures in accordance with Chapter 7 of this publication. Apply cathodic protection to submerged portions of ship. Avoid use of dissimilar metal couples.

(continued)

TABLE 6.2 (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Texas Towers and Other Stationary, Cylindrical Piling	Atmospheric corrosion, chemical pollution, splash and submerged zones, differential oxygen content, and dissimilar metals.	Steel	Paint structures in accordance with Chapter 7 of this publication. Protect legs of towers in splash and tidal zones with a corrosion-resistant protective jacket that will not create any serious galvanic couple with the structure. Avoid dissimilar metal couples. Apply cathodic protection to submerged portions of structures.

TABLE 6.3
Waterside Piping

Power Plant Equipment

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Boilers	Oxygen, carbon dioxide, and high causticity.	Steel	Install and maintain deaerators. Establish correct chemical treatment for boiler water and maintain properly. Maintain alkaline pH of boiler water. Used welded tanks rather than riveted tanks. Repair minor leaks immediately to avoid caustic embrittlement. Install cathodic protection.
Condensers	Oxygen, carbon dioxide, excessive turbulence, high temperature, and stress.	Steel, Muntz metal, Admiralty metal, red brass, copper, aluminum - brass and copper nickel.	Streamline water boxes, injection nozzles, and piping. Avoid sharp angular changes in direction, low-pressure pockets, and obstructions. Use propeller-type circulating pumps. (Seal pump glands to prevent air intake.) Limit water velocity to 5-7 fps. Use lowest possible operating temperature. Remove dissolved air or gases from liquid. Use stress-reliever materials and support adequately to prevent vibration and cyclic stresses. Use proper copper alloys for liquids involved. Install cathodic protection.

(continued)

TABLE 6.3. Continued

Aboveground Structures Containing Electrolytes

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Pumps	Oxygen, carbon dioxide, and dissolved minerals, turbulence, caviation, stress, high velocity, dissimilar metal couples, high temperatures, foreign materials, and electrolysis.	Cast iron, cast steel, brass, bronze, and copper.	Deaerate fluid and streamline flow. Relieve stresses. Use lowest velocity and temperatures possible. Avoid dissimilar metal couples. Use high silicon cast iron.
Hot Water Storage Tanks	Oxygen and dissolved minerals, dissimilar metal couples, excessive temperatures, and contamination of water by copper.	Steel and galvanized steel.	Avoid copper piping on inlet side of tanks. Avoid dissimilar metal couples. Use heavy-grade or galvanized tanks. Apply cathodic protection. Use glass or vitrified tanks.
Process Tanks and Vessels	Oxygen, temperature turbulence, velocity, aeration, moisture contamination, acids, and dissimilar metals.	Steel, nickel alloys, nickel-chromium alloys, copper alloys, synthetic rubbers, plastics, ceramics, glass, lead, aluminum, tin, high silicon cast iron, and carbon.	Depending on process involved, use proper materials and coating system to resist corrosion. Closely control operation and maintenance to prevent changing conditions that could increase corrosion rate. Use ceramics, synthetics, glass, and plastics for electrical insulating properties. Apply cathodic protection.
Sewage Disposal Plants	Acid condition of sewage (low pH), exposure to atmosphere, dissimilar metals, temperature, and aeration.	Steel and concrete.	Treat sewage to alkaline pH. Apply paint coatings to metal above sewage lines. Apply cathodic protection.

(continued)

TABLE 6.3. (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Surface Condensers	High temperatures, velocity, acidity, oxygen concentration, dissolved minerals, and dissimilar metals.	Steel, Muntz metal, Admiralty metal, red brass, copper, aluminum - brass, and copper-nickel.	Use lowest temperatures and velocity possible. Use inhibitors in cooling waters, deaerate, and add chemicals to make water alkaline. Use electricity insulated parts. Apply cathodic protection.
Water Storage Tanks, Surface and Elevated	Oxygen and dissolved minerals, exposure to atmosphere, dissimilar metals, galvanic cells, and corrosive water.	Steel, concrete, and wood.	Treat water. Apply paint coatings to interior and exterior. Apply cathodic protection to interior of all metal tanks and to bottom of surface metal tanks. Place surface tanks on pad of clean sand oiled with sulfur-free oil.
Water Treatment Plants (including flocculators and sedimentation basins)	Dissolved minerals and gases, water treatment chemicals, dissimilar metals, galvanic cells, and concrete-coated steel.	Steel, cast iron, concrete, copper, brass, bronze, babbitt, and galvanized steel.	Paint or coat metal parts. Avoid the use of dissimilar metals. Use cathodic protection when applicable. Treat water to remove minerals. Use insulating materials.

TABLE 6.4
Underground Structures

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Buried Power, Communication, and Fire Alarm Cables	Corrosive steel and water, stray, long-line, and galvanic currents.	Lead sheath, neoprene or or plastic jacket, and parkway cable.	Drain soil water when possible. Apply cathodic protection. Drain stray current if present. (Supply negative return for ground currents.) Use insulating sections in sheath over rubber-insulated cables. Use asphalt-impregnated-jute coverings. Avoid dissimilar metal couples. Use clean sand backfill.
Power, Communication, and Fire Alarm Cables in Duct	Corrosive water, stray, long-line, and galvanic currents.	Lead sheath and neoprene or or plastic jacket in fiber ducts or steel conduit.	Drain water when possible. Drain stray current if present. Use a corrosion-resistant sheath such as neoprene or plastic and use insulating sections in the cable sheath. Use a corrosion-resistant jacket over lead sheath. Avoid dissimilar metal couples. Make conduit continuously conductive and bond cable sheath to it. Apply cathodic protection.
Domestic and Fire Protection Water Distribution Systems	Corrosive soils, bacteria, different soil types or electrolytes, concentration cells, dissimilar metals, and stray or long-line currents.	Steel, cast iron, asbestos-cement, copper, lead, brass, bronze, Monel metal, and stainless steel.	Use asbestos-cement pipe in very corrosive soils when pressure and surges do not exceed rating of pipe. Select backfill with proper drainage. Avoid using dissimilar metals. Use insulating joints between dissimilar metals and different soil types. Use proper coatings. Drain stray current if present. Apply cathodic protection when possible.

(continued)

TABLE 6.4. (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Gas Distribution Systems	Corrosive soils, bacteria, different soil types or electrolytes, concentration cells, dissimilar metals, and stray or long-line currents.	Cast iron, steel, bronze, and lead.	Use proper coatings. Select backfill with proper drainage. Apply cathodic protection. Drain stray current if present. Avoid using dissimilar metals. Use insulating joints between dissimilar metals, different soil types, and other structures.
Exterior Steam Lines and Returns	Corrosive soils, different soil types, concentration cells, dissimilar metals, stray or long-line currents, and bacteria.	Steel, wrought iron, cast iron or bronze valves, vitrified tile, concrete vermiculite filler, asbestos-cement, natural asphalt, or resinous hydrocarbon.	Use proper coatings. Use sand backfill with good drainage. Apply cathodic protection. Drain stray current if present. On metal-cased lines, coat seal and vent casings, and apply cathodic protection. Drain steam tunnels and conduit casings. Avoid dissimilar metal couples. Install insulating joints.
Compressed Air Distribution System	Corrosive soils, dissimilar metals, concentration cells, stray and long-line currents, and bacteria.	Steel, bronze, and brass valves, and copper.	Use coatings or galvanized steel. Select backfill with good drainage. Apply cathodic protection. Drain stray current if present. Avoid dissimilar metal couples. Install insulating joints to reduce galvanic currents.
Underground Fuel Oil Tanks and Piping, Other Buried Tanks, and Avgas Storage and Distribution Systems	Corrosive soils, concentration cells, stray and long-line current, bacteria, and dissimilar metals.	Steel, brass, or bronze valves valves, and copper piping.	Apply coating and wrapping in accordance with Chapter 7 of this publication. Select a backfill with good drainage, clean sand if possible. Avoid dissimilar metal couples. Apply cathodic protection. The hazards of certain products, such as avgas and other volatile or

(continued)

TABLE 6.4. (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Underground Fuel Oil Tanks, etc. (cont'd)			combustible liquids, require that every precaution be taken to assure complete protection and reduce hazards to personnel.
Tank Bottoms in Contact with the Ground	Corrosive soil and differential moisture content and/or differential oxygen content of soil between center portion of bottom and outer portion.	Steel and prestressed concrete.	Install tank bottoms on a sand pad impregnated with a sulfur-free oil. Sand should be well drained. Asphalt paving also makes a good tank foundation. Apply cathodic protection to tank bottoms. Drain stray current if present. Prestressed concrete tanks may present special corrosion problems on the tension members.
Metallic Sewers	Soil corrosion, dissimilar soil types, stray and long-line currents, dissimilar metals, concentration cells, bacteria, and sewer gases inside pipe.	Steel and cast iron.	Use heavy-grade cast iron soil pipe dip-coated with coal tar enamel. Bond across all joints in cast iron pipe with a bond wire where cathodic protection is applied. Avoid using vitrified clay fitting with metallic piping. Apply good bituminous coating both inside and outside of pipe. Avoid dissimilar metals. (Concrete-covered steel pipe can be used; however, it must not connect to bituminous-coated or bare pipe.) Prestressed concrete pipe may present special corrosion problems on the tension members. Concrete lining can be used if the upper portion is coated with chlorinated rubber paint to prevent attack by sewer gas. Drain stray current if present.

(continued)

TABLE 6.4. (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Metallic Culverts	Soil corrosion, erosion, stray current, concentration cells, and bacteria.	Steel	Use galvanized steel and/or a bituminous coating. Use clean sand backfill. Apply cathodic protection. Drain stray current is present.
Deep Wells	Soil corrosion, bacteria, long-line currents from different soil strata, stray currents, dissimilar metals, and concentration cells.	Steel and steel alloys.	Isolate well from surface piping by using an insulating joint. Use cathodic protection. Drain stray current if present. Use corrosion-resistant steel alloys in very corrosive soils.
Salt Water Lines	Soil corrosion, long-line currents from different soil strata, stray currents, dissimilar metals, and concentration cells.	Steel and cast iron.	Use coatings and clean sand backfill. Apply cathodic protection. (On cast iron, bond across pipe joints with bond wire.) Drain stray current if present. Avoid dissimilar metal couples.
Tower Footings	Soil corrosion, different soil types, and stray and galvanic currents.	Galvanized steel.	Set tower footings in concrete. Tower footings may be given a bituminous coating before being set in concrete. The tower structure should be grounded by using magnesium or zinc anodes. Anode grounds should be made where the soil resistivity is low. Apply cathodic protection to tower footings in soils of low resistivity. Avoid connecting towers together that are in different soil types, by use of ground wire. The ground wire can be sectionalized at boundaries of different soil types.

(continued)

TABLE 6.4. (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Building Columns	Soil corrosion, different soil types, and stray, long-line, and galvanic currents.	Steel and concrete.	Set Column footings in concrete. Apply cathodic protection. Use a bituminous coating.
Electrical Grounding Systems	Soil corrosion and stray, long-line, and galvanic currents.	Copper, galvanized steel, and and zinc.	Avoid dissimilar metal couples. Use insulating joints and insulated wire.Apply cathodic protection. Drain stray current if present.
Sheet Piling, H-Piling, and Reinforcing Rods	Soil corrosion, different soil types, differential moisture and oxygen in soil, dissimilar metals, and bacteria.	Steel	Use protective coatings and painting. Apply cathodic protection. Avoid use of dissimilar metals. Use insulating sections. Drain stray current if present.
Propane and Butane Lines and Tanks	Soil corrosion, different soil types, differential moisture, and oxygen in soil, dissimilar metals, bacteria, and stray and long-line currents.	Steel, galvanized iron pipe, copper, brass fittings.	Paint threads on galvanized iron and steel pipes. Use bituminous coating or tape coverings on black iron pipe. Use a heavy bituminous coating on tanks. Apply cathodic protection to tanks and piping. Avoid dissimilar metals. Install insulating fittings. Drain stray current if present. Use clean sand backfill.
Hydraulic Lines and Tanks	Soil corrosion, different soil types, differential moisture, and oxygen in soil, dissimilar metals, bacteria, and stray and long-line currents.	Steel, brass, bronze, copper, and cast iron fittings.	Use heavy bituminous coatings. iron and steal pipes. Apply cathodic protection. Drain stray current if present. When galvanized pipe is used, paint exposed threads. Avoid dissimilar metals. Install insulating fittings.

(continued)

TABLE 6.4. (Continued)

Structure	Major Causes of Corrosion	Construction Materials	Corrosion Mitigation Methods
Radiant Heating Systems in Soil or Concrete	Corrosive soils, differential environment, dissimilar metals, stray and long-line currents, elevated temperatures, and seepage of snow-melting chemicals through concrete.	Steel, copper, and wrought iron.	Drain stray current if present. Avoid dissimilar metals. Avoid using copper-plated steel tubing. Apply cathodic protection. Avoid contact between piping and reinforcing steel. Use concrete spacing blocks between piping and reinforcing iron. Copper pipe is recommended for use in soil. If galvanized pipe is used, it should be placed in clean sand backfill and exposed threads should be painted. In concrete, black iron or galvanized iron pipe can be used. Copper pipe is also recommended. All portions of the piping should be encased in concrete and should not contact the soil at any point. Isolate any piping in the ground from piping encased in concrete by using an insulating bushing or coupling.

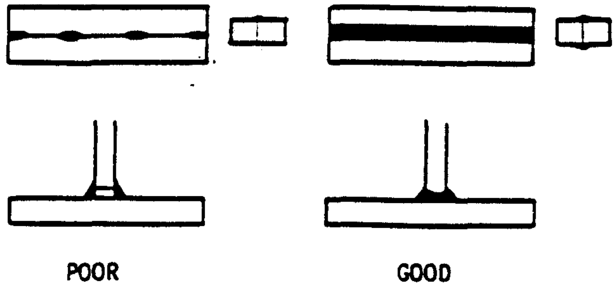
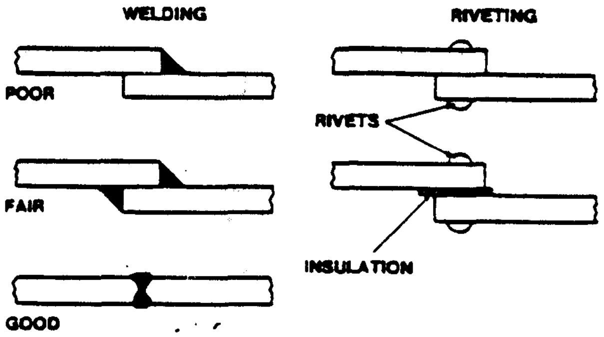


FIGURE 11—Joining Practices



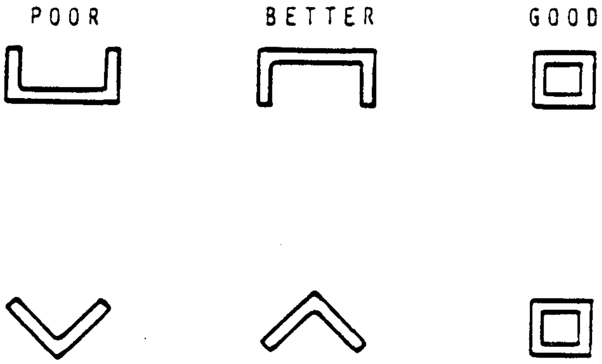


Figure 6-1
Structural Features That Lead to Corrosion

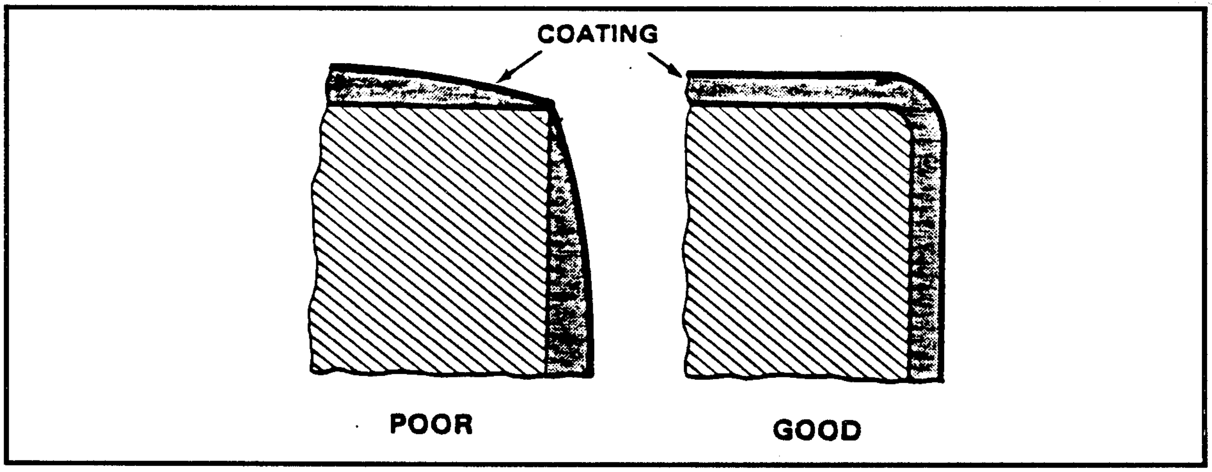


Figure 6-2
Aboveground Galvanic Cells from Dissimilar Metals

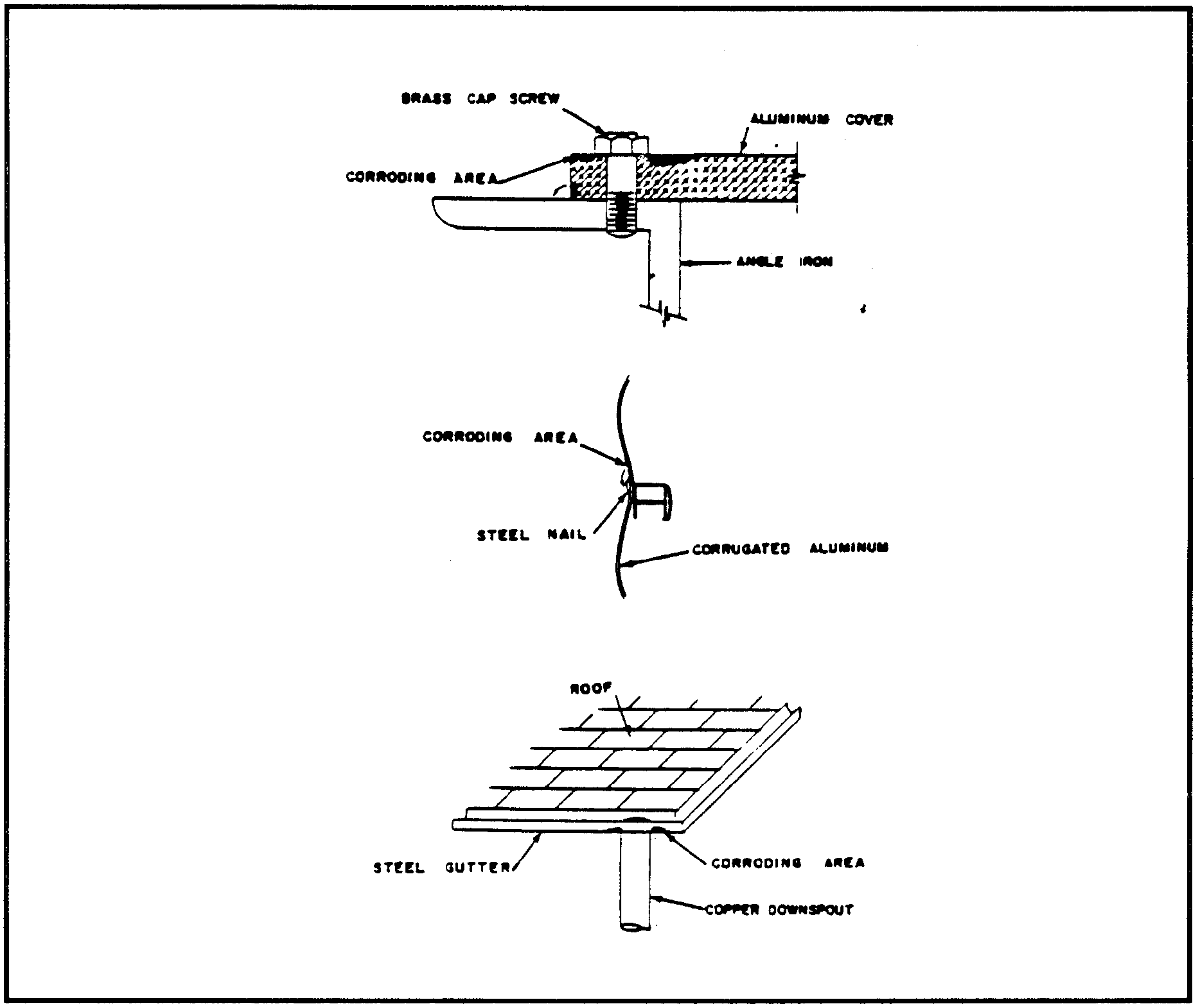


Figure 6-3
Edge Effects and Coatings

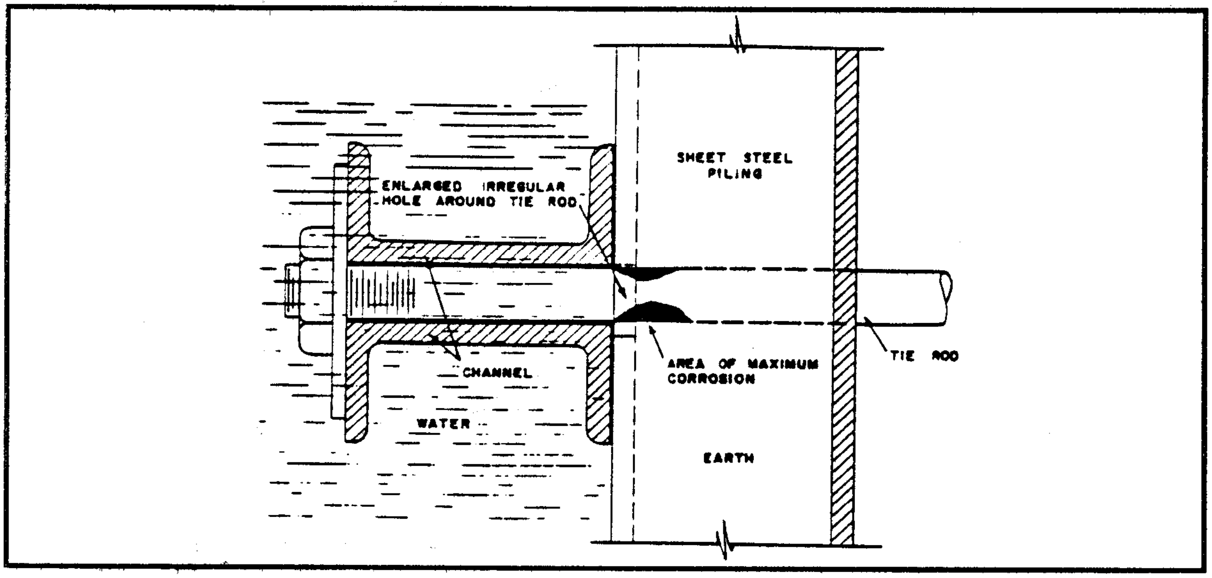


Figure 6-4
Tie-Rod Corrosion

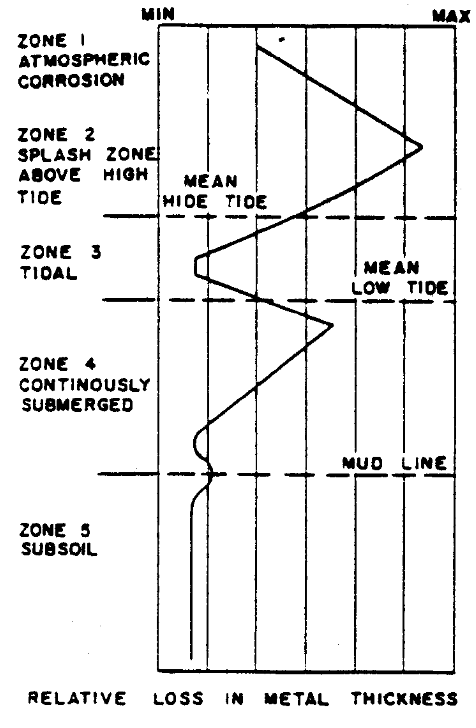


Figure 6-5
Pile Corrosion Profile

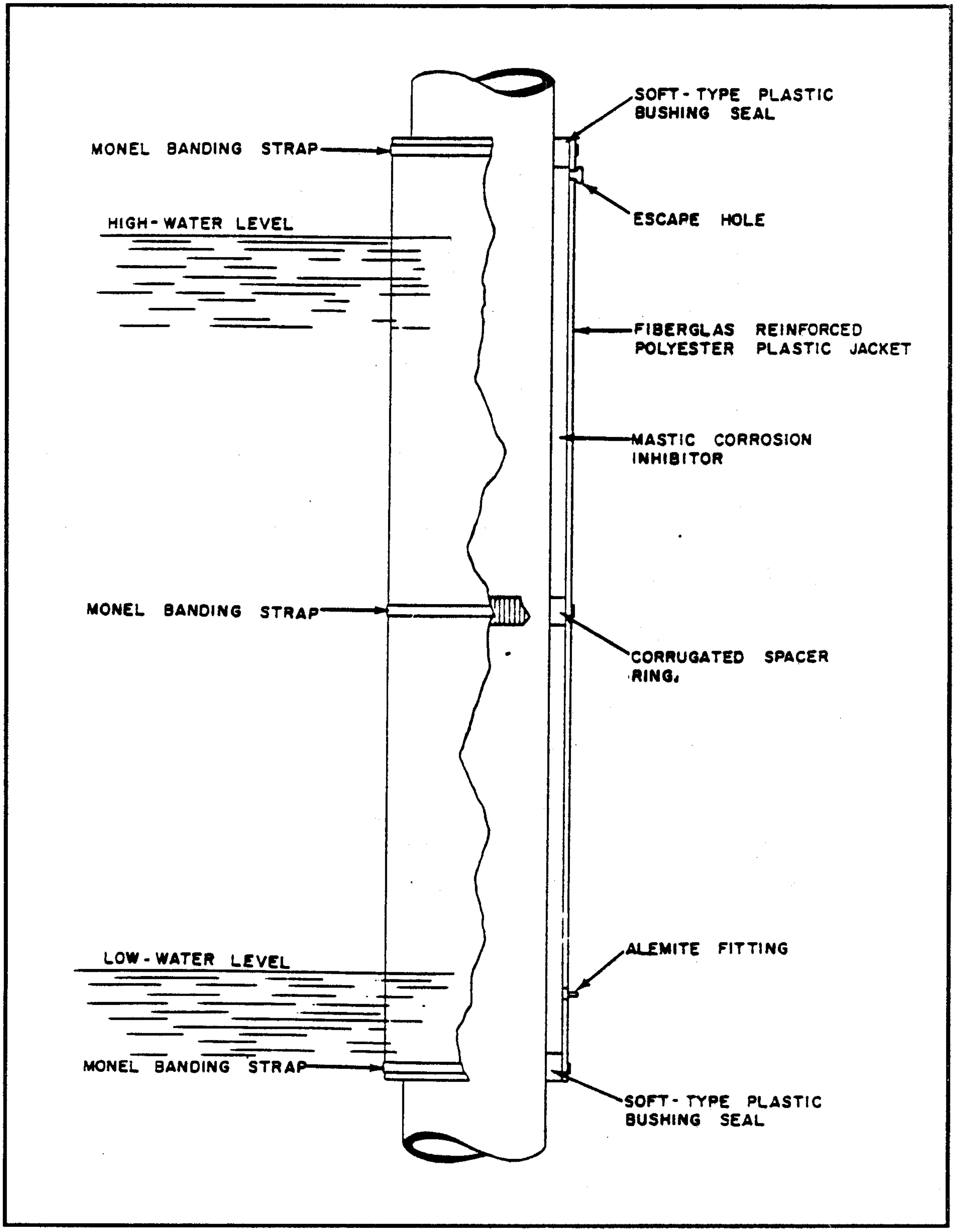


Figure 6-6
Protective Jacket

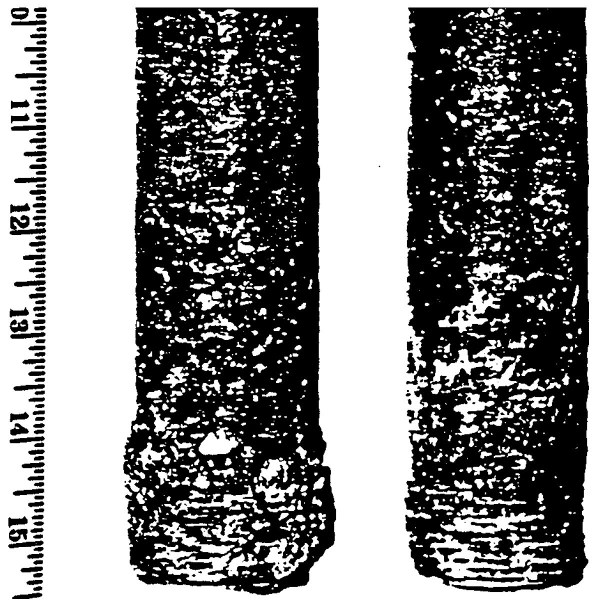


Figure 6-7
Example of Thread Corrosion

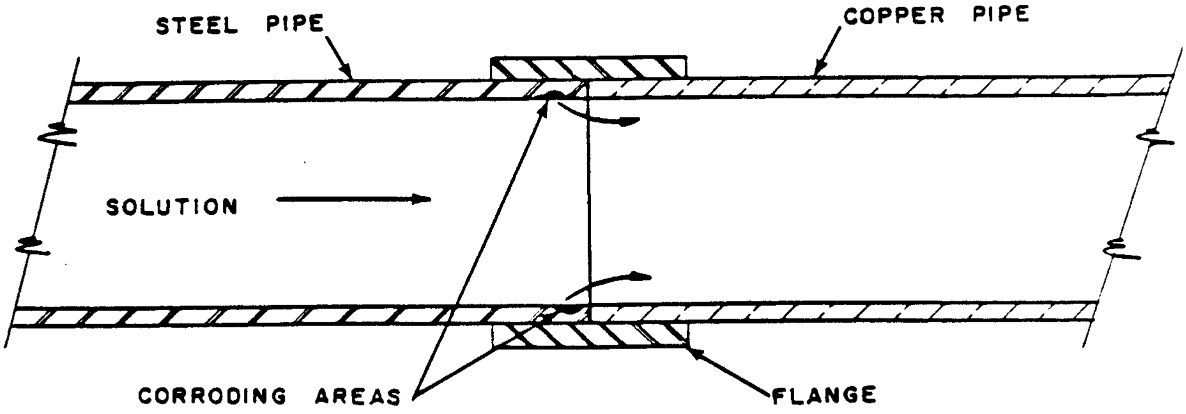


Figure 6-8
Interior Corrosion Resulting From Mating Copper and Steel Pipe

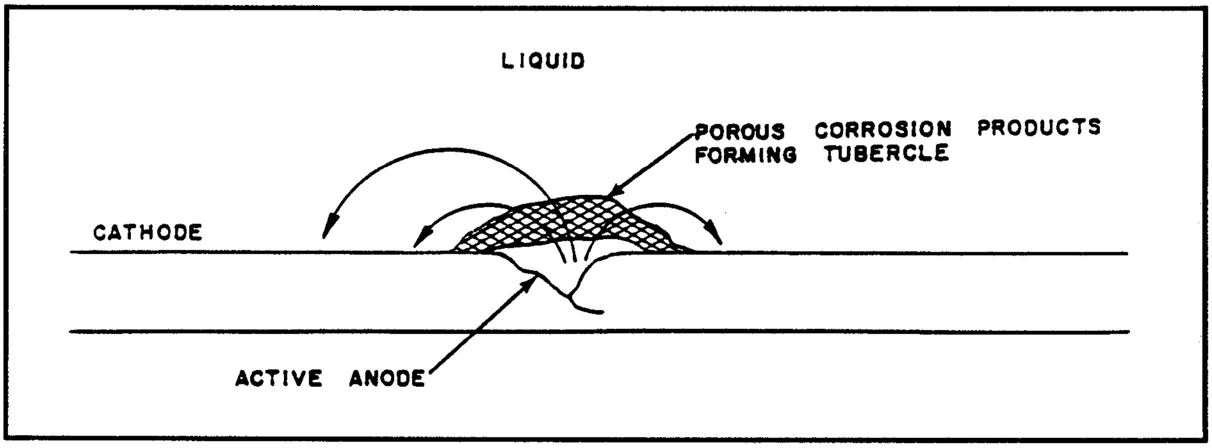
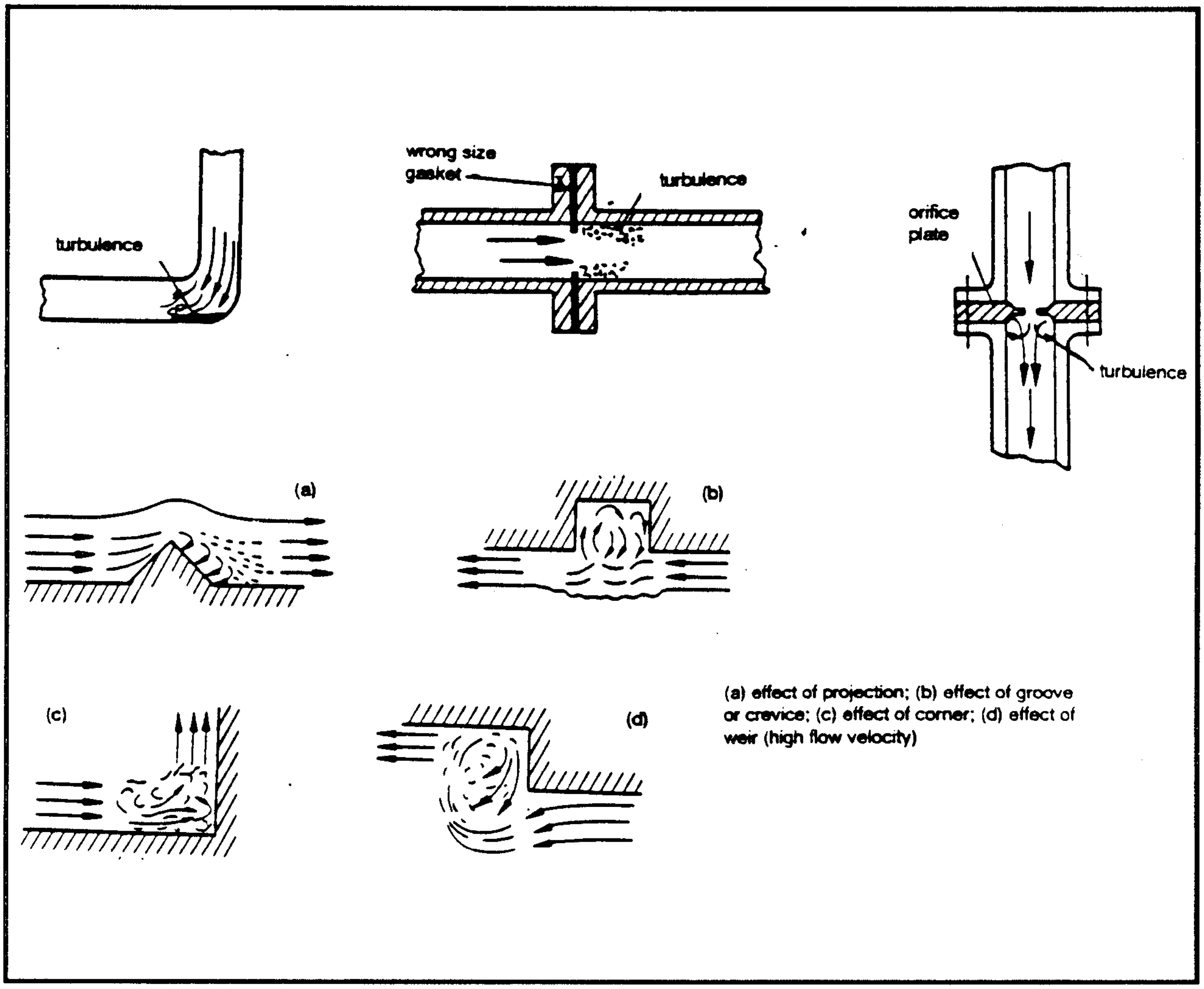
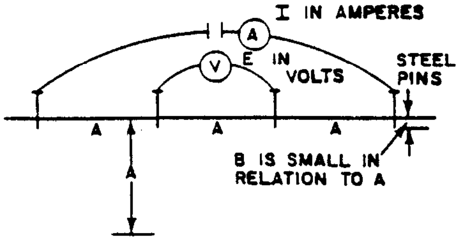


Figure 6-9
Oxygen Concentration Cell: Rust Tubercle on Tank Wall



(a) effect of projection; (b) effect of groove or crevice; (c) effect of corner; (d) effect of weir (high flow velocity)

Figure 6-10
Velocity Related Attacks



A = SPACING IN FEET

ρ = AVERAGE RESISTIVITY TO A DEPTH OF 'A' FEET IN OHM - CMS

$\rho = \frac{191\ AE}{I}$

SAMPLE RESISTIVITY TABLE FOR ONE LOCATION

A - FT	E - MV	I - MA	ρ - OHM - CM
2	1575	232	2,590
4	725	247	2,240
6	415	270	1,760
8	270	280	1,470
10	187	270	1,325
12	145	265	1255

Figure 6-11
Four-Pin Method for Measuring Soil Resistivity

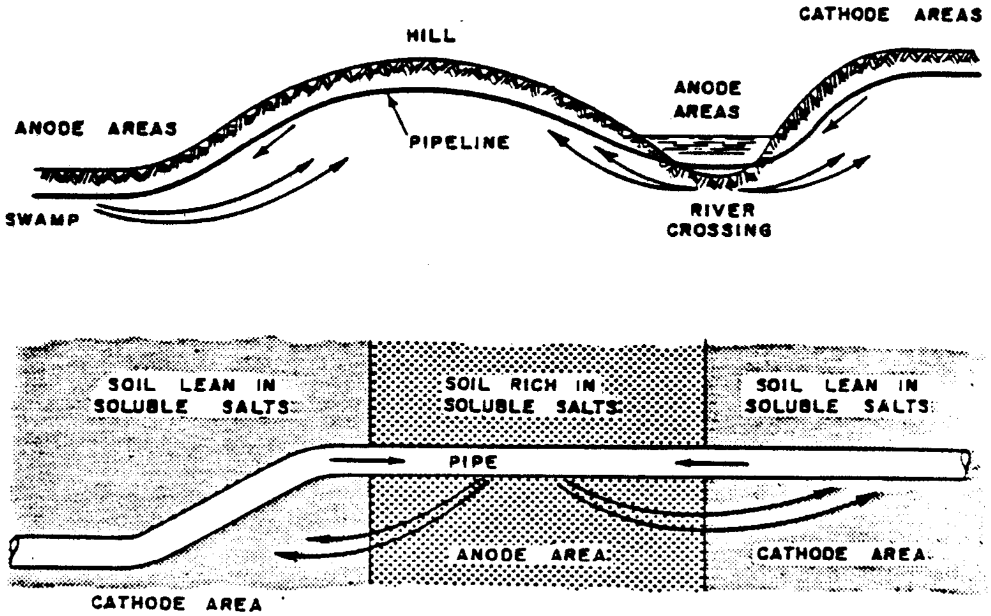


Figure 6-12
Long-Line Currents: Differential Environment Underground

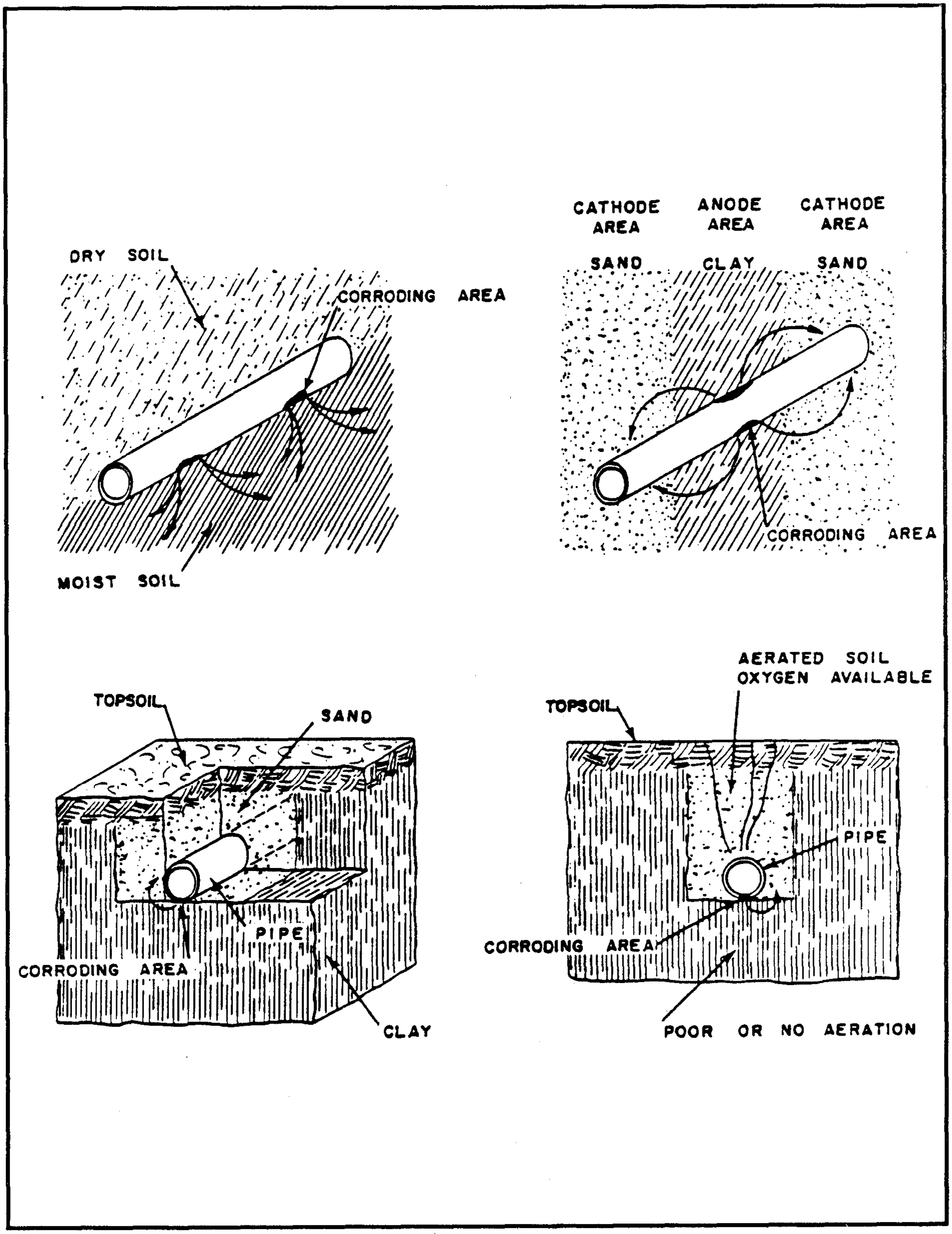


Figure 6-13
Differential Environment Underground

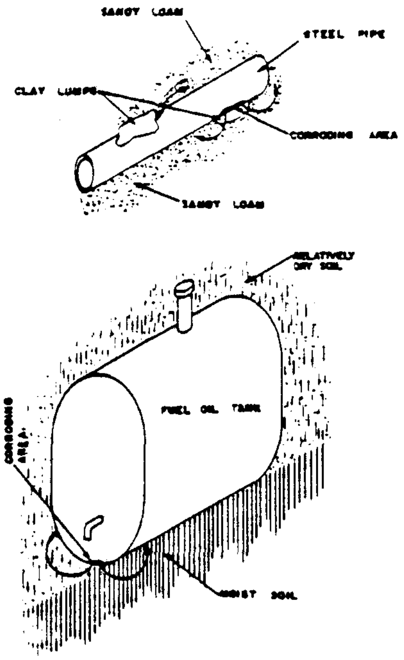


Figure 6-14
Additional Differential Environment Underground

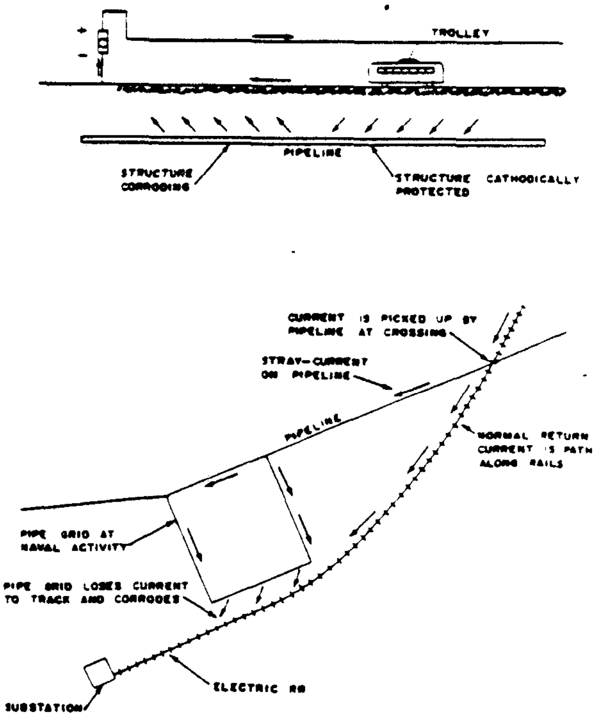


Figure 6-15
Stray Current Electrolysis From Electric Railway

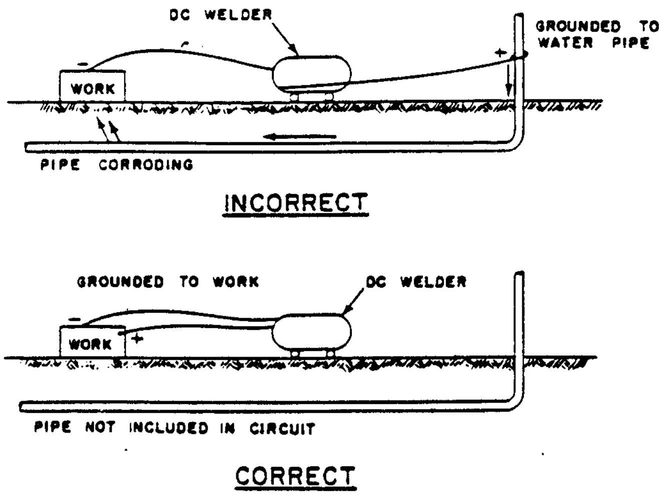


Figure 6-16
Stray Current Electrolysis From Local Sources

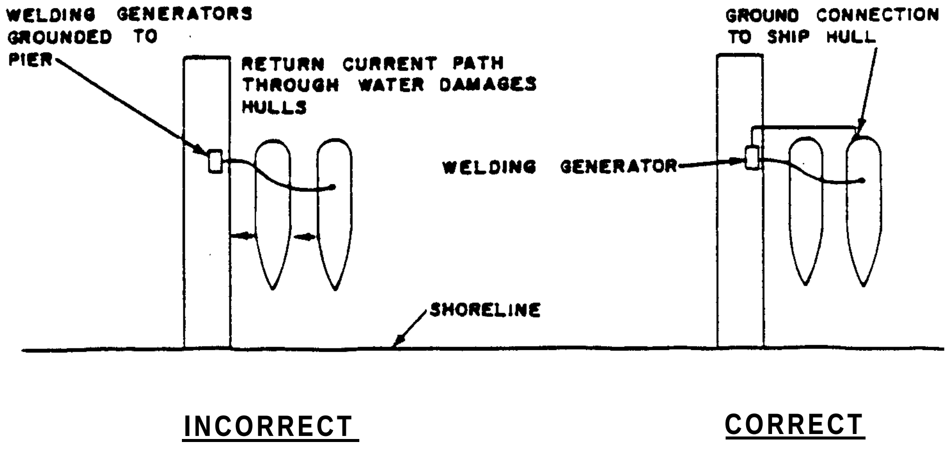


Figure 6-17
Correct and Incorrect Grounding