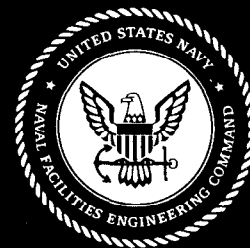**Naval Facilities Engineering Command**
200 Stovall Street
Alexandria, Virginia 22332-2300   APPROVED FOR PUBLIC RELEASE

Corrosion Control

NAVFAC MO-307
September 1992

i

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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Assistant Commander for
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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.

AMENDMENT NUMBER	AMENDMENT DATE	POST DATE	POSTED BY (LAST NAME)

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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 <u>Corrosivity of Environment</u>. 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 <u>Environmental Contamination</u>. 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 <u>Manpower</u>. 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.
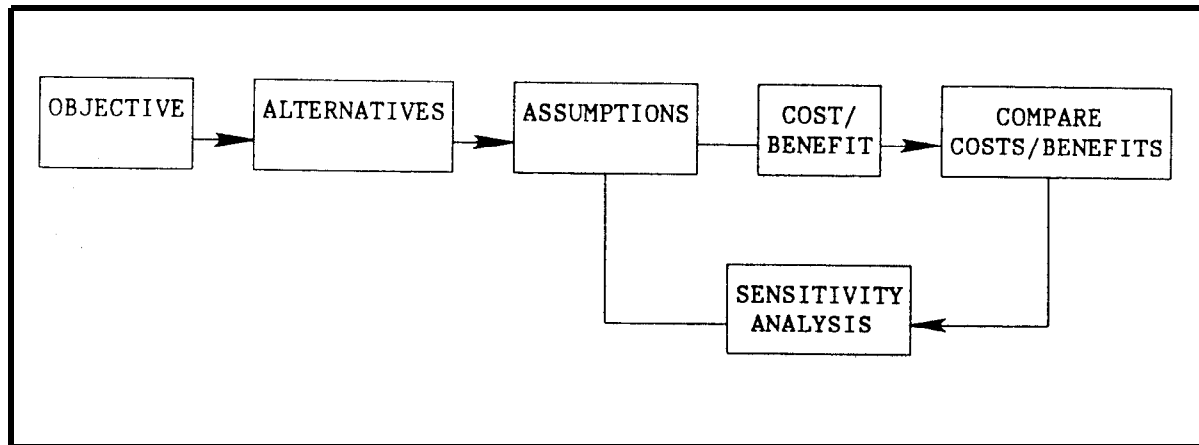
Figure 3-1
Six Steps of Economic Analysis

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.

3-2

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.

3-3

3. The <u>technological life</u> 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. <u>Sunk Costs</u>. 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. <u>One-Time Costs</u>. 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. <u>Recurring Annual Costs</u>. 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. <u>Depreciation</u>. Depreciation has no effect on cash flow for Government investments (Ref 3).

5. <u>Inflation</u>. 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. <u>Cost Documentation</u>. 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 sen-

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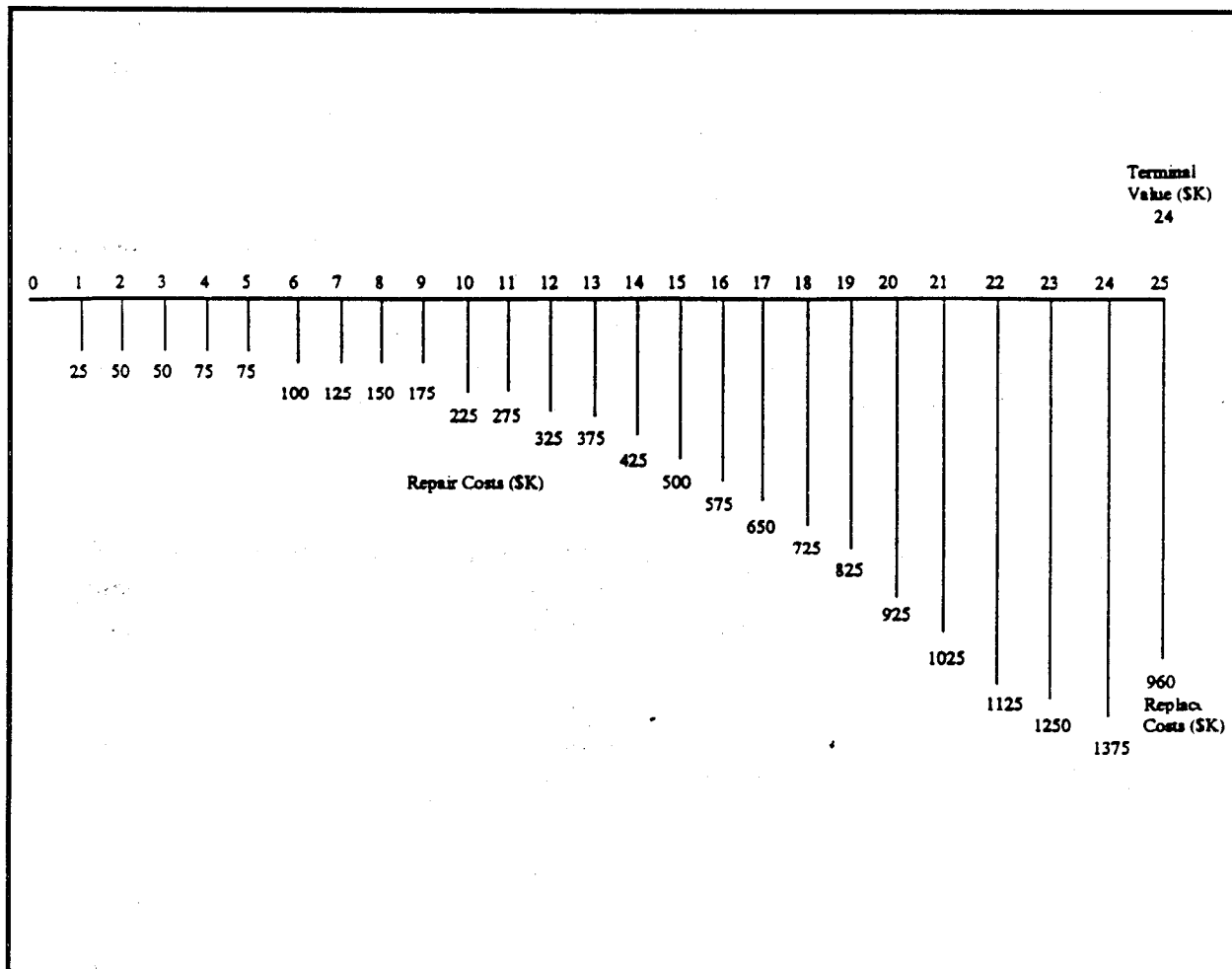
Figure 3-2
Cash Flow Diagram - Continue Repairs on Existing Line.
The Cash Flow Diagram Represents the Magnitudes and Timing of Costs and
Benefits for the Entire Economic Life of an Alternative

3-8

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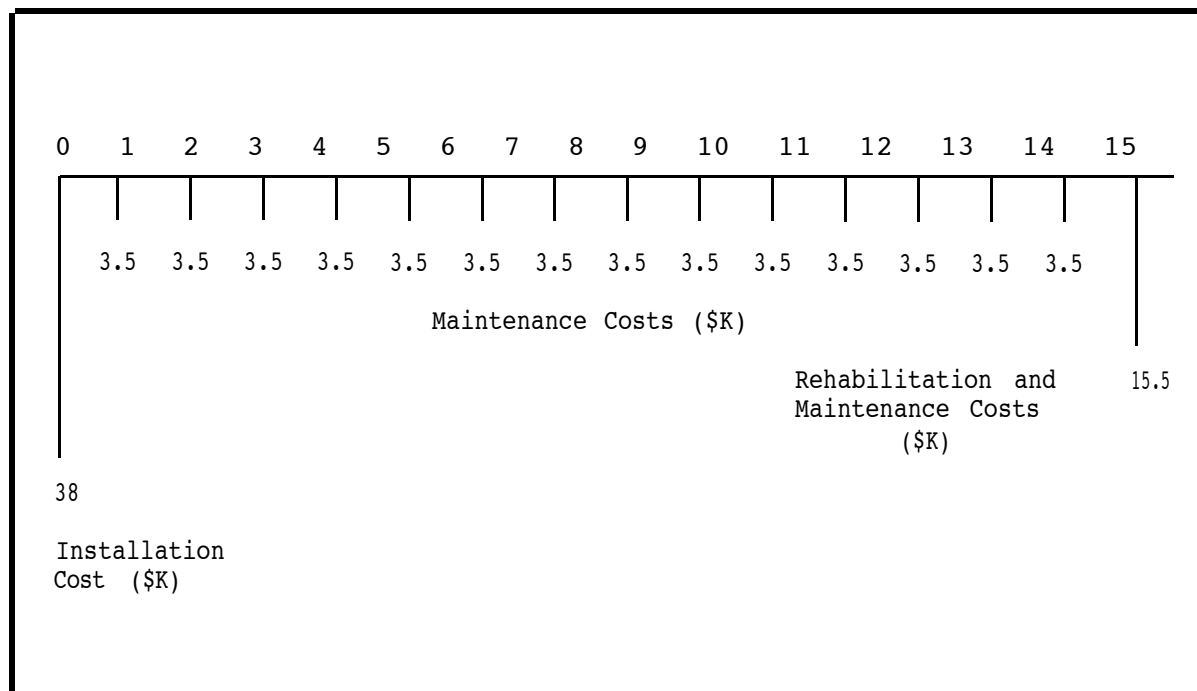
Figure 5-3
Cash Flow Diagram - Retrofit Cathodic Protection
on Existing Line

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					

3-10

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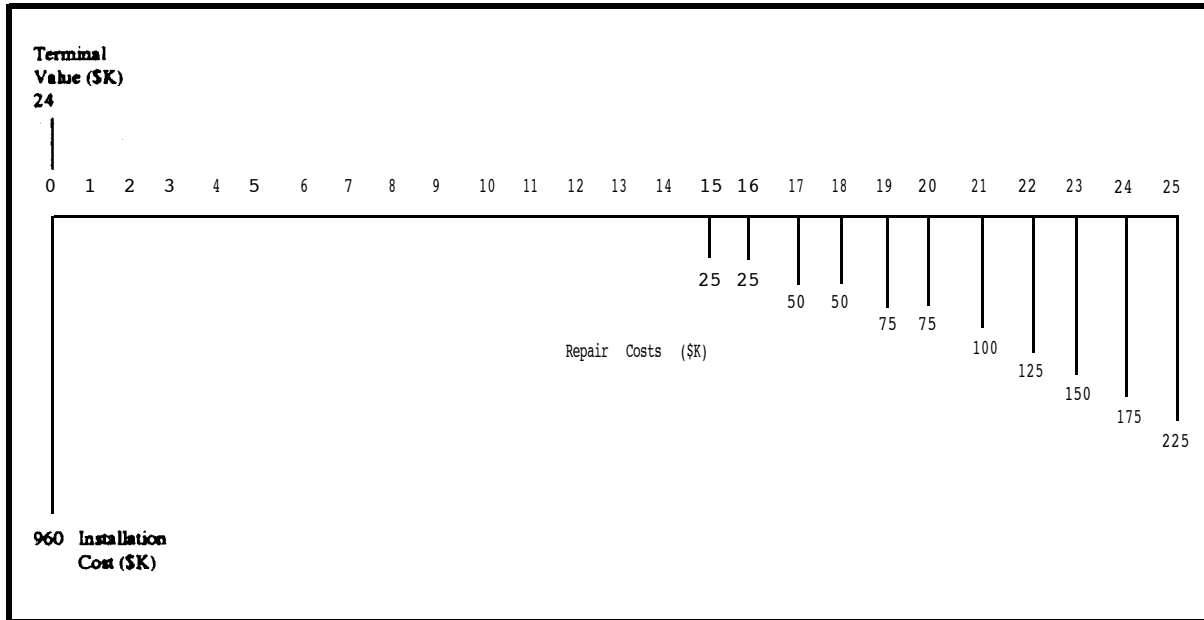
Figure 3-4
Cash Flow Diagram - Replacement of Existing Line

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

3-11

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).

3-12

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
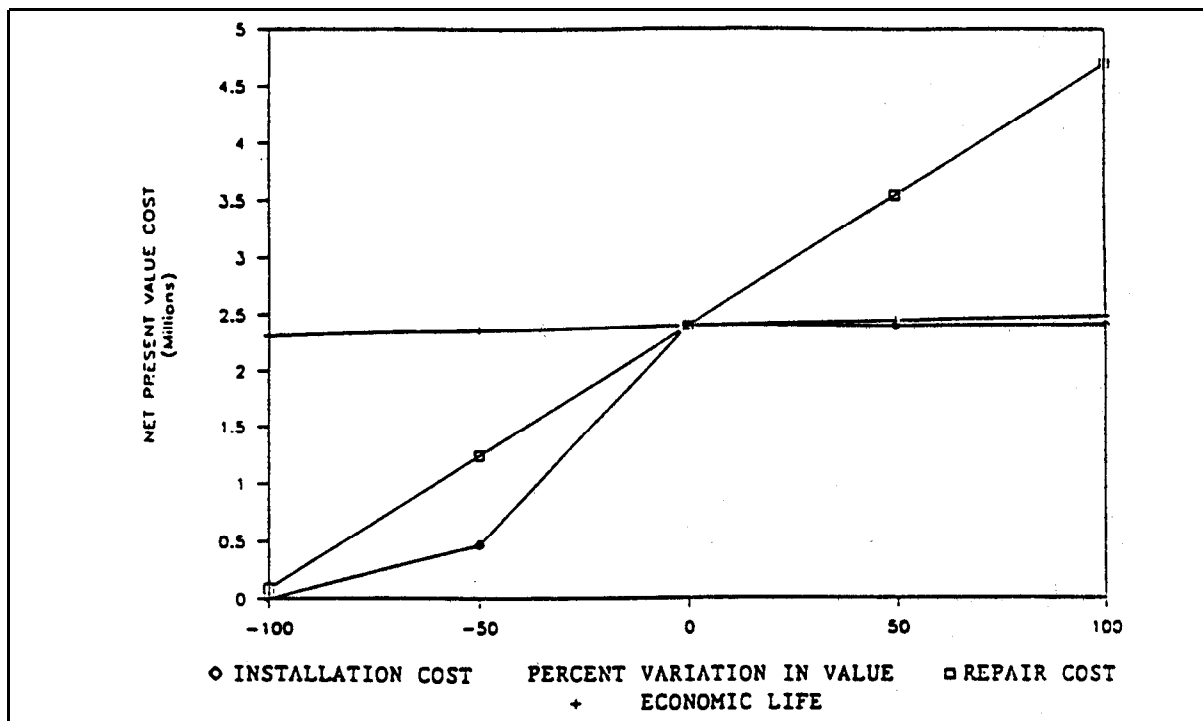
Figure 3-5
Determination of the Dominant Cost Factor
Alternative 1 - Continue Repairs
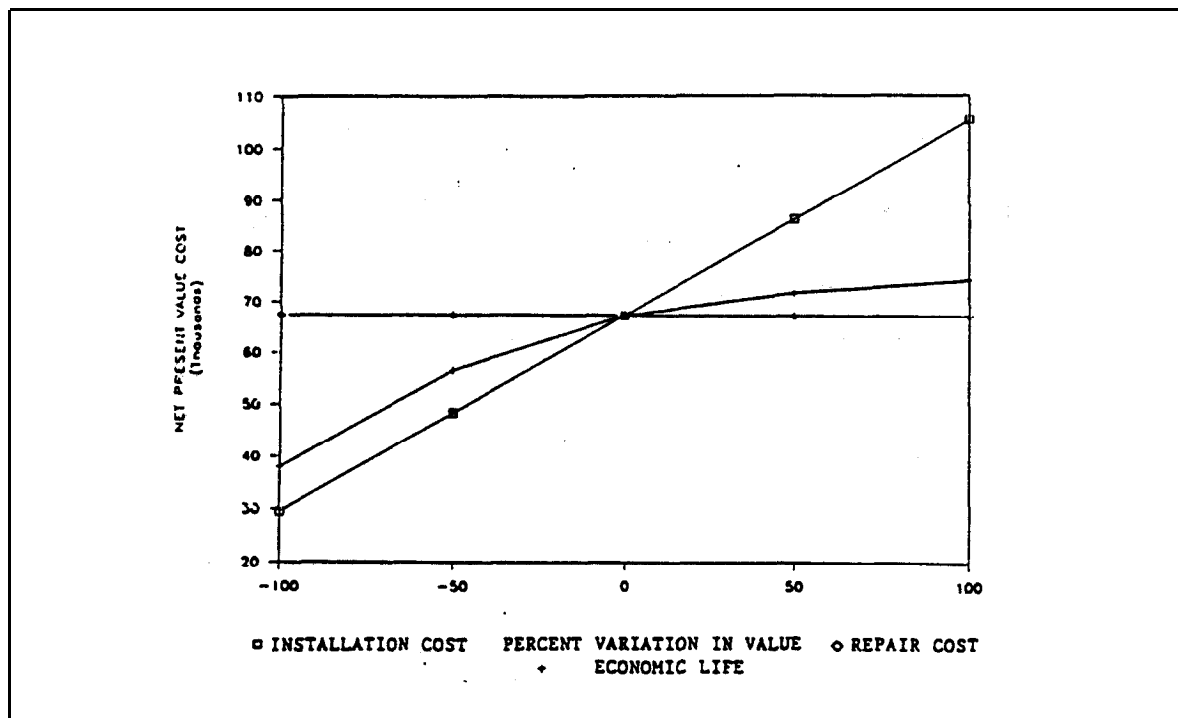
Figure 3-6
Determination of the Dominant Cost Factor
Alternative 2 - Cathodic Protection
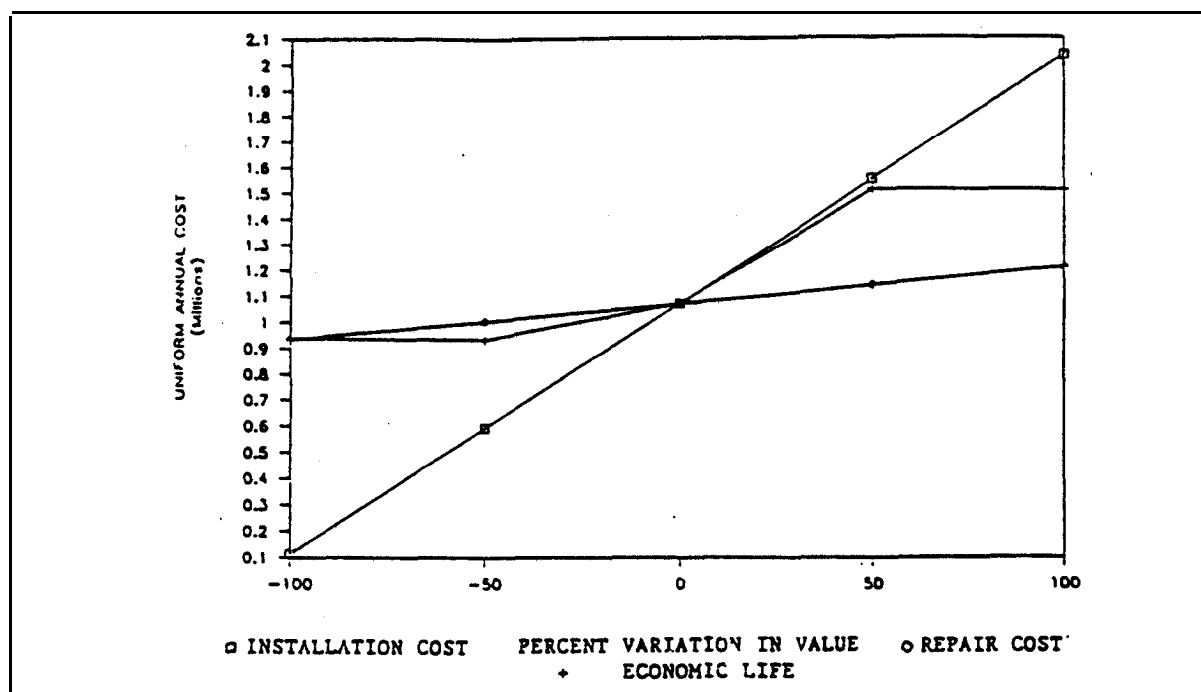
Figure 3-7
Determination of the Dominant Cost Factor
Alternative 3 - Replacement

3-14

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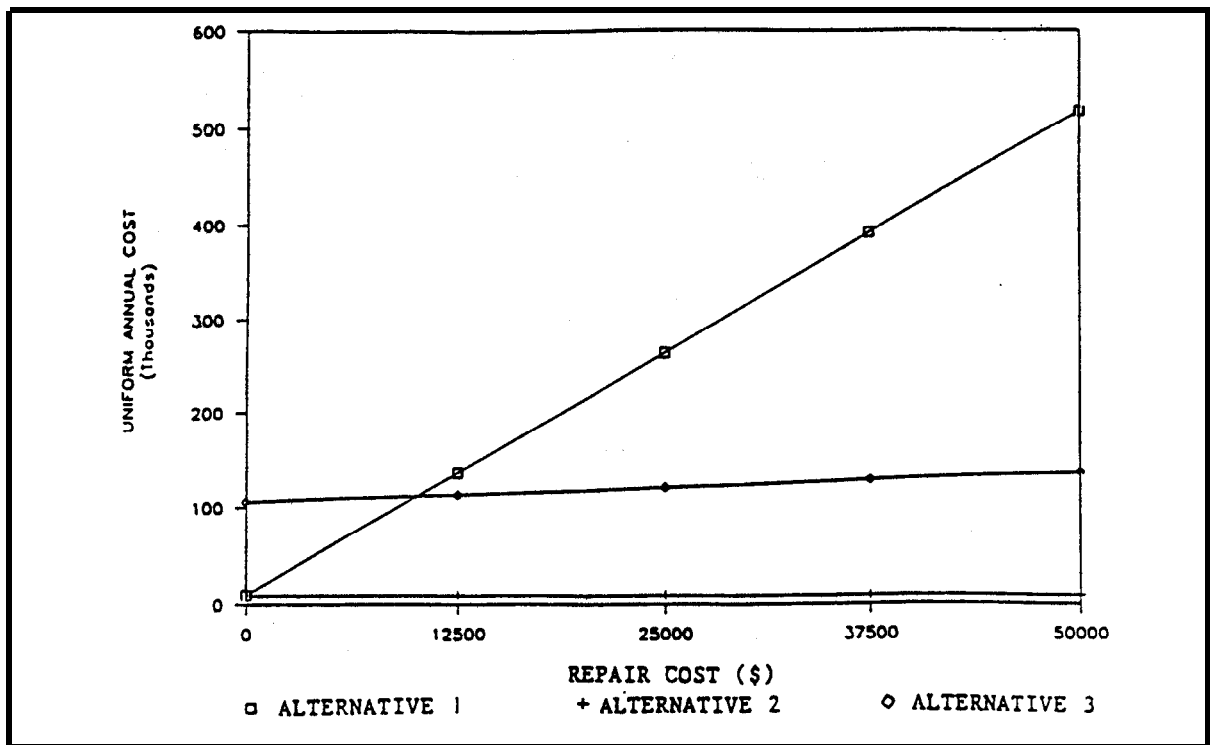
Figure 3-8
Sensitivity Analysis
Vary Repair Costs - All Alternatives

3-15

- **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 =

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

where:

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

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

Set:

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

3-16

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

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.

3-17

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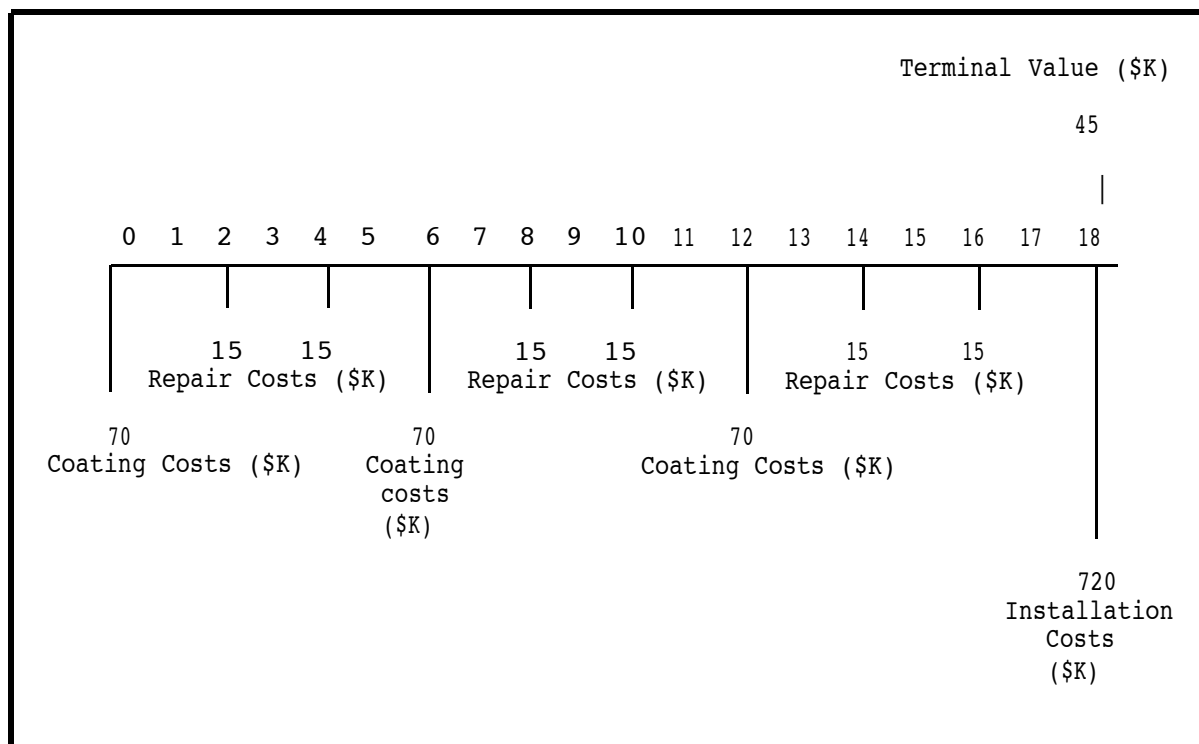
Figure 3-9
Cash Flow Diagram - Continue Repairs and Coatings of
Existing Tank/No Cathodic Protection

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

3-19

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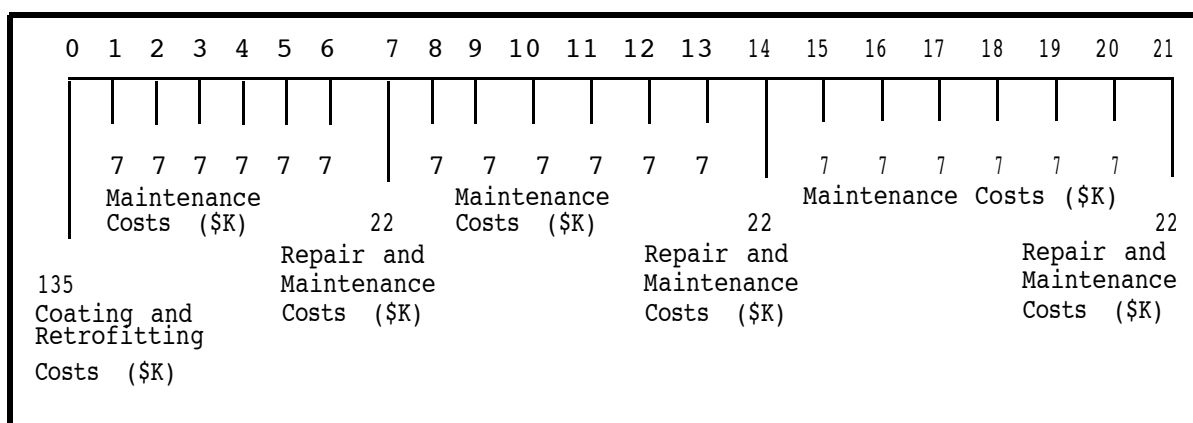
Figure 3-10
Cash Flow Diagram - Continue Repairs and Coatings of
Existing Tank/Retrofitting Cathodic Protection

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.

3-21

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/ft^2 or $ 60,000
Paint material:	+0.08/ft^2 or + 8,000
Paint application:	+0.45/ft^2 or +45,000
Total	$ 1.13/ft^2 or $113,000

Maintenance paint cost (10% repainting):

Labor, equipment, related costs:	$0.225/ft^2 x 10,000 ft^2 = $2,250
Material costs:	0.08/ft^2 x 10,000 ft^2 = + 8 0 0
	Total: $3,050
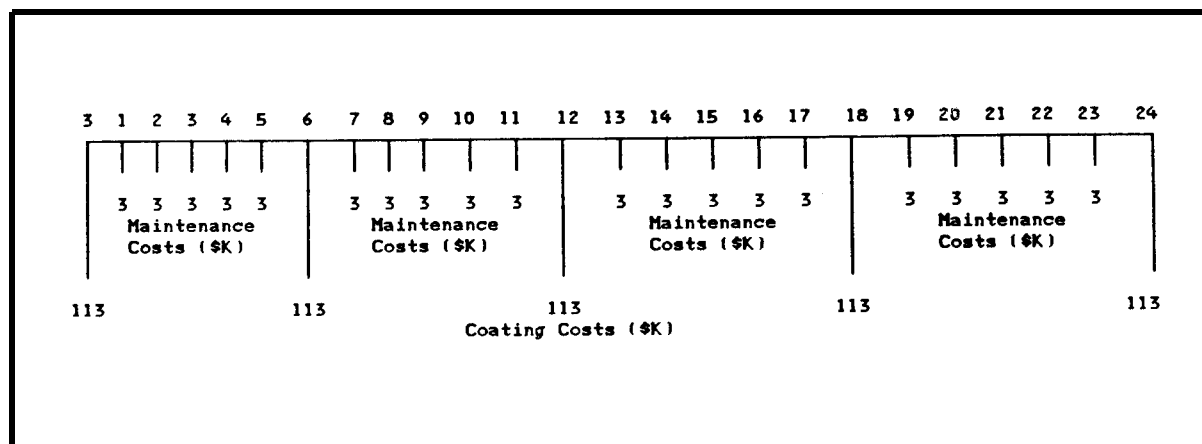
Figure 3-11
Cash Flow Diagram - Continue Applying a Three-Coat Alkyd Coating System

3-22

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
O-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/ft^2	or $ 80,000
Paint material:	+ 0.11/ft^2	or + 11,000
Paint application:	+0.60/ft^2	or +60,000
Total:	$ 1.51/ft^2	or $151,000

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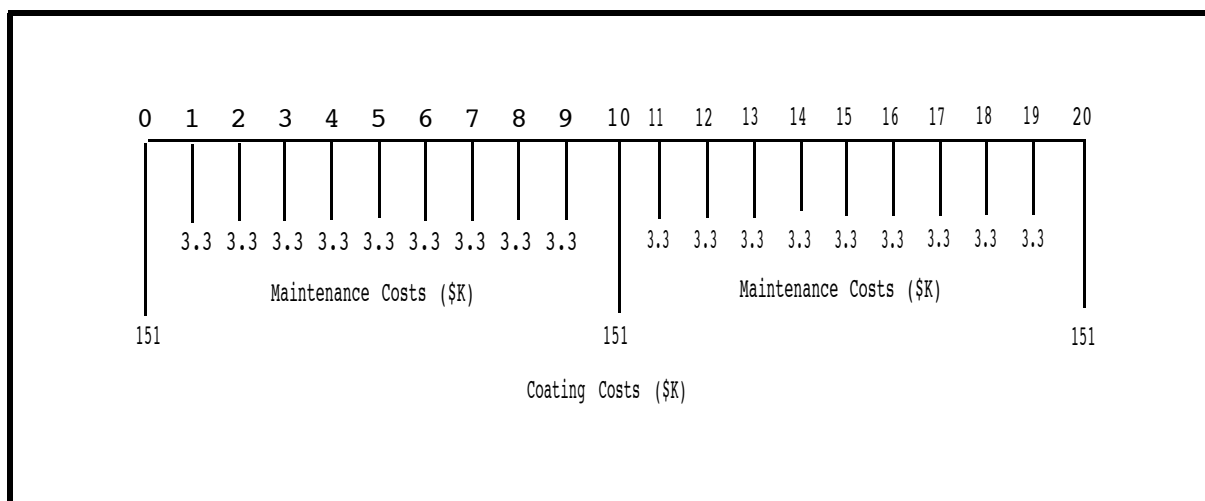
Figure 3-12
Cash Flow Diagram - Continue Applying an Epoxy Coating System

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.

3-24

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 o r +45,000
Total:	$ 1.03/ft^2 or $ 103,000

3-25

Maintenance paint cost (10% repainting):

Labor, equipment, related costs:	$0.225/\text{ft}^2$ x 10,000 ft^2 =	$2,250
Material costs:	0.080/ft^2 x 10,000 ft^2 =	+800
	Total:	$3,050
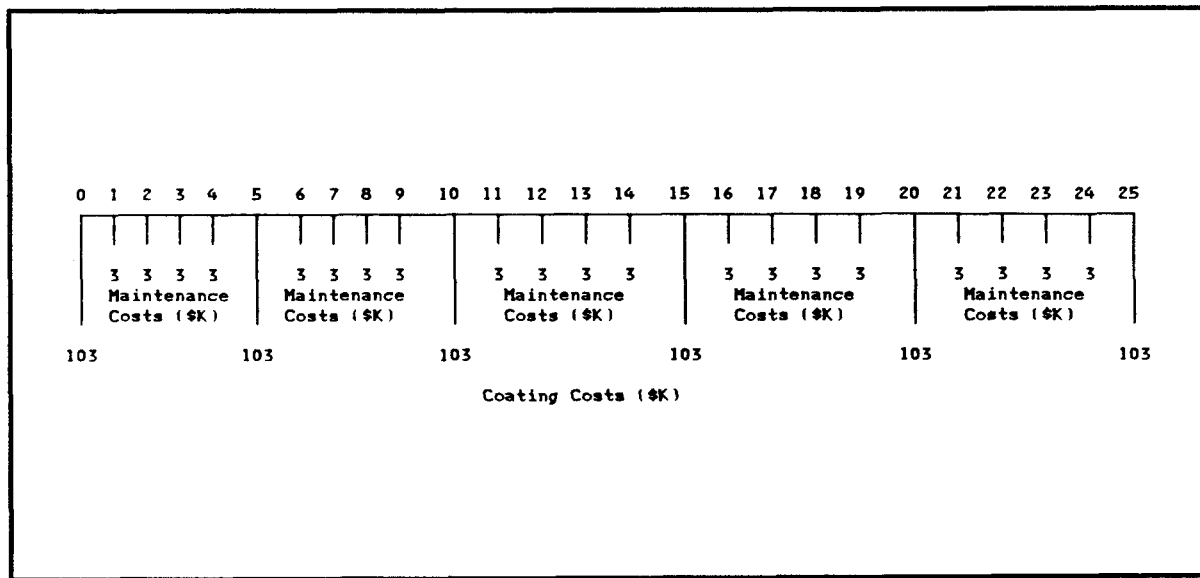
Figure 3-13

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
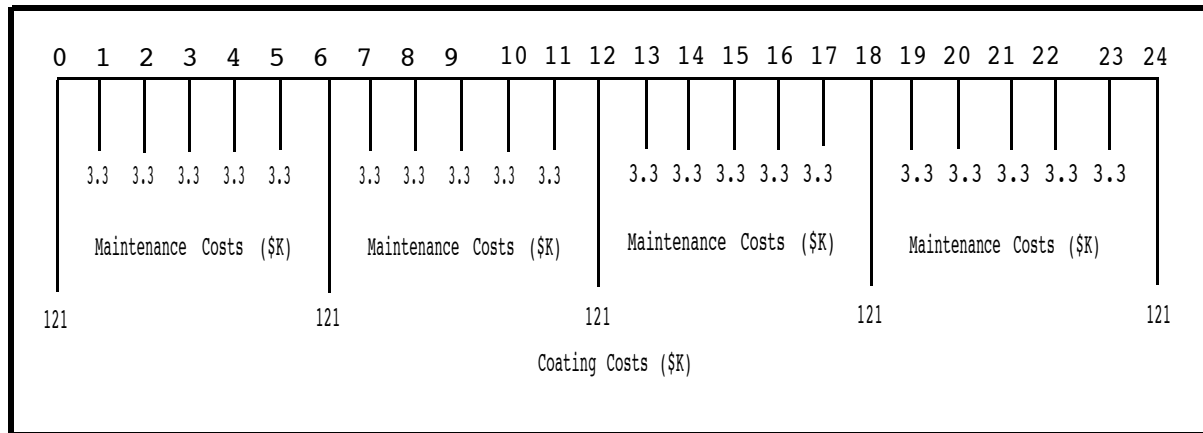
Figure 3-14

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

3-27

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.

<u>Maintenance Painting Required</u>	<u>Economic Life</u>
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/ft^2 x 10,000 ft^2 = $12,000

3-29

Primer (inorganic zinc)

Labor, equipment, related costs	$0.60/ft^2 x 10,000 ft^2 = $6,000
Material costs	$0.11/ft^2 x 10,000 ft^2 = $1,100

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
	$2.77/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/ft^2 x 1,000 ft^2 =	$3,000
Material costs	$0.11/ft^2 x 1,000 ft^2 =	+ 1 1 0
	$3.11/ft^2	$3,110

Collection and disposal of
Abrasive (increases cost by a factor of 2)   x   2
                        Total maintenance cost $6,220

3-30

```
      0       1   2   3   4  5  6   7     8   9   10    11    12


                              6.2
                          Maintenance
                          Painting ($K)

     55.4                                              55.4
   Coating                                           Coating
   Costs ($K)                                        Costs ($K)
```

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

```
 0  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15



                               6.3
                           Maintenance
                           Painting Costs
                               ($K)

 56.2                                              56.2
 Coating                                           Coating
 Costs ($K)                                        Costs ($K)
```
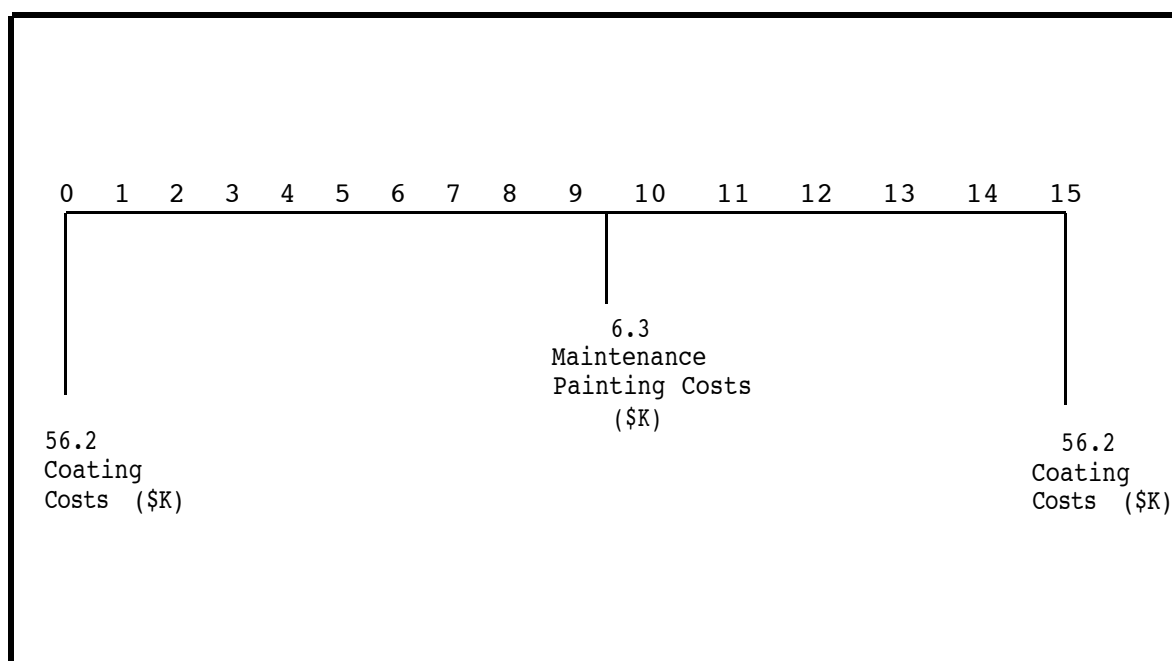
Figure 3-16
Cash Flow Diagram - Coated at the Site After the
Tower is Erected (zinc rich epoxy primer)

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		

3-33

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/ft^2 x 10,000 ft^2 = $6,000

Primer (inorganic zinc)
  Labor, equipment, related costs $0.30/ft^2 x 10,000 ft^2 = $3,000
  Material costs $0.11/ft^2 x 10,000 ft^2 = $ 1,100

Intermediate coat (epoxy-polyamide)

  Labor, equipment, related costs $0.15/ft^2 x 10,000 ft^2 = $ 1,500
  Material costs $0.09/ft^2 x 10,000 ft^2 = $ 900

Finish coat (aliphatic polyurethane)
  Labor, equipment, related costs $0.20/ft^2 x 10,000 ft^2 = $2,000
  Material costs <u>$0.07/</u>ft^2 x 10,000 ft^2 = <u>$ 700</u>
    $1.52/ft $15,200

Collection and disposal of abrasive
  (increases cost by a factor of 2) <u>x 2</u>
    Total cost to coat $30,400

Maintenance painting cost (10% repainting):
  Labor, equipment, related costs $3.00/ft^2 x 1,000 ft^2 = $3,000
  Material costs <u>$0.11/</u>ft^2 x 1,000 ft^2 = <u>+ 110</u>
    $3.11/ft^2 $3,110

Collection and disposal of abrasive
  (increases cost by a factor of 2) <u>x 2</u>
    Total maintenance cost $6,220

3-34

Cost to recoat 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 (inorganic zinc)

        Labor, equipment, related costs $0.60/ft^2 x 10,000 ft^2 = $6,000
        Material costs $0.11/ft^2 x 10,000 ft^2 = $ 1,100

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
                                           $2.77/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)

3-35

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 $0.50/\text{ft}^2$ x 10,000 ft^2 = $5,000

Primer (inorganic zinc)
Labor, equipment, related costs $0.16/\text{ft}^2$ x 10,000 ft^2 = $ 1,600
Material costs $0.11/\text{ft}^2$ x 10,000 ft^2 = $ 1,100

Intermediate coat (epoxy-polyamide)
Labor, equipment, related costs $0.06/\text{ft}^2$ x 10,000 ft^2 = $ 600
Material costs $0.09/\text{ft}^2$ x 10,000 ft^2 = $ 900

Finish coat (aliphatic polyurethane)
Labor, equipment, related costs $0.12/\text{ft}^2$ x 10,000 ft^2 = $ 1,200
Material costs $\underline{$0.07/\text{ft}^2}$ x 10,000 ft^2 = $ \underline{700}
$1.11/\text{ft}^2$ $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

3-36

Maintenance painting cost (10% repainting):

Labor, equipment, related costs $3.00/$ft^2$ x 1,000 ft^2 = $3,000

Material costs $\underline{\$0.11/ft^2}$ x 1,000 ft^2 = $\underline{+\ 110}$

  $3.11/$ft^2$ $3,110

Collection and disposal of abrasive
  (increases cost by a factor of 2)   x $\underline{\ \ 2}$

  Total maintenance cost $ 6,220

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

Surface preparation (conventional blasting)

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

Primer (inorganic zinc)

Labor, equipment, related costs $0.60/$ft^2$ x 10,000 ft^2 = $6,000

Material costs $0.11/$ft^2$ x 10,000 ft^2 = $ 1,100

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 $\underline{\$0.07}/ft^2$ x 10,000 ft^2 = $\underline{\$\ 700}$

  $2.77/$ft^2$ $27,700

Collection and disposal of abrasive
  (increases cost by a factor of 2)   x$\underline{\ \ 2}$

  Total cost to recoat $55,400

```
    0     1  2  3  4  5  6  7  8  9  10   11  12  13  14  15  16


                                        6.2
                                  Maintenance and
                                  Painting Costs
                                       ($K)
       13.8                                             55.4
    Coating                                           Coating
    Costs ($K)                                        Costs ($K)
```

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

3-38

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
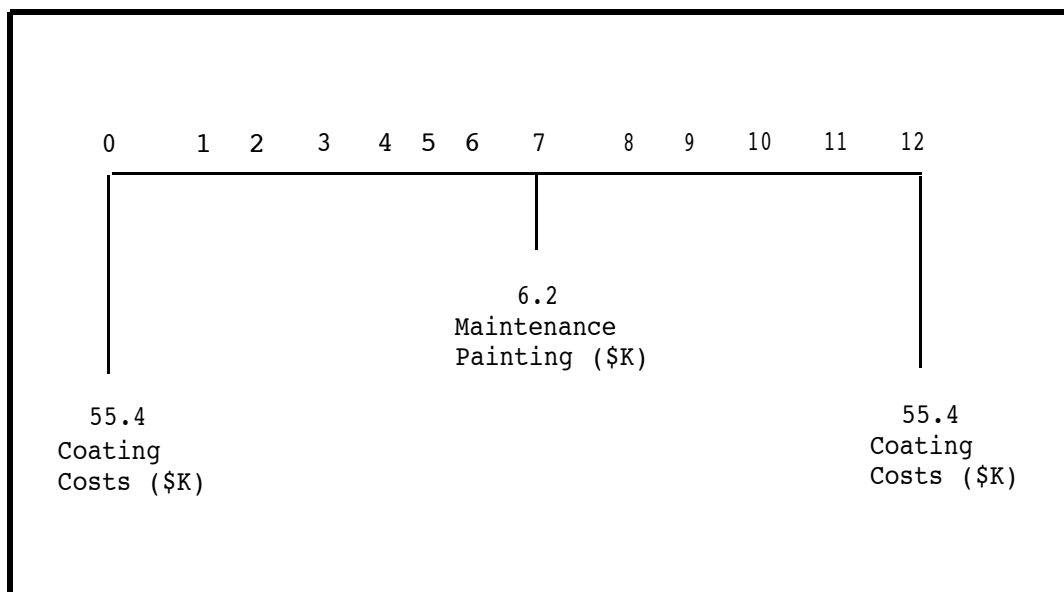   Total coating cost: $3,138

3-40

Maintenance coating cost (10% recoating):

Coating Touch Up

Labor, equipment, related costs	$2.625/ft^2 x 942 ft^2 = $ 247
Material costs	$0.090/ft^2 x 942 ft^2 = $ 8
	$2.715/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

3-41

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/ft^2 x 942 ft^2 = $ 659

Application of petroleum paste and tape
      Labor, equipment, related costs $1.00/ft^2 x 942 ft^2 = $ 942
      Material costs $2.20/ft^2 x 942 ft^2 = $2.072
                          Total coating cost: $3,673

Maintenance Coating Cost (10% recoating):

Coating touch up
      Labor, equipment, related costs $1.35/ft^2 x 94.2 ft^2 = $ 127
      Material costs $2.20/ft^2 x 94.2 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   = - 8 0 0
                  Total replacement cost: = $14,800

3-42
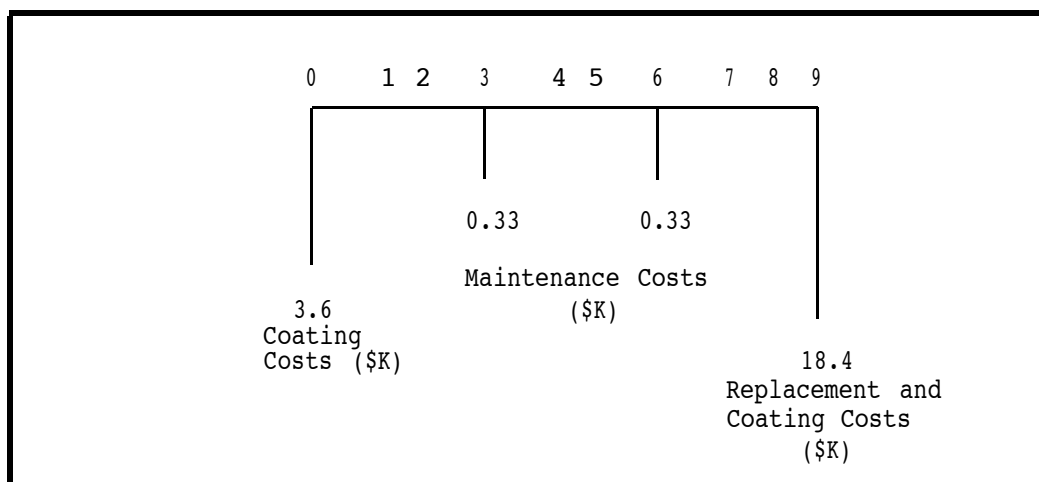
Figure 3-20
Cash Flow Diagram - Tape and Application
of a Petroleum Paste

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.

3-43

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.

3-44

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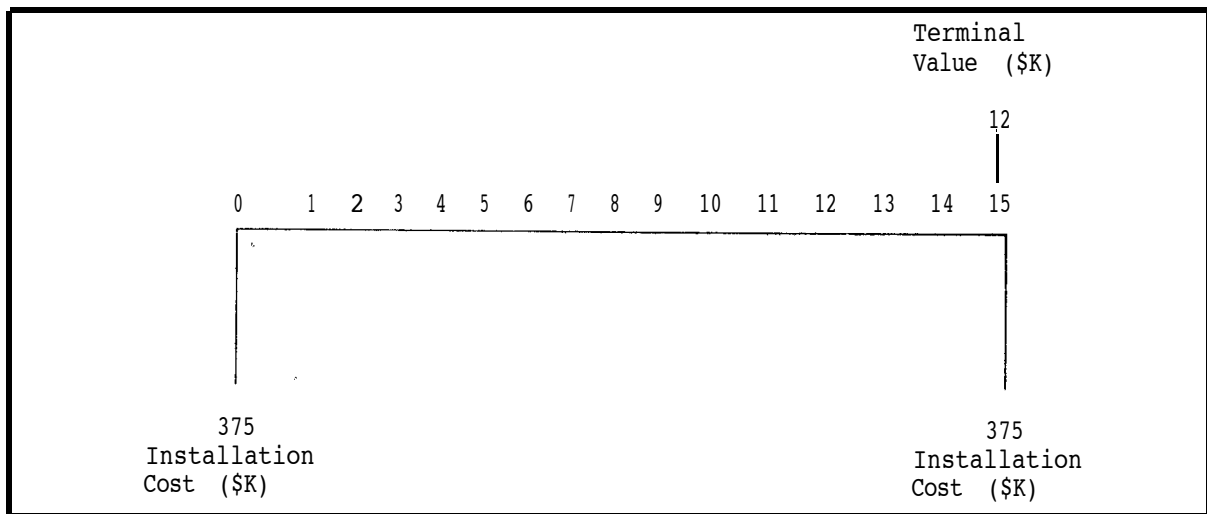
Figure 3-21
Cash Flow Diagram - Provide No Corrosion
Prevention or Control

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

3-45

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

3-46

Alternative 3 - Provide cathodic protection and coat the seawall.

Cost of new installation:

<div style="margin-left: 2em">

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

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Cost of annual cathodic protection
maintenance $5/ft x 1,000 ft = $ 5,000
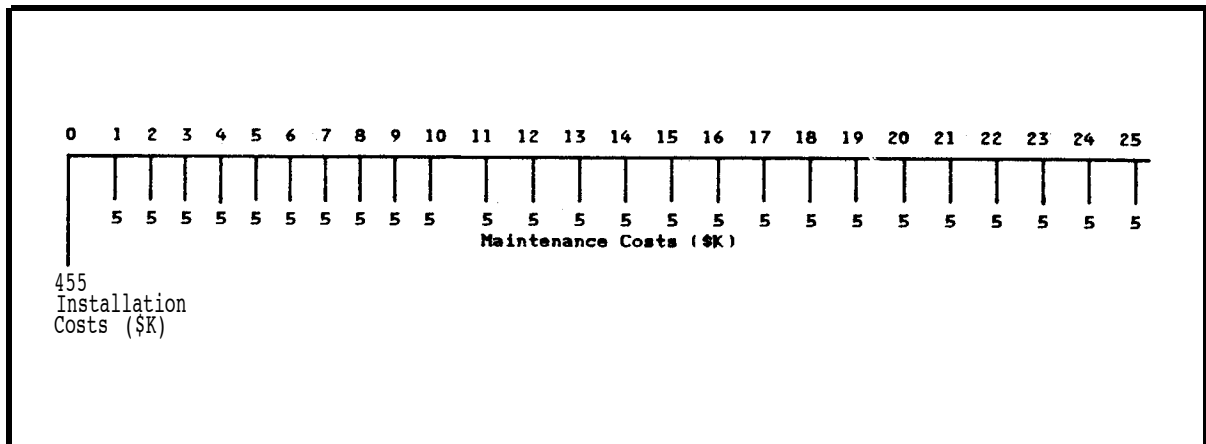
Figure 3-23
Cash Flow Diagram - Provide Cathodic Protection
and Coat the Seawall

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

3-47

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).

3-48

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:	<u> -8 ft x 1,000 ft = - 8,000 </u>
	$12/ft $12,000
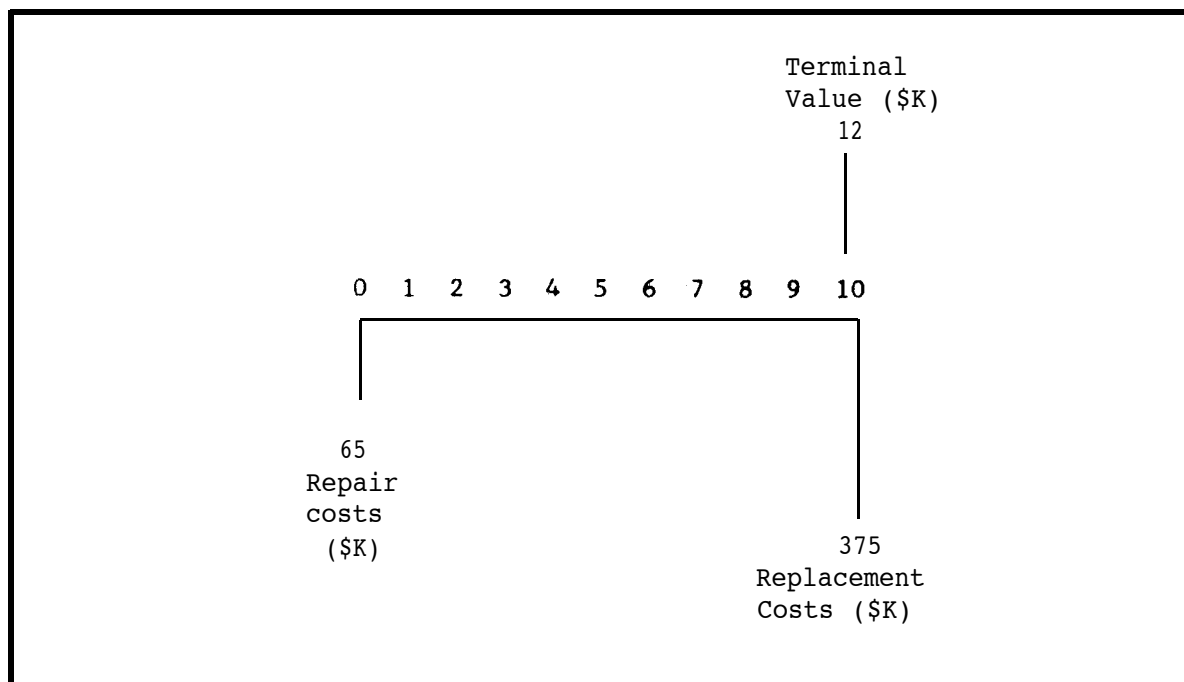
Figure 3-24
Cash Flow Diagram - Mechanical Repair of Existing Seawall
(no corrosion prevention or control)

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

3-50

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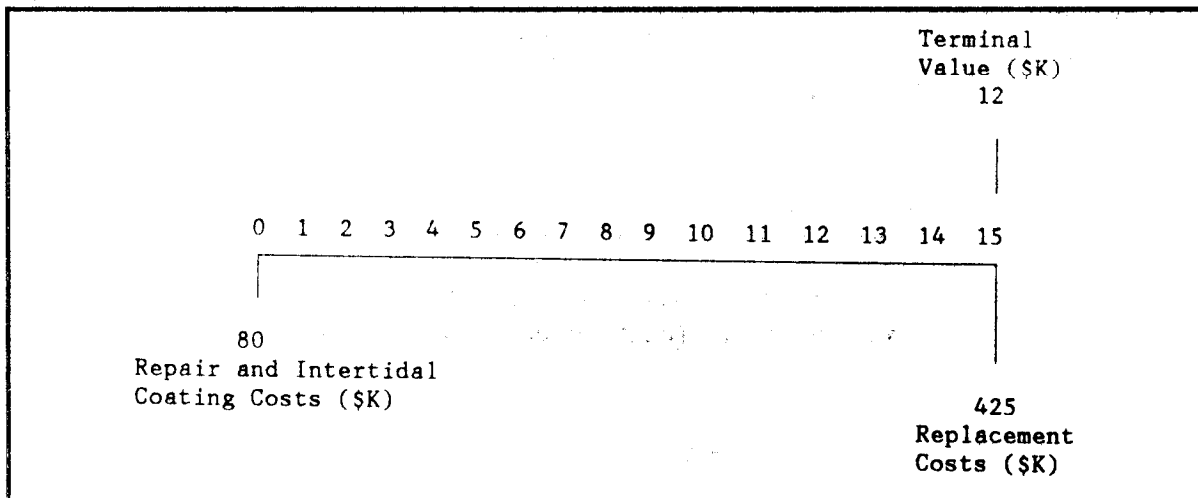
Figure 3-25
Cash Flow Diagram - Mechanical Repair of Existing Seawall (coat only)

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

3-51

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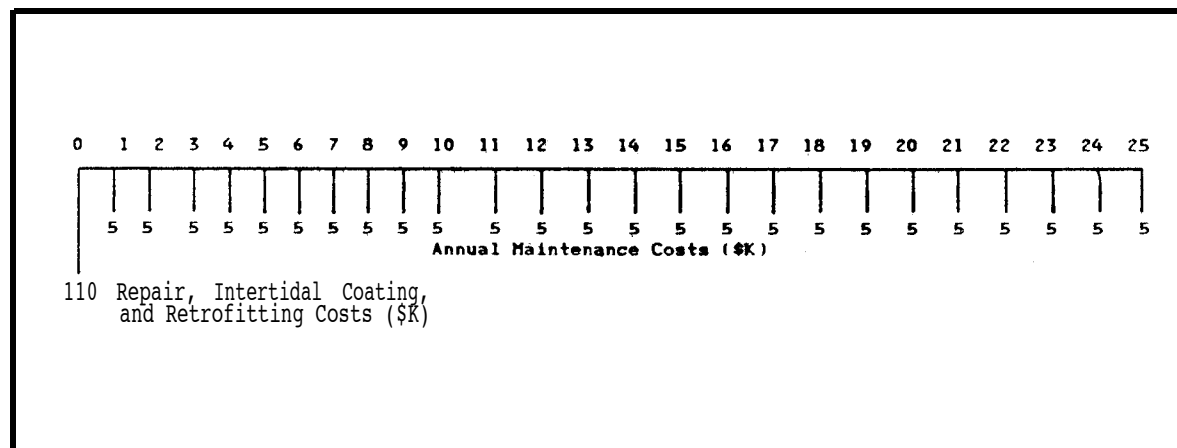
Figure 3-26
Cash Flow Diagram - Mechanical Repair
of Existing Seawall (coat and cathodic protection)

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
1-25	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
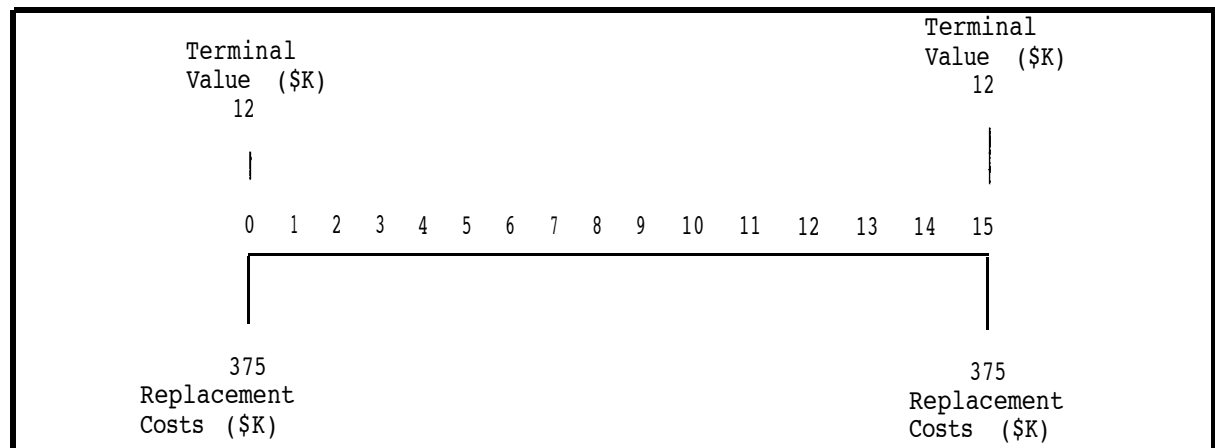
Figure 3-27
Cash Flow Diagram - Replace the Seawall
(no corrosion prevention or control)

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

3-53

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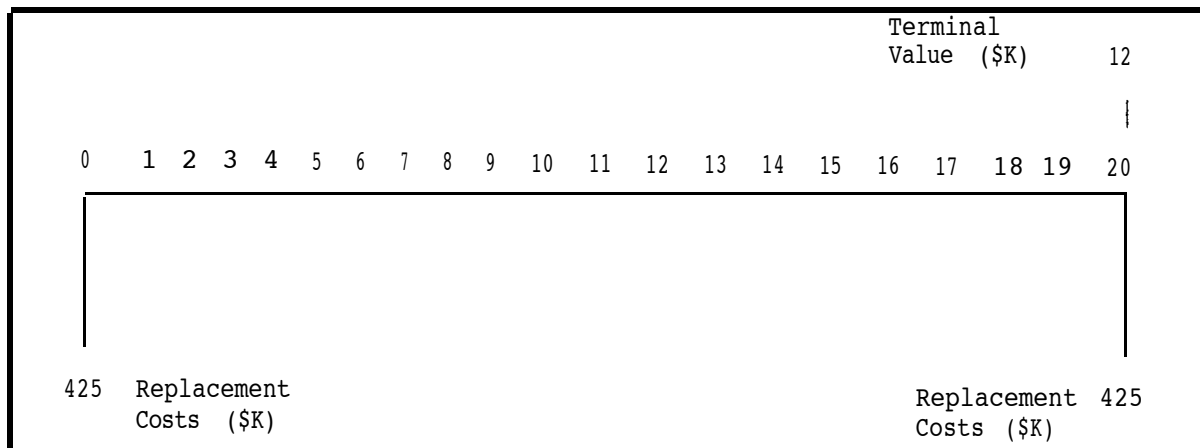
Figure 3-28
Cash Flow Diagram - Replace the Seawall (coat only)

Alternative 5 (economic life - 20 years)

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

3-54

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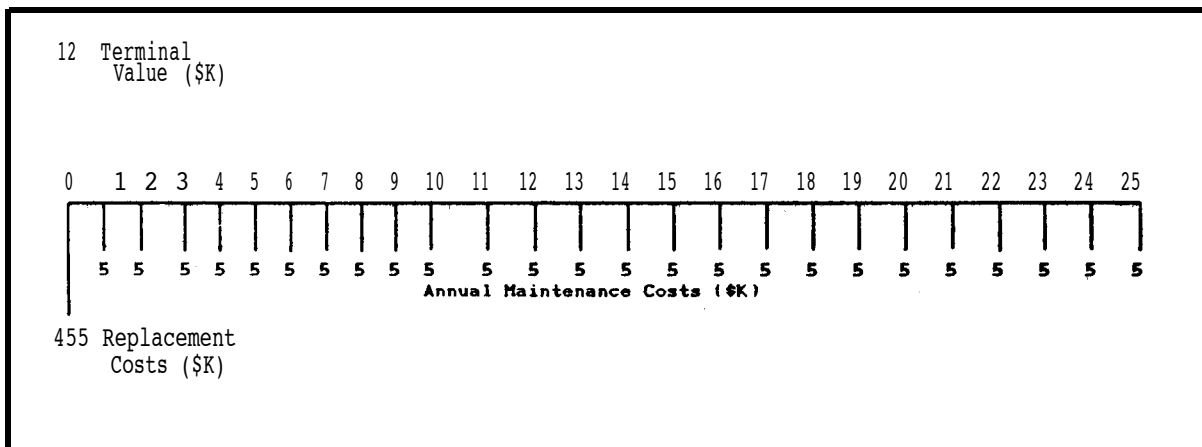
Figure 3-29
Cash Flow Diagram - Replace the Seawall
(coat and cathodic protection)

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					

3-55

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 h r
	$ 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

3-58
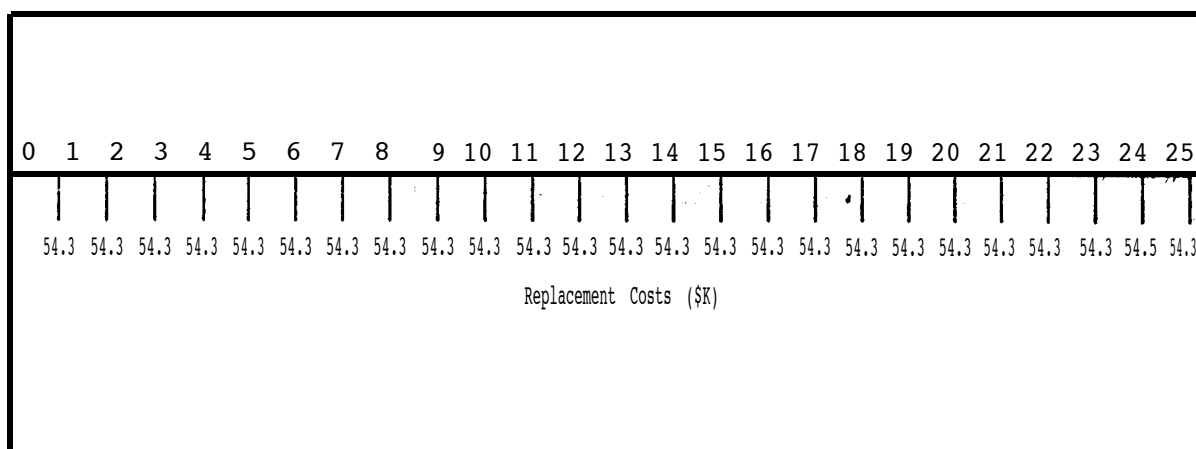
Figure 3-30
Cash Flow Diagram - Hollow Core Wood Interior,
Steel Exterior Doors

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

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(b) Hours required (replace) <u>x   9</u> 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):   <u>x   47</u>
Annual cost to replace 47 doors: $31,146.00
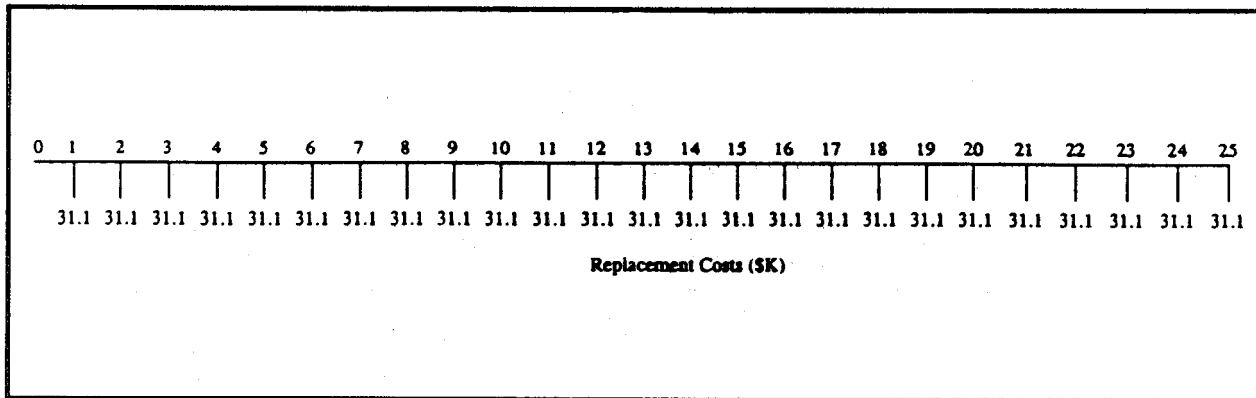
Figure 3-31
Cash Flow Diagram - Fiberglass Gelcoat Balsa
Wooden Core Exterior Doors

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					

3-60

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

3-61

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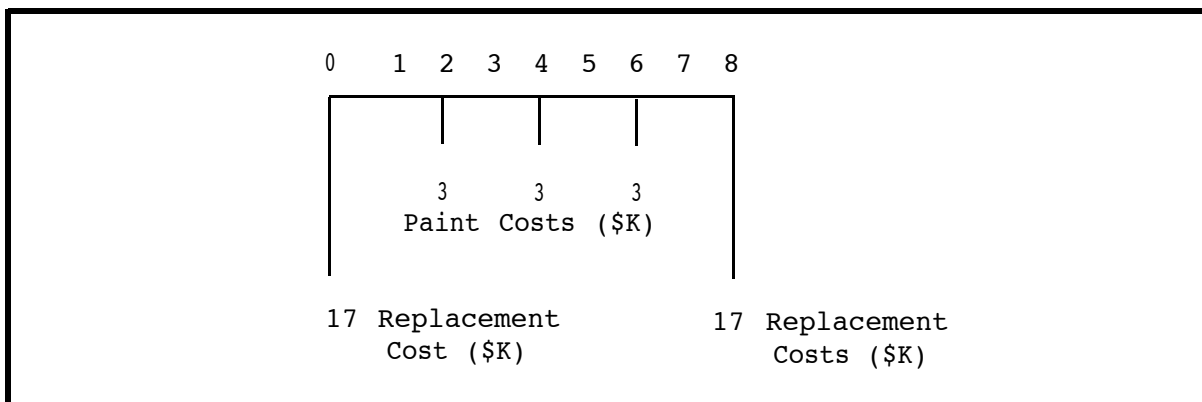
Figure 3-32
Cash Flow Diagram - Galvanized Steel Rain Gutters

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		

3-63

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.

```
     0     1  2  3  4  5  6  7  8  9  10  11  12
     ┌──────────────────────────────────────────┐
     │                                          │
     │                                          │
     │                                          │
     │                                          │
     │                                          │
     │                                          │
     16.8                                    16.8
     Replacement                             Replacement
     Costs ($K)                              Costs ($K)
```
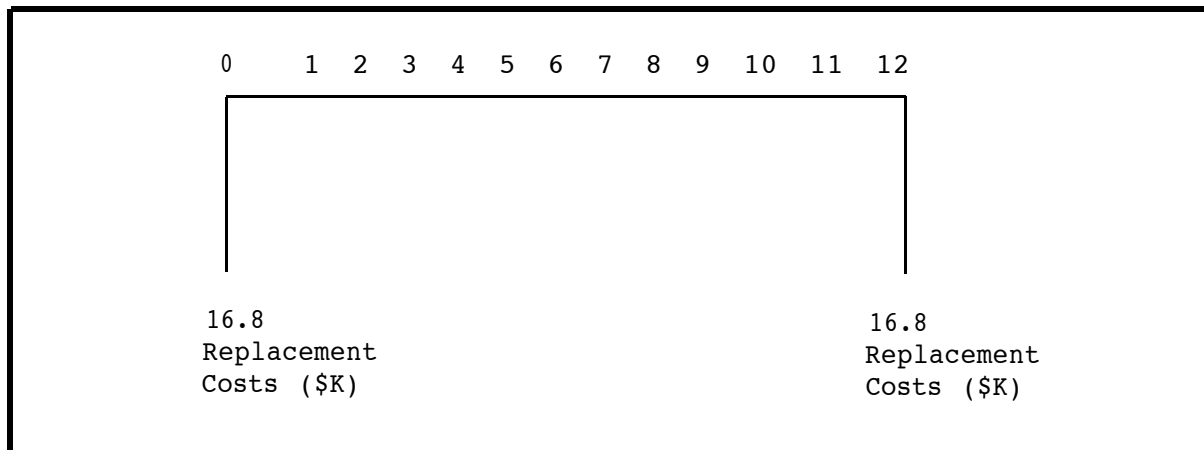
Figure 3-33
Cash Flow Diagram - Plastic Rain Gutters

Alternative 2 (economic life - 12 years)

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

3-64

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.
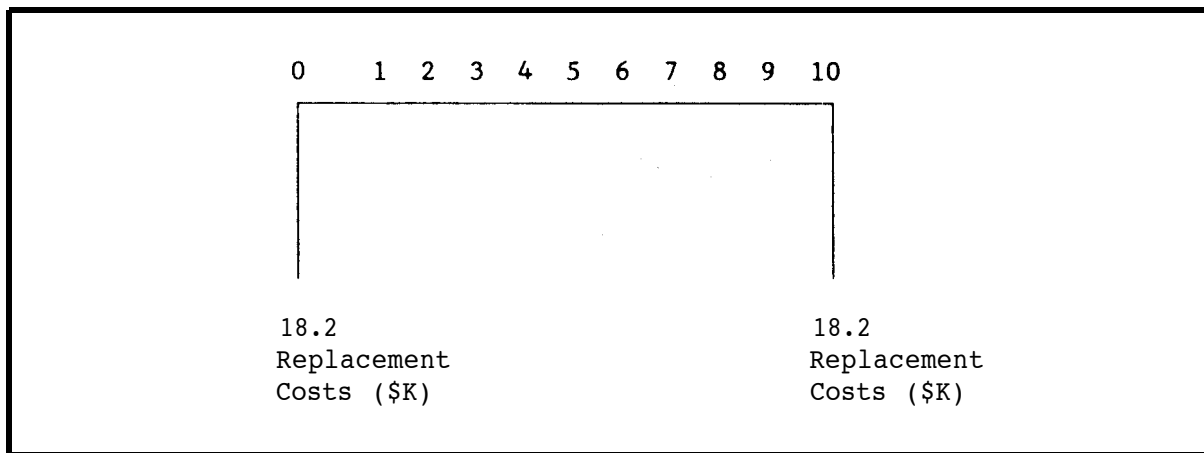
Figure 3-34
Cash Flow Diagram - Aluminum Rain Gutters

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

3-66

   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 <u>$1.50/ft</u> x 1,200 ft = <u>$1,800</u>
              $2.75/ft $3,300

Terminal value (cost): Salvage value $ 0

                Cost to remove fence <u>$180</u>:
                            $180

3-67

```
                    Terminal Values ($K)
                      0.18              0.18


                        │                 │
                        │                 │

                      0   1   2       3


                          ┌───────────────┐
                          │               │

                      3.3              3.3
                    Replacement Costs ($K)
```

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		

3-68

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

3-69

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

```
              Terminal Values ($K)
      0.18                          0.18

        |                             |
        |                             |
        |                             |

      0     1   2   3   4   5   6   7
        _____
       |                           |
       |                           |

      3.3                          3.3
            Replacement Costs ($K)
```

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

3-70

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

```
    0.18      Terminal Value ($K)      0.18

     |                                  |
     |                                  |
     |                                  |

     0    1  2  3  4  5  6  7  8  9  10

     |_____|
     |                                  |
     |                                  |

    3.7                                3.7
    Replacement                        Replacement
    Costs ($K)                         Costs ($K)
```

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

3-71

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

```
   0.18                Terminal Value ($K)                0.18

    |                                                      |
    |                                                      |

   0  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15
   |_____|
   |                                                      |
   |                                                      |

   3.3               Replacement Costs ($K)              3.3
```

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	

```
0.18 Terminal Value ($K)                        Terminal Value ($K)    0.18

 I                                                                       I
 0    1 2 3  4 5 6  7 8 9 10 11  12 13 14 15 16 17  18  19 20 21  22  23 24  25

 3.7                          Replacement  Costs ($K)                    3.7
```

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.
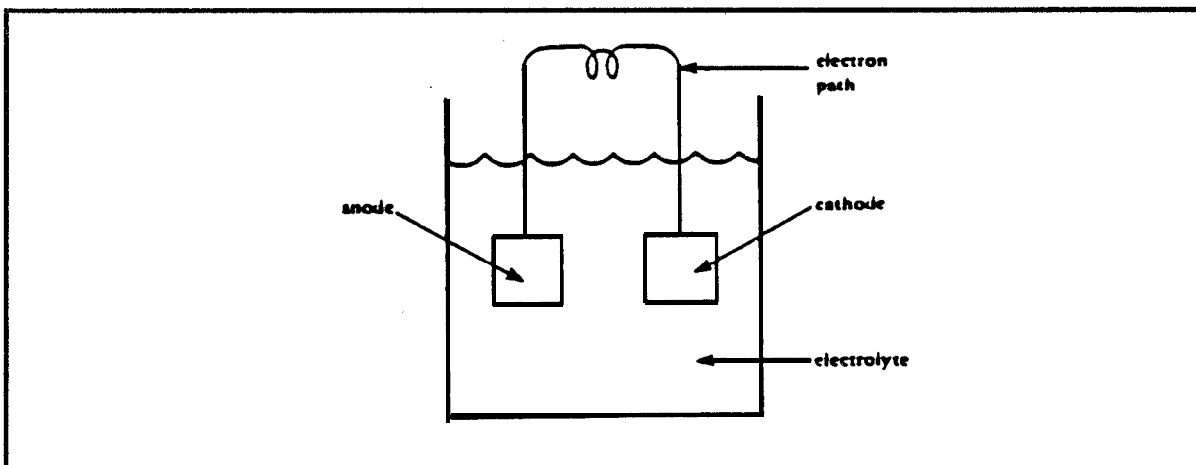
Figure 4-1
Electrochemical Cell

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:

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

where: M° = uncharged metal atom at the metal surface

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

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

4-2

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:

$$F e^{\circ} \longrightarrow F e^{++} + 2 e^{-}$$

where: $F e^{\circ} =$ metallic iron

$F e^{++} =$ 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:

$$R^{+} + e^{-} \longrightarrow R^{\circ}$$
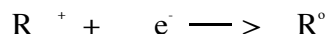
where: $R^{+} =$ a positive ion in solution

$e^{-} =$ an electron in the metal

$R^{\circ} =$ 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:

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

4-3

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:

$$H^+ + e^- \longrightarrow H^\circ$$
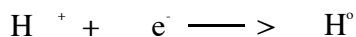
Where: H^+ = positive hydrogen ion in solution

e^- = electron

H° = 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:

$$2\ H_2O + O_2 + 4\,e^- \longrightarrow 4\ OH^-$$
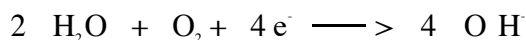
In this reaction, two water molecules combine with one oxygen molecule and four electrons to form four hydroxyl (OH) ions. This reaction requires oxygen and proceeds rapidly when the oxygen content of the environment is high. The production of hydroxyl ions makes the solution in the area of the cathodes 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:

$$M^\circ + R^+ \longrightarrow M^+ + R^\circ$$
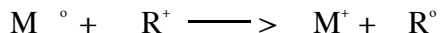
In this formula, the electrons, which are exchanged in equal amounts, are not noted.

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:

$$M^{\circ} \longrightarrow M^{+} + e^{-}$$
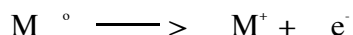
That an excess of materials, which appear on the left of the arrow, will increase the reaction rate whereas an excess of the materials on the right will decrease the reaction rate.

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:

$$2 \ H_2O + O_2 + 4 \ e^{-} \longrightarrow 4 \ OH^{-}$$
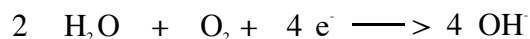
In this case, the availability of oxygen can limit the reaction rate. The availability of oxygen can be affected by both the amount of oxygen dissolved in the electrolyte and by the velocity of flow that provides a continuous source of water that is rich in oxygen.

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 break-down 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 cor-rosion 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 metal-lic 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.

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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.
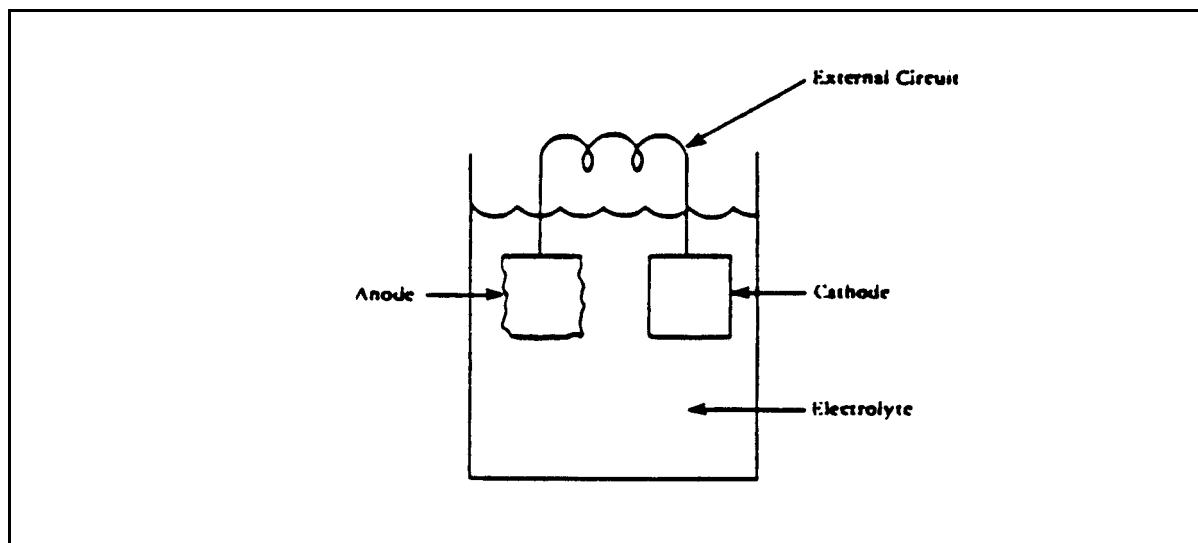
Figure 4-2
Galvanic Cell

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

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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

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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.
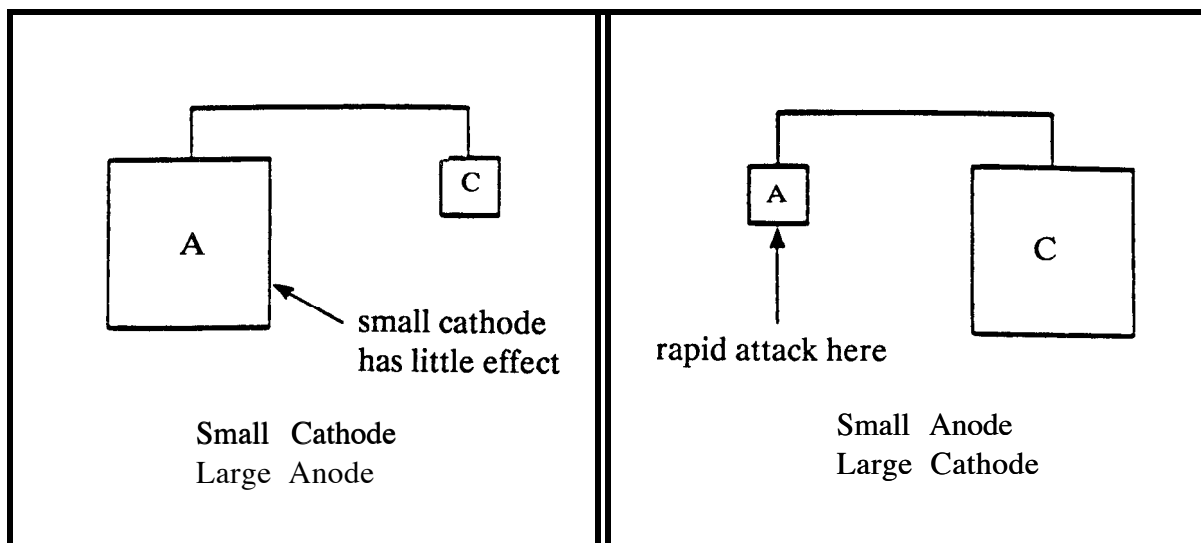
Figure 4-3	Figure 4-4
Benign Area Relationship	Adverse Area Relationship

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.

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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 non-metal 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.

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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:

$$2 \ H_2O \ + \ O_2 + \ 4 \ e^- \longrightarrow 4 \ OH^-$$
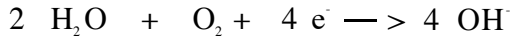
The law of mass action indicates that, where the oxygen content is high, the cathodic reaction will occur more readily than when the oxygen content is low. Thus areas where the oxygen content is low will not be as effective a cathode, anodic reactions will predominate and the area will act as an anode. 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:

$$M \ ^\circ \longrightarrow M^+ + \ e^-$$
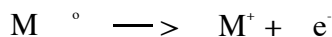
a buildup of metal ions inhibits the reaction. In areas where the anodic reaction is inhibited, cathodic reactions predominate and those areas become cathodes. In areas where the relative content of metal ions is low, the reaction can proceed freely and those areas tend to become anodic. In metal ion 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.

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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

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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.

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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.

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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 <u>Hydrogen Embrittlement</u>. 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

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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 Corrosion Fatigue. 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

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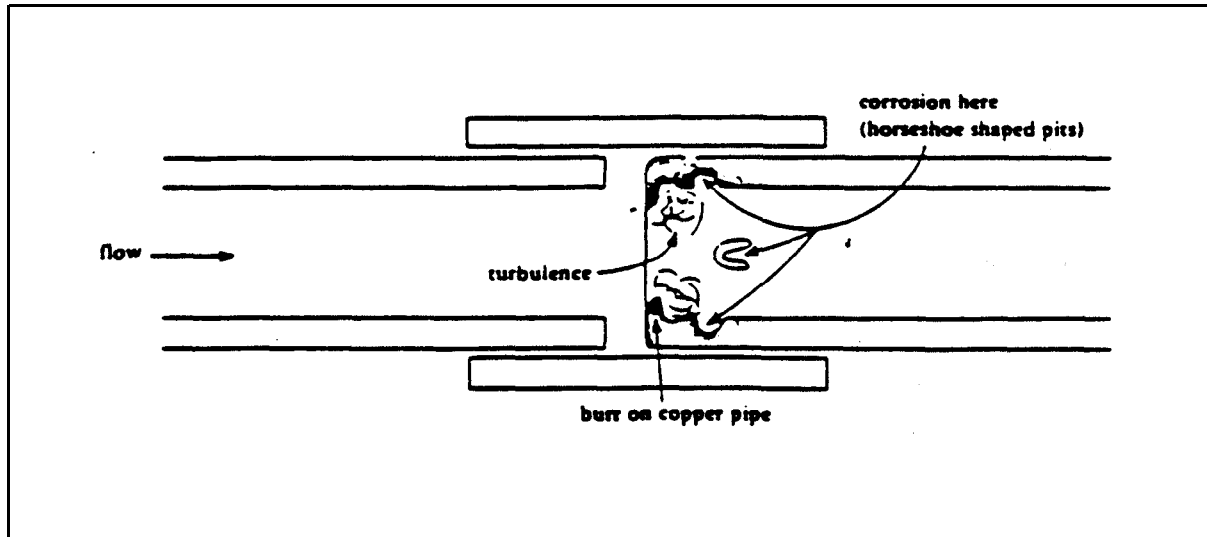
Figure 4-5
Horseshoe-Shaped Pits Created by Erosion Corrosion

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.

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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.

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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.

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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 Electrolyte. 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 Commonly Used Materials. A wide variety of metals are used in atmospheric environments. Steel and aluminum alloys are the most widely used, but stainless

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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

6-2

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 in-

staces, 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 <u>Structural Features That Lead to Corrosion.</u> 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 <u>Examples of Corrosion and Means for Control.</u> 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 <u>**Examples of Corrosion and Means for Control.**</u> 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)

6-8

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)

6-11

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.

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.

6-14

(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.

6-15

(continued)

TABLE 6.3.   (Continued)

6-16

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

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.

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.

6-21

(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.

POOR   GOOD

FIGURE 11—Joining Practices

WELDING   RIVETING

POOR

FAIR

RIVETS

GOOD   INSULATION

POOR   BETTER   GOOD
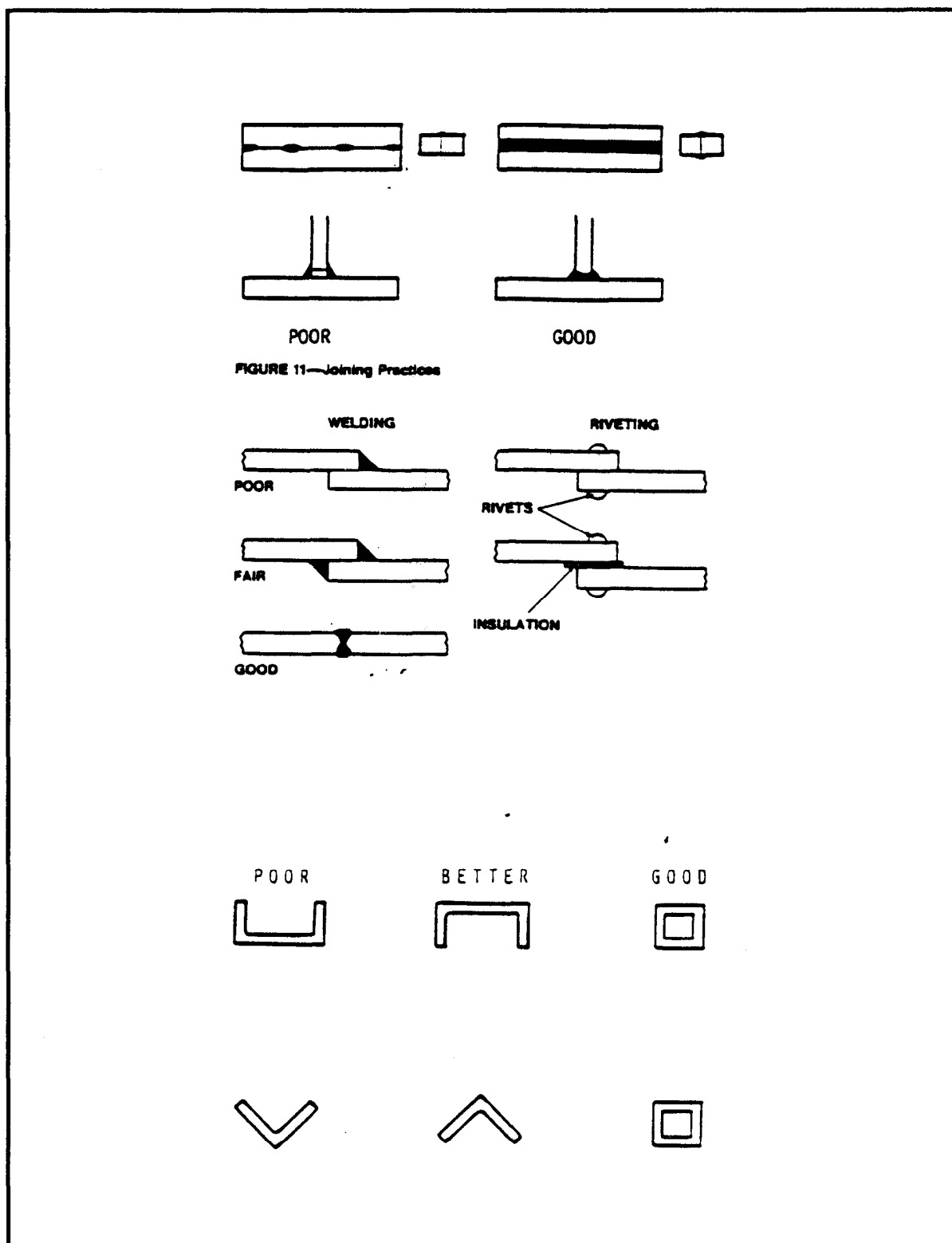
Figure 6-1
Structural Features That Lead to Corrosion

6-23

COATING

POOR   GOOD
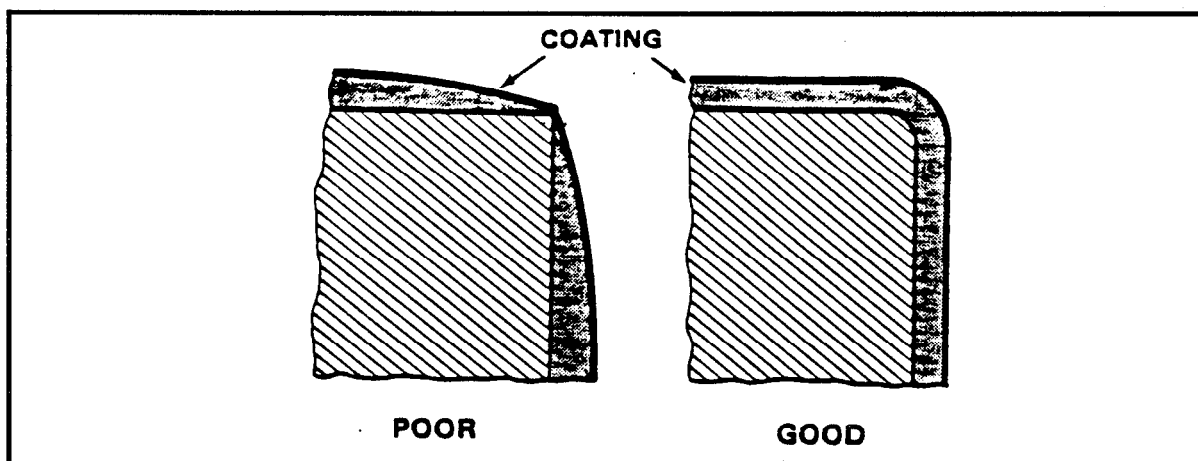
Figure 6-2
Aboveground Galvanic Cells from Dissimilar Metals

BRASS CAP SCREW   ALUMINUM COVER

CORRODING AREA

ANGLE IRON

CORRODING AREA

STEEL NAIL   CORRUGATED ALUMINUM

ROOF

STEEL GUTTER   CORRODING AREA

COPPER DOWNSPOUT
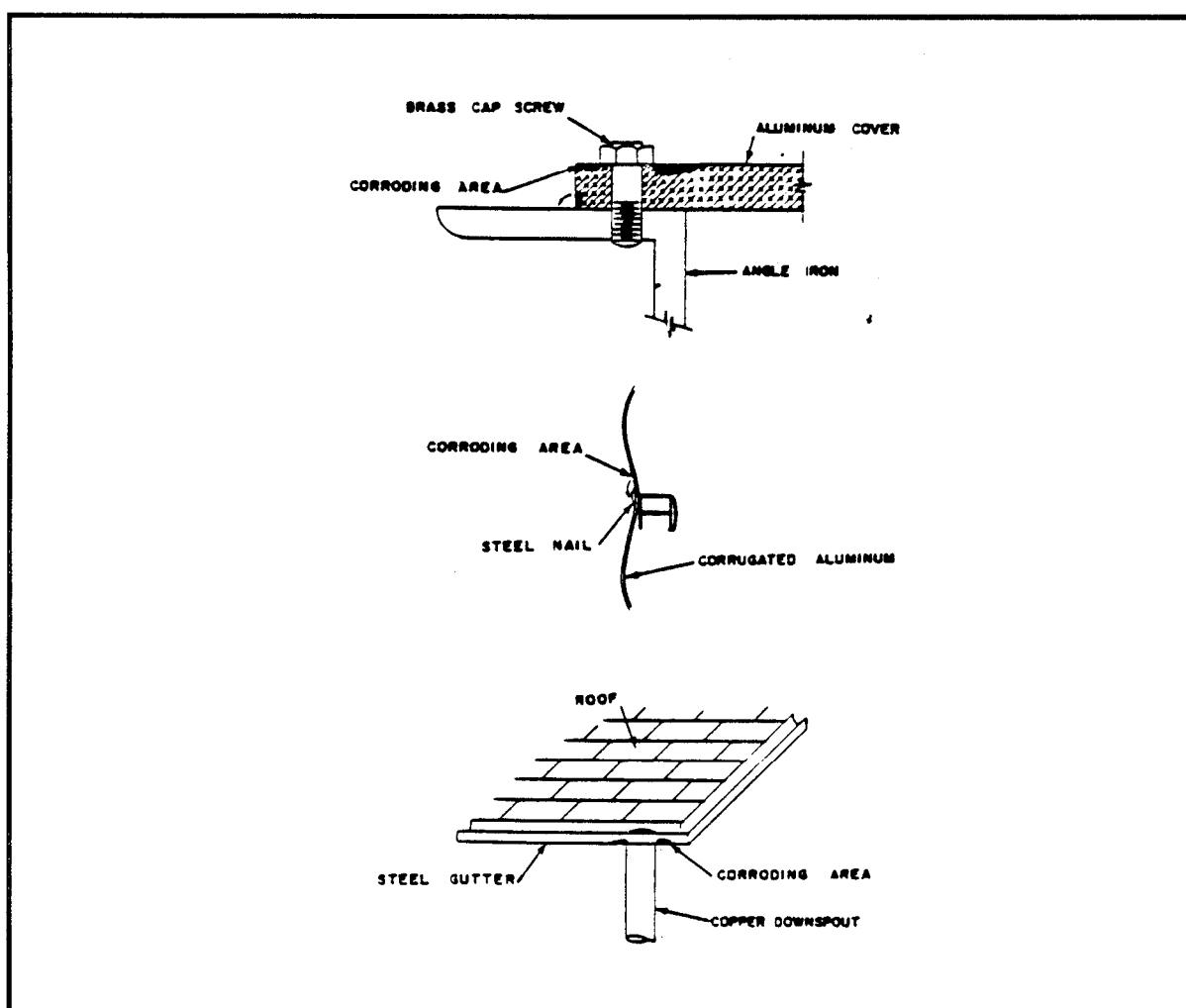
Figure 6-3
Edge Effects and Coatings

6-24
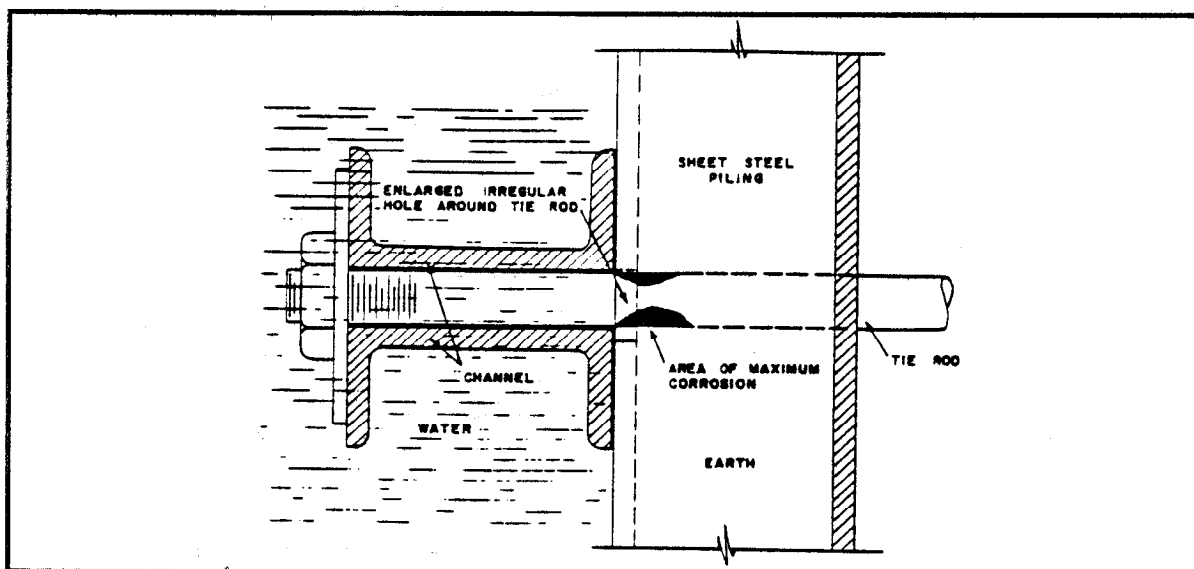
Figure 6-4
Tie-Rod Corrosion
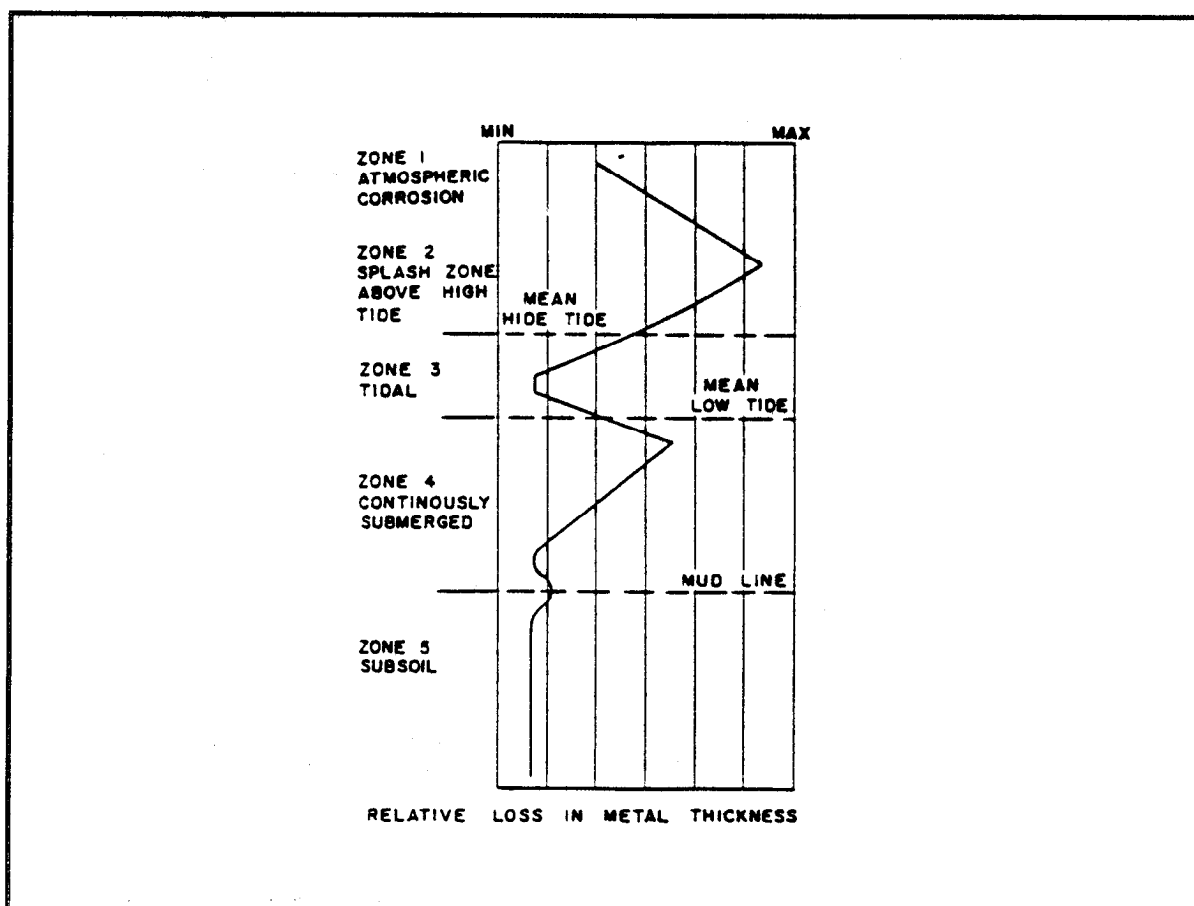
Figure 6-5
Pile Corrosion Profile

6-25
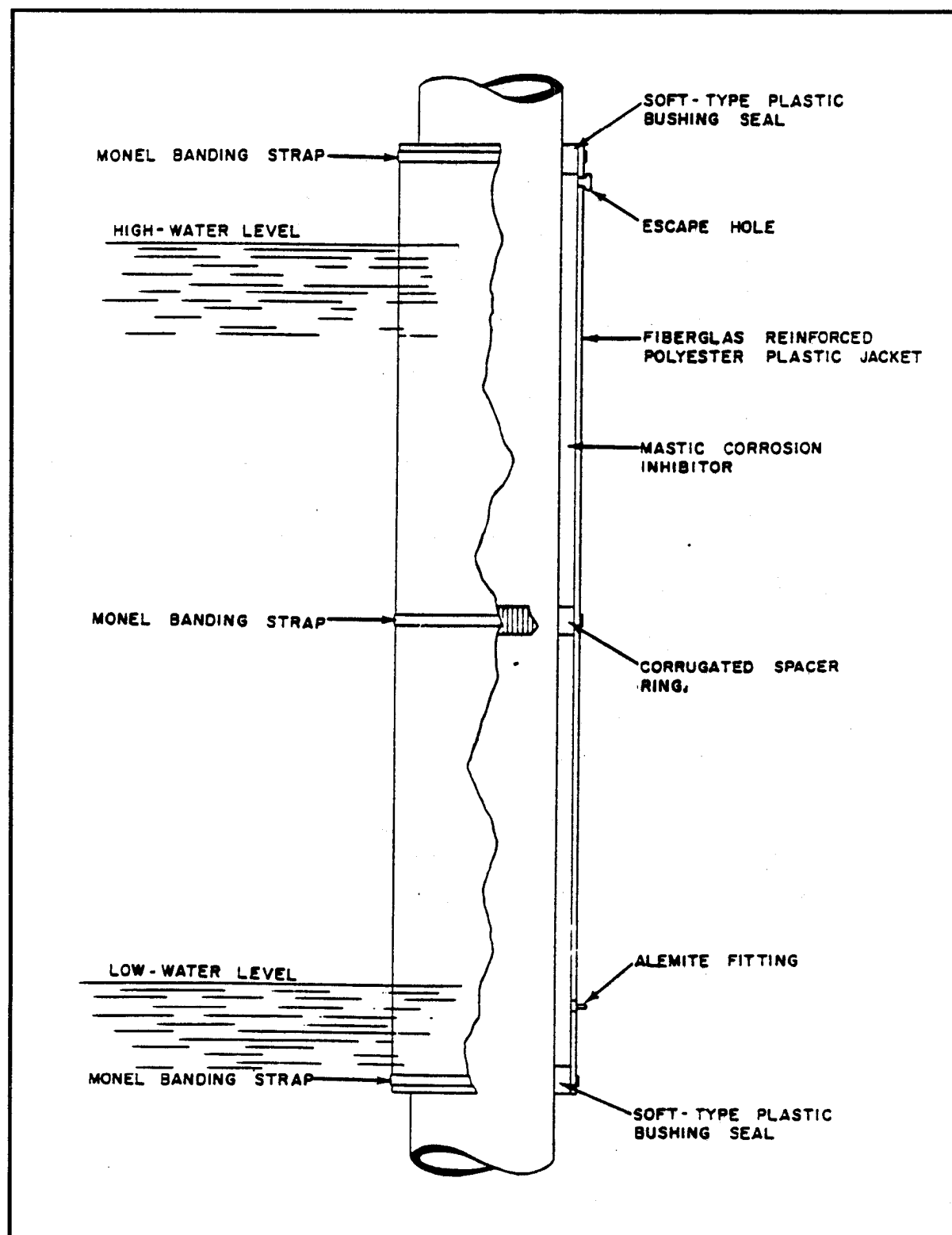
Figure 6-6
Protective Jacket

6-26
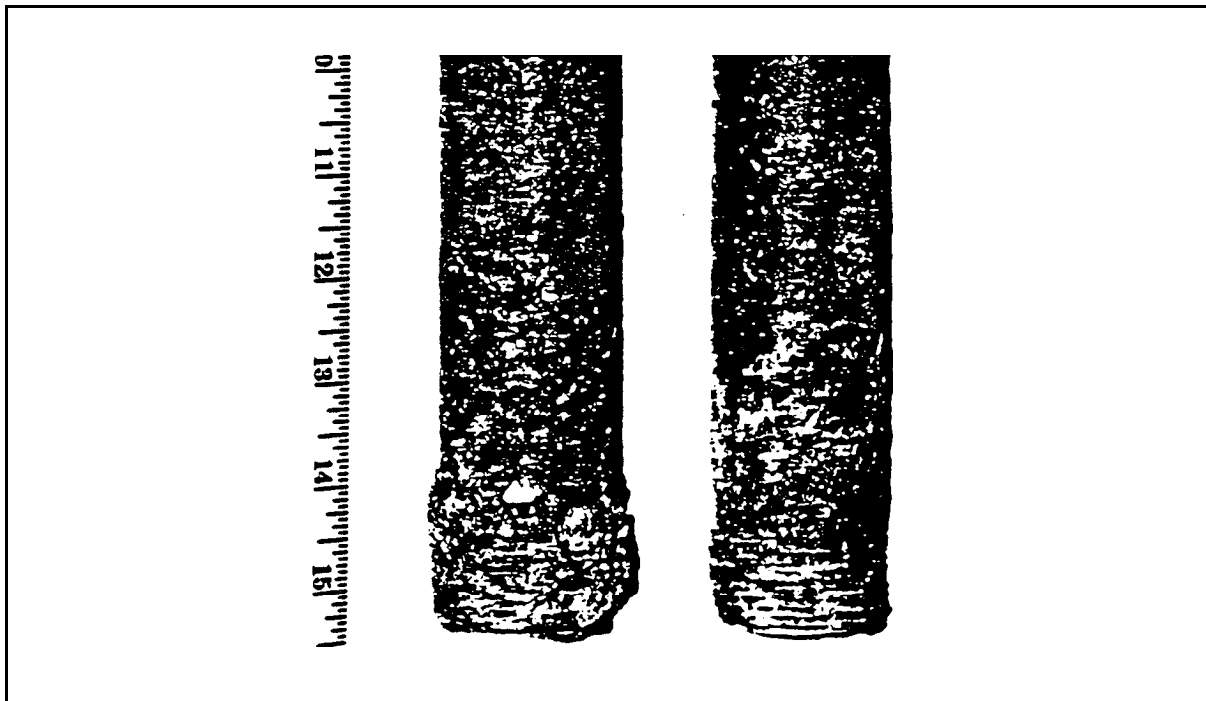
Figure 6-7
Example of Thread Corrosion
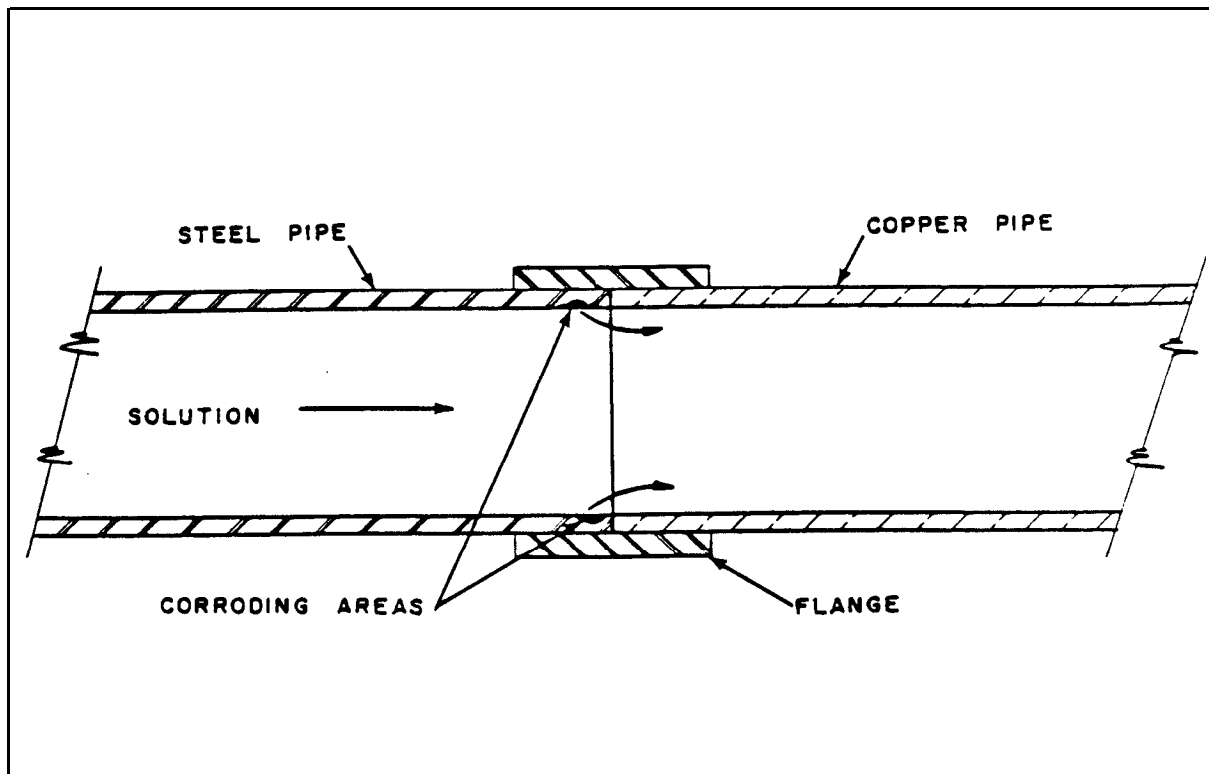
Figure 6-8
Interior Corrosion Resulting From Mating Copper and Steel Pipe

6-27
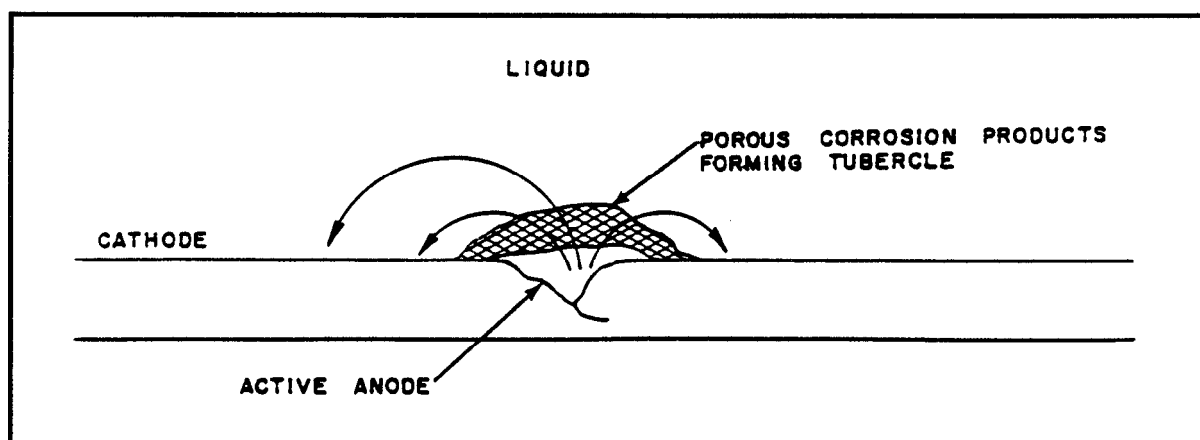
Figure 6-9
Oxygen Concentration Cell: Rust Tubercle on Tank Wall
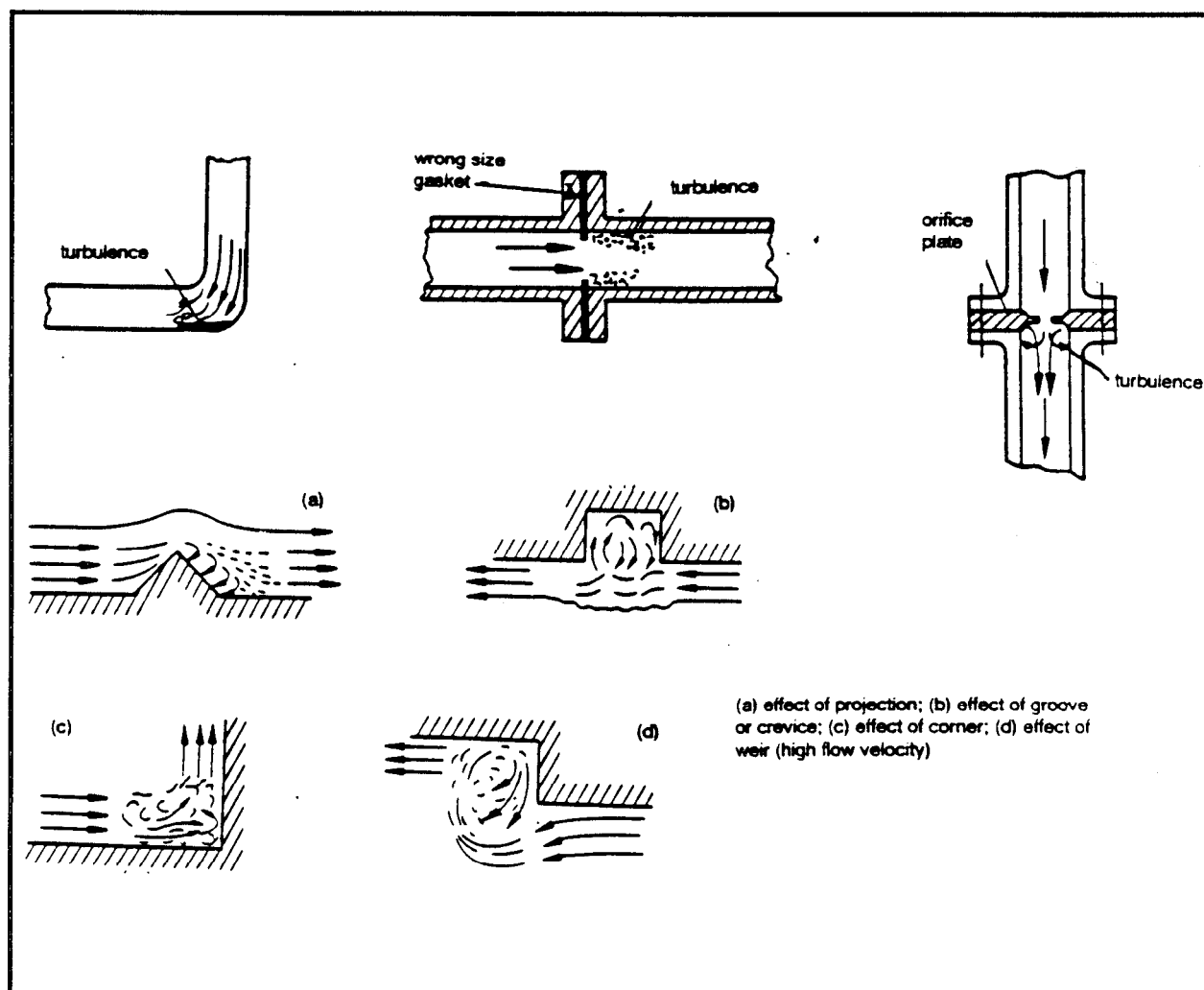
Figure 6-10
Velocity Related Attacks

I IN AMPERES

E IN VOLTS

STEEL PINS

B IS SMALL IN RELATION TO A

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	2590
4	725	247	2240
6	415	270	1,760
8	270	280	1,470
10	187	270	1,325
12	145	265	1255
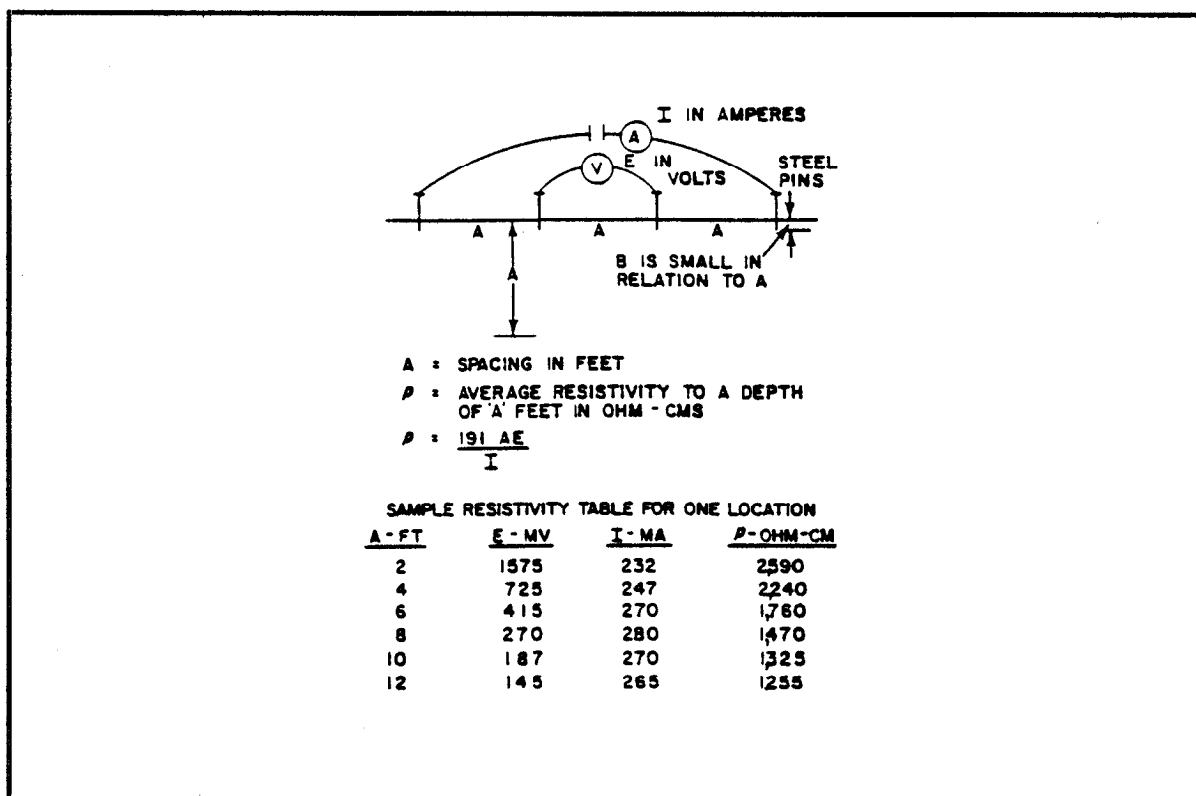
Figure 6-11

Four-Pin Method for Measuring Soil Resistivity

CATHODE AREAS

HILL

ANODE AREAS

ANODE AREAS

PIPELINE

SWAMP

RIVER CROSSING

SOIL LEAN IN SOLUBLE SALTS

SOIL RICH IN SOLUBLE SALTS

SOIL LEAN IN SOLUBLE SALTS

PIPE

ANODE AREA

CATHODE AREA

CATHODE AREA
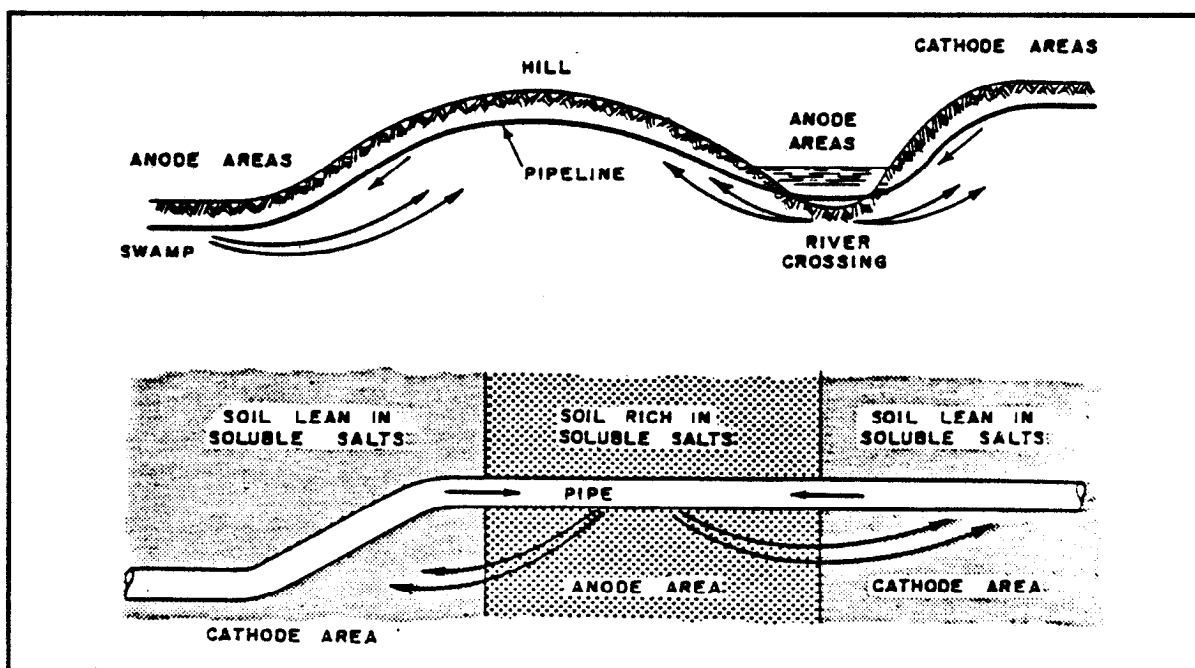
Figure 6-12

Long-Line Currents: Differential Environment Underground

6-29
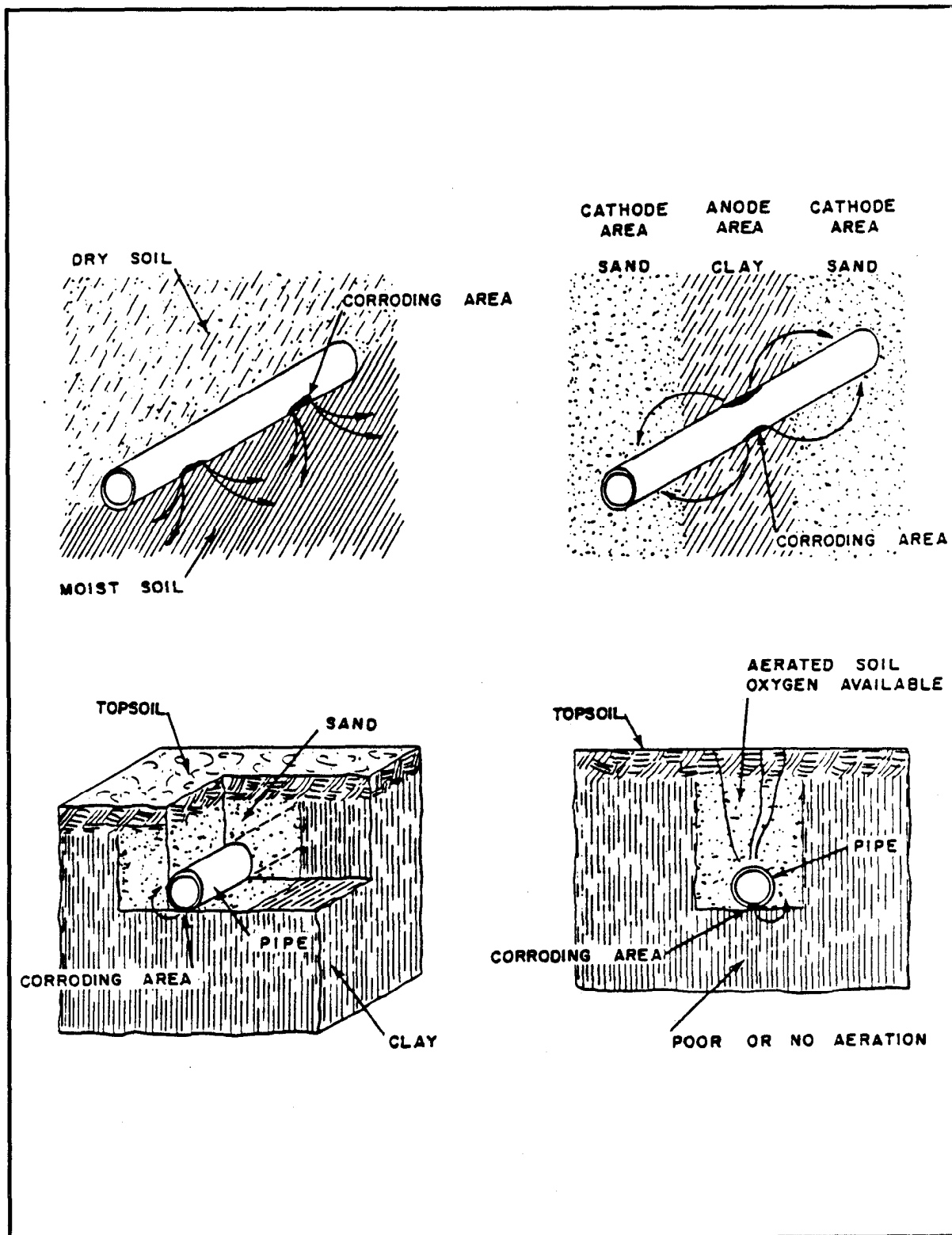
Figure 6-13
Differential Environment Underground

6-30
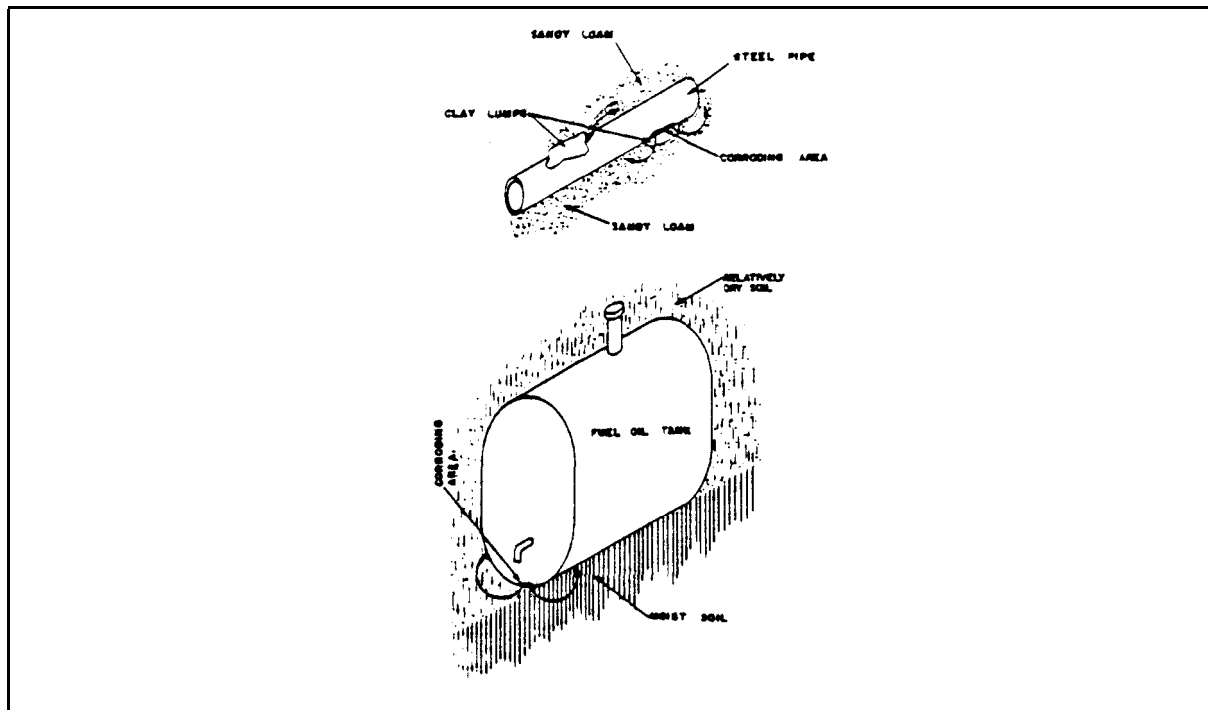
Figure 6-14
Additional Differential Environment Underground
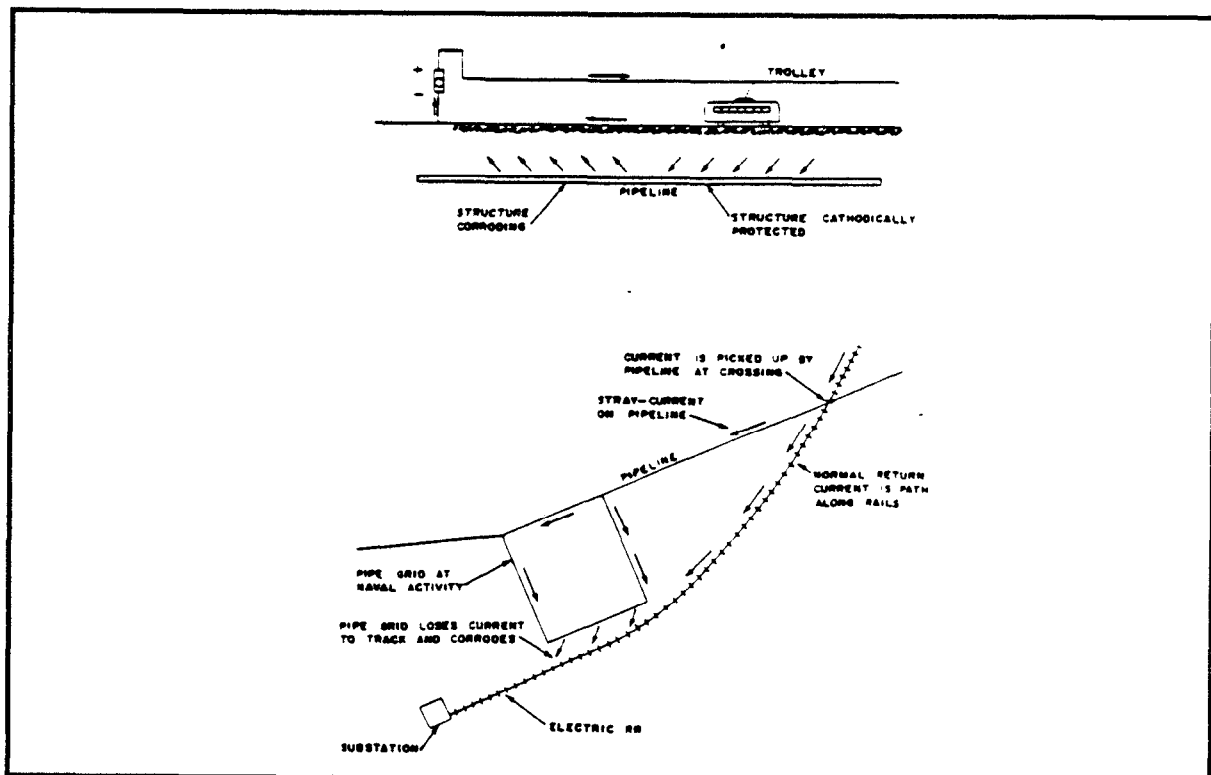
Figure 6-15
Stray Current Electrolysis From Electric Railway

6-31
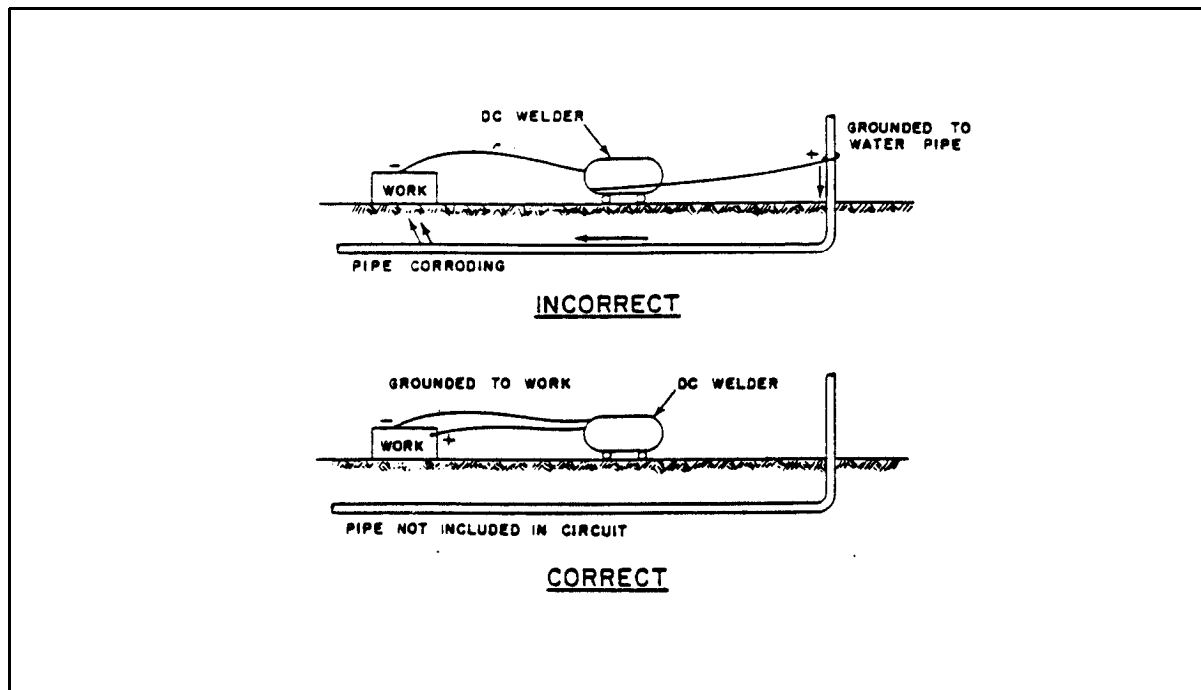
Figure 6-16
Stray Current Electrolysis From Local Sources
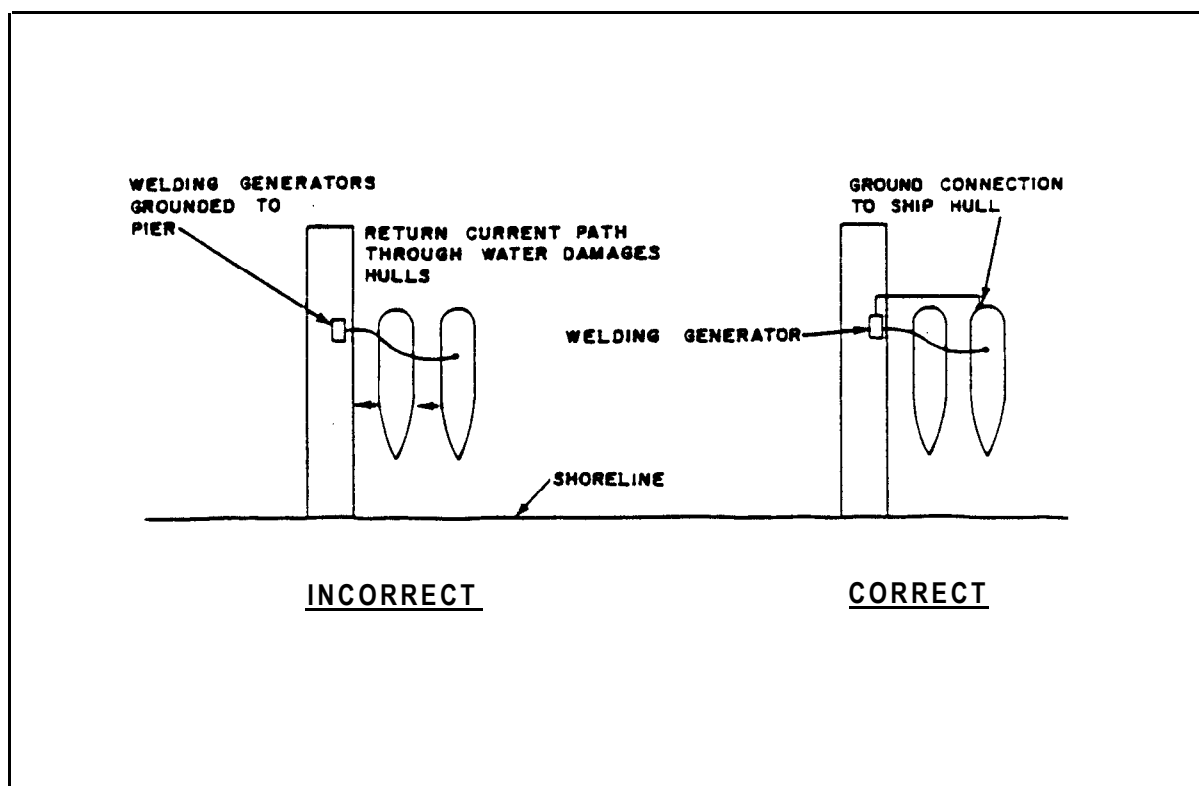
Figure 6-17
Correct and Incorrect Grounding

6-32

CHAPTER 7. CORROSION CONTROL BY COATINGS

7.1 INTRODUCTION. This chapter presents information on the effective use of organic coatings to protect metal, particularly steel, shore facilities from corrosion. This chapter provides a general understanding of the principles involved in coating operations, so that guide specifications for actual coating of facilities can be used most effectively.

7.1.1 Scope. This chapter covers coating of metal surfaces encountered at Naval shore activities,including their selection, application (and surface preparation), and maintenance in a state of acceptable condition. It does not cover painting of other substrate surfaces or painting of ships or aircraft. The coatings covered are limited to organic paint materials, with the exception of inorganic zinc coatings which are included, because they are most commonly used in conjunction with organic coatings and are applied by spray, like organic coatings. Powder coatings are also described, although their application is somewhat different from typical brush, roller, or spray application.

7.1.2 Coatings as Part of Corrosion Control Program. While coating metal surfaces is the most commonly used method of corrosion control, it cannot be used effectively without interacting with other methods of corrosion control. These include, but are not limited to, designing proper components; selecting proper materials, components, and cathodic protection; and using corrosion inhibitors.

7.2 METHODS BY WHICH COATINGS PROTECT METALS FROM CORROSION.
Coatings have three basic mechanisms for protecting metals from corrosion, although more than one of these mechanisms may be used by a coating. These mechanisms are: barrier protection, cathodic protection, and corrosion inhibitors.

7.2.1 Barrier Protection. Most coatings provide corrosion protection by forming a barrier relatively impermeable to moisture and electrolytes necessary for corrosion. Obviously, for optimum protection, the barrier should be as impermeable, thick, and continuous as practical.

7.2.2 Cathodic Protection of Steel. Some protective coatings have a high loading of fine zinc particles, so the particles in the cured film are in electrical contact with each other and with the underlying steel. This permits a type of cathodic protection. Presently, two basic types of zinc-rich coatings are used on steel: organic and inorganic products.

7.2.3 Inhibitive Pigments. Some pigments are added to primers to inhibit corrosion at the coating/metal interface. Red lead is the most common example of an inhibitive pigment.

7.3 COMPOSITIONS AND PROPERTIES OF COATINGS.

7.3.1 Components of Coatings and Their Functions. All ingredients used to formulate a coating can be placed in one of three basic categories: solvent, resin, and pigment. Each of these categories has a special function in the coating's formulation.

Solvent. The solvent is used to dissolve the resin material that actually forms the coating film. It also reduces the viscosity of the product to permit easier application, as well as affecting its leveling, drying, durability, and adhesion. Because the different organic polymers in different resins greatly differ in their solubilities, some resins require much stronger than others to dissolve them. In water-based coatings, the water is a dispersing rather than a dissolving agent.

The emission of virtually all organic solvents in coatings gives rise to photochemical smog. Thus, there is a great pressure to reduce the amount of solvent in coatings or to use water-based coatings.

Resin. The resin is the binder or film-forming part of the coating that is responsible for most of the properties of the coating. Thus, coatings are identified by the generic types of their resins. The resin and the solvent portions of coatings are sometimes called the nonvolatile and the volatile vehicle, respectively, and are sometimes referred to collectively as the vehicle.

Pigment. The pigment constitutes the solid portion of a coating. It is generally heavier than the liquid vehicle portion and may settle out on prolonged standing. Pigments are usually modified or unmodified natural earth materials, although less stable organic pigments are occasionally used. The chief function of the pigment is to provide opacity (hiding) to protect the organic vehicle from degradation by sunlight. Titanium is the pigment most frequently used to give opacity to white paints and light tints.

Pigments also provide color, improve adhesion and weather resistance, decrease moisture permeability, and control gloss. Leafing pigments, such as aluminum, tend to form parallel plates in the film to effectively increase its thickness by increasing the path moisture must penetrate. Other things being equal, the finer the pigment particle size and the less the pigment/resin ratio, the glossier will be the coating.

The pigment and the resin portions are sometimes called the solids portion, since they remain after all the solvent has evaporated. Obviously, the greater the coating solids, the greater will be the dry film thickness received from a given wet film thickness.

There are also many additives or extenders added to coatings to modify gloss or consistency, emulsify components, improve weathering, or obtain some other desirable

property. They are considered to be in the resin or pigment part depending whether they exist in the coating as a liquid or solid.

7.3.2 **Mechanisms of Curing.** All coatings cure from one of three basic mechanisms: air-oxidation of drying oils, solvent or water evaporation, or a chemical reaction of components. Coatings that cure by the same basic mechanism tend to be compatible with each other but not with coatings that cure by other mechanisms.

Air Oxidation of Drying Oils. Coatings that cure by air oxidation of drying oils have oxygen from the air react with the unsaturated fatty acids in their drying oils. By this reaction, liquid resins are converted to a solid film.

Examples of coatings that are cured by this mechanism are unmodified drying oils (e.g., linseed oil), alkyds (usually formed by reaction of oils with phthalic anhydride), silicone alkyds, oleoresinous phenolics, and epoxy esters. They wet surfaces very well and generally perform well in mild environments, but they have limited durability in chemical environments, particularly alkaline environments. They cannot be used in water immersion service, except for oleoresinous phenolics. Formulating oil-based coatings with low solvent content presents difficulties and requires unique changes.

Solvent Evaporation. Coatings that cure by simple solvent evaporation are sometimes called lacquers. They are made by dissolving solid resins in an appropriate solvent. After application, the solvent evaporates to deposit the resin in a thin film. No chemical change occurs to the resin. Resins that are softened by solvent or heat are called "thermoplastic."

Examples of coatings that cure by this mechanism are vinyls (polyvinyl chlorides) and chlorinated rubbers. The polyvinyl-butyral resin used in wash primers also belong to this category, as do asphaltic and coal tar coatings. Coatings of this class have limited solvent resistance, since they were deposited from a solvent, but are easy to topcoat and repair because the topcoat solvent bites into the undercoat to bond tightly. Because lacquers are high in solvent (VOC) content, their use will be greatly curtailed.

Water Evaporation. Latex and many other water-borne coatings cure by simple water evaporation. Emulsified particles of solid resin coagulate to form a film as the water is lost. The range of acceptable ambient temperature and humidity values is much more critical for water-borne than for other coatings.

Examples of latex coatings are acrylics and vinyls (polyvinyl acetate). Latex films are quite flexible but tend to be more permeable and less durable than many other films.

Chemical Reaction. Coatings that cure by chemical reaction are usually the most durable. They are generally packaged in two separate containers and mixed to initiate the reaction. Components must be combined in the specified proportions in the manner specified by the supplier to achieve a complete reaction. Sometimes, an "induction period" is required after mixing and before application to permit the reaction to get started. After mixing, there is always a "pot life" during which the coating must be applied, before the reaction has advanced so far as not to permit proper application and curing.

Examples of this class are epoxies, coal tar epoxies, urethanes, and polyesters. Because the chemical reaction is irreversible, they are called "thermosetting" coatings. Although this makes the coating very chemical and solvent-resistant, it also makes the cured coatings difficult to topcoat. Thus, the topcoat is best applied while the undercoat still has some residual tack. After the coating has completely cured, it is necessary to first spray a thin tie coat and then apply a full coat to it when it is still tacky.

Another example of chemically curing coatings is the inorganic zinc coating. They may cure by different types of reaction. Thus, some cure by reaction with water from the air, and thus cure slowly in dry environments. A one-package urethane water-based inorganic zinc coating cures by chemical reaction after evaporation of the water.

Zinc-rich organic coatings may contain different organic resins. Their curing mechanisms are those of the resin-solvent evaporation for zinc-rich vinyls and chemical reaction for zinc-rich epoxies.

7.4 ENVIRONMENTAL, HEALTH, AND SAFETY RESTRICTIONS ON COATINGS.
Environmental restrictions have greatly limited the compositions of coatings, the surface preparation, and the coating application techniques that can be used in many locations. These restrictions can be expected to become even tighter in the near future. Although much general information is provided in this section, personnel concerned with products or procedures described should confer with local authorities to determine what are the prevailing regulations.

7.4.1 <u>VOC Limitations.</u> Volatile organic compounds (VOCs) make up the solvent portion of coatings. Regulations have been enacted in many locations that have not achieved the ozone level established by the Environmental Protection Agency. These regulations cover architectural coatings, coatings for miscellaneous metal parts (shop Painting), aerospace coatings, and architectural coatings. This chapter will concern itself only with VOC restrictions on architectural coatings and coatings for miscellaneous metal parts, since the others are outside the scope of this manual. An architectural coating is for a structure fixed in place, while a miscellaneous metal part is defined as a structural component that can be taken to a shop for coating. Presently,

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most architectural coatings have a VOC limit of 250 g/liter, while metal part coatings have a VOC limit of 340 g/liter.

The effects of the two regulations of concern are such as to cause reformulation or elimination of virtually all coatings previously used on metals. Only the latex military coatings seldom specified for steel are in conformance. Indeed, use of latex coatings on steel has created many costly problems, because it not only is hard to formulate a high-performance water-based coating for metals, but the range of acceptable temperature and humidity conditions for suitable application is limited.

VOC emissions into the air have been further reduced by regulations restricting the methods of shop application of coatings to those with 65 percent transfer efficiency. For most configurations coated in shops, this effectively means that spray applications must be accomplished by electrostatic spray, or air-assisted airless spray.

7.4.2 Lead and Chromium Concerns. Lead and chromium pigments have been used for many years as corrosion inhibitors for metal primers. Recently, concern has been expressed for possible toxic effects of these pigments in coatings. Thus, lead can no longer be used on housing or other structures where children might come into contact. Probably more important are new regulations concerning the removal of lead-based coatings. They require that removal of existing coatings be preceded by testing the coatings for lead and that lead-containing paint be contained during removal, the air be monitored for lead in the particulates formed during removal, and that the old paint and blasting abrasive be disposed of in a manner required for toxic waste. This great expense, as well as health concerns for children exposed to lead-based paints, has effectively eliminated their use for Navy and Marine Corps facilities. Concern has also been expressed for problems in removing chromium-containing coatings. Thus, using coatings containing lead or chromium is not recommended. When removing old coatings, they should be tested for lead, chromium, and other heavy metals, and then removed and disposed of in accordance with appropriate local regulations.

The corrosion inhibitive pigments commonly used for coatings are listed below in two columns, those considered to be toxic and those considered relatively nontoxic:

Toxic	Nontoxic
Red Lead	Zinc Oxide
White Lead	Zinc Phosphate
Zinc Chromate	Zinc Molybdate
Strontium Chromate	Calcium Borosilicate
Basic Lead Silica-Chromate	Calcium Phosphosilicate
	Zinc Phosphosilicate

7.4.3 Mercury. Mercury-containing mildewcides were once routinely added to most oil-based and latex house paints to control the growth of mildew. These compounds used in a low concentration were effective in controlling the growth of most mildew organisms. Recent concern over toxic effects of mercury compounds has restricted the use of mercurials in coatings. Synthetic organic mildewcides approved by the Environmental Protection Agency have replaced mercury mildewcides in most coatings. The products, however, are required in much greater amounts than mercurials to be effective against mildew organisms, some have not shown long term effectiveness, and others may prove to be more hazardous than originally suspected. Investigations are being conducted into determining the most effective and safe use of mildewcides in coatings. In the mean time, these products should be handled such as to limit exposure.

7.4.4 Asbestos. Asbestos fibers were once used extensively to reinforce coatings. They are no longer used, because these fibers pose a health hazard if they get into the air. Thus, old asbestos-containing coatings (e.g., asbestos-filled bituminous coatings) should not be sanded, nor asbestos-cement products be coated, less asbestos fibers be released.

7.4.5 Coal Tar. Coal tar and asphalt coatings were once extensively used. Their use is greatly restricted now because of toxicities of some of their ingredients, because they do not perform well in sunlight, and because of new VOC limitations. One of their chief uses was to line steel potable water storage tanks. Now epoxy coatings, which are considered safer, are used for this purpose.

7.4.6 Organotins. Organotin compounds were found to be very effective in coatings to control the attachment and growth of fouling organisms on the hulls of marine vessels. Concern has greatly limited the use of antifouling paints containing these products. Now the use of such coatings is permitted only on large ships and on aluminum boats, because the other available products containing cuprous oxide will cause galvanic corrosion of aluminum. Cuprous oxide antifouling coatings (e.g., MIL-P-15931) are used routinely elsewhere, where they may be effective for 2 or more years depending on the service.

7.4.7 Urethane Resins. Urethane coatings are of a health concern because of toxic effects of their isocyanate components. To alleviate these concerns, the amount of free isocyanate has been limited, and strict safety procedures have been established for applying urethane coatings.

7.4.8 Abrasive Blast Cleaning. Because abrasive blasting is the preferred method of preparing the surfaces of most metals for coating, it should be considered despite the restrictions and costs in its use.

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Particulates. Particulates produced during dry abrasive blasting pose a health threat. Regulations have been imposed to restrict blasting options to such procedures as blasting in closed buildings, using approved abrasives, wet abrasive blasting, and water blasting. The options will be discussed in the section on surface preparation. California's South Coast Air Quality Management District has imposed fees on abrasive blasting related to the amount of particulates produced. Since a much greater quantity of particulates is produced when blasting with sand than with shot or grit, promulgation of this action elsewhere may greatly restrict the use of sand in abrasive blasting.

Silica. Because silica abrasive used in blast cleaning may cause silicosis, its use has been eliminated in Naval Sea Systems Command operations (shipboard use). Because of this and other considerations, use of silica (sand) abrasive is not recommended on shore facilities, unless there is a compelling reason. If this is the case, special precautions should be taken to protect the workers.

Toxic Coatings. Since toxic coatings (e.g., lead-based paints) require special containment and disposal when removed by blasting, it is important to keep the amount of toxic waste (contaminated spent abrasive) as low as possible. This can be done by using the vacuum blasting technique described in the section on surface preparation.

7.5 SELECTION OF COATINGS.

7.5.1 General. Before selecting a coating, four basic questions must be answered:

1. What is the type (e.g., steel) and condition of the substrate?

2. What is the basic function of the coating on the substrate?

3. What is the nature of the environment?

4. What are the desired properties of the coating?

In actual practice answers to the first three questions will normally determine the answer to the fourth question, which in reality dictates what coating system is most appropriate. Another important question may be what methods of surface preparation and application are available, since time, money, accessibility, or environmental restrictions may limit the methods that can be used. Historically, life cycle costing has been the bottom line in selecting a coating system. Now, the cost of coating removal and disposal has become a very important factor. Thus, long-term, high-performance coatings are almost always the coatings of choice for new construction.

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Spot repair of coatings is best accomplished with a material similar to that already in place, in order to avoid incompatible products. Because of new environmental restrictions, this may not be possible. Then, special care may be required to insure compatibility. The one exception to spot repairing with a like material occurs with inorganic zinc coatings with organic topcoats. Since inorganic zinc coatings do bond well to organic coatings, zinc-rich organic coatings are used.

7.5.2 General Properties of Differently Curing Coatings. Each of the generic coating types formulated for metal surfaces that are commonly used in Naval shore facilities will be discussed separately.

The advantages and limitations of using the different coatings are listed separately after each discussion.

Oil-Based Coatings. Oil-based coatings were the first coatings used to protect steel from corrosion. They are still used extensively today but have only limited service lives in severe environments. Because the drying oil wets surfaces so well, they are more tolerant of incomplete surface preparation than are other coatings (e.g., they perform reasonably well on steel cleaned by hand or power tools). These coatings deteriorate rather rapidly in water immersion (except for oleoresinous phenolics) or on alkaline surfaces, such as galvanized steel and or concrete. For this reason they are not used in these environments. Oil-based coatings include unmodified drying oils, alkyds, epoxy esters, and oleoresinous phenolics. Unmodified drying oils can be formulated into VOC-conforming coatings more easily than the other resins. It is usually necessary to use the exempt solvent 1, 1, 1-trichloromethane to be VOC conforming. This solvent may be eliminated from exemption in a few years because of toxicity concerns.

Advantages	Limitations
Easy to apply, topcoat, and repair	Poor alkali resistance
Moderate cost	Poor immersion service
Good wetting of surfaces (easy surface preparation)	Poor chemical/solvent resistance
Fairly good gloss retention	Poor heat resistance
Can be relatively flexible	Limited weather resistance
Fair exterior durability	
From renewable sources	

Latex Coatings. Latex coatings have been a boom to homeowners because they are easy to apply to a variety of surfaces and are easy to clean up. They are also environmentally acceptable, as they are VOC conforming, even if they may contain compatible organic solvents. Limitations include limited durability, especially on steel and other metals; poor chemical and solvent resistance; and limited acceptable application condi-

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tions. Their excellent flexibility is offset by their poor wetting of surfaces. When applied over a smooth enamel, it is necessary to lightly sand the enamel to achieve good topcoat bonding. They are available as acrylics, vinyls (polyvinyl acetates), or copolymers of these resins. Acrylic latexes may be applied over epoxy systems to provide improved exterior weathering.

Advantages	Limitations
Low cost	Limited durability
Easy to apply, topcoat, and repair	Poor chemical/solvent resistance
Good flexibility	Poor wetting of surfaces
Environmentally acceptable	Poor immersion service
	Poor heat resistance
	Must apply above 70°F

Bituminous Coatings. Bituminous (coal tar and asphalt) coatings have been used for many years.

Advantages	Limitations
Low cost	Poor exterior weathering
Good water resistance	Poor chemical/solvent resistance
Good film build	Available in black only
Easy surface preparation	
Easy to apply	

Lacquers (Vinyls and Chlorinated Rubber Coatings). Vinyl and chlorinated rubber lacquers have excellent water and chemical resistance, but poor solvent resistance. They have a low rate of film build up because they have a high solvent content. However, because of their short drying time, the film can rapidly build up. The high solvent content causes them to exceed VOC limits. This greatly reduces their use. They have relatively good gloss retention and durability if they have enough titanium dioxide content to protect the resins from sunlight. They usually require a greater degree of blast cleaning than the coatings previously described in this section. The first vinyls developed required wash priming of the steel to achieve good adhesion, but later formulations do not.

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Advantages	Limitations
Good chemical and water resistance	Poor solvent resistance
Easy to repair and topcoat	Poor heat resistance
Rapid drying and recoating	Low film build up
Applicable at low temperatures	
Has good durability/gloss retention	

Epoxy Coatings. Epoxy coatings have some of the best combinations of chemical, solvent, and water resistance. They form a tightly adhering, hard, slick film with good abrasion resistance and durability. Their shortcomings include inflexibility, poor weathering (chalking and poor gloss retention in sunlight), and difficulties associated with a chemically-curing coating (two- package mixing, limited pot life, and difficulty in topcoating, as described earlier). The surface must be cleaned to a near white finish, but epoxy-polyamide coatings are a little more tolerant of incomplete cleaning. Of the two types of epoxy most commonly used on shore facilities, epoxy-polyamides usually have the better water-resistance and amine-cured epoxies have the better chemical resistance. Epoxies can be formulated to make them high solids (even 100% solids) or water-based to make them VOC conforming.

Advantages	Limitations
Excellent chemical, solvent, and water resistance	Chalks freely in sunlight
	Poor gloss retention
Hard, slick, durable film	Curing must be above 50°F
Excellent adhesion	Clean, blasted surface required
Good abrasion resistance	Two-package coating; limited pot life
Can be made VOC conforming	May be difficult to topcoat

Coal Tar Epoxy Coatings. Coal tar epoxy coatings have coal tar added to the epoxy formulation. This increases the water resistance and film build up per coat while reducing the price. The properties of coal tar epoxies are similar to other epoxies, but they become more brittle (inflexible) in sunlight.

Advantages	Limitations
Good resistance to water and petroleum products	Chalks freely in sunlight
	Slow curing
Good film build up	Clean, blasted surface required
Good abrasion resistance	Two-package coating; limited pot life
	May be difficult to topcoat

Urethane (Polyurethane) Coatings. Chemically curing, two-component urethane coatings have a greater range of properties available than do epoxies. They can be elastomeric or rigid and have excellent or poor exterior weathering (chalk-resistance, discoloration, and gloss retention). They have good resistance to chemicals, solvents, and water. Their chief concern is the highly toxic isocyanate component. Personal protection equipment required during application can make applying this coating more difficult. Urethane coatings do not usually bond to metals as well as epoxy coatings and so are often applied over epoxy primers. On the other hand, aliphatic urethanes are often applied as finish coats to epoxy systems to provide good exterior weathering. Urethanes can be formulated with high solids to make them VOC conforming.

Advantages	Limitations
Excellent chemical, solvent, and water resistance	Highly toxic; personal protection required
Applicable at low temperatures	Moisture sensitive; must seal containers tightly; gloss drops with high humidity
Can have excellent gloss retention and chalk resistance	Clean, blasted surface required
Good durability/abrasion resistance	Two-package coating; limited pot life
May be hard or flexible	May be difficult to apply or topcoat
Can be made VOC conforming	

Zinc-Rich Inorganic Coatings. Inorganic zinc coatings are tough, abrasion resistance products that provide cathodic protection to steel. They require the highest level of surface preparation (the cleanest surface) of all generic types of coating and perhaps the greatest skill in applying them successfully. Because the heavy zinc particles tend to settle rapidly to the bottom of wet paint, the paint pot must be kept at the same elevation as the spray equipment (it can only be applied by spraying), the pot must be constantly agitated, and the material hose from the pot to the spray gun should be as short as practical. Inorganic zinc coatings are usually applied at 3 to 5 mils dry film thickness. Applying the inorganic zinc coatings in greater thicknesses may result in mud cracking.

Inorganic zinc coatings require topcoating with organic coatings (e.g., epoxies) for long-term performance in immersion and other severe service. Because they are porous, topcoat solvents or air may penetrate the coating and later emerge though the wet topcoat to form small bubbles and leave holidays in the coating. Thus, tie-coats (1 to 2 mils of wet topcoat) are usually first sprayed on inorganic zinc primers to fill the voids, and a full topcoat is applied while the tie-coat is still tacky. Topcoats must be alkali resistant to avoid alkali degradation by the alkaline zinc corrosion products

formed during cathodic protection. As mentioned in Paragraph 7.5.1, topcoated inorganic zinc coatings are repaired using compatible zinc-rich organic coatings.

In new construction, steel is usually abrasively blasted and primed with inorganic zinc primer in a shop under controlled conditions to give high quality application not received so easily in the field. Also, there is less contamination of the environment by the blasting particulates. The preconstruction primer may then be topcoated later after the structure steel has been erected. Welding has been successfully reported through some inorganic zinc coatings. If the primer can be properly maintained, abrasive blasting may not be required later for maintenance painting.

Advantages	Limitations
Excellent abrasion resistance	High costs
Excellent heat resistance	Requires a skilled applicator
Excellent corrosion resistance by cathodic protection of steel	Constant stirring required during application
May be shop, weld-through, or permanent primer for topcoats	Requires careful selection and application of topcoats
	Stringent surface preparation requirements
	Unsuitable for acid or alkali environments
	May have special curing requirements

Zinc-Rich Organic Coatings. Several resins can be used to formulate zinc-rich organic coatings. These include epoxies, urethanes, and vinyls. In each case, the mechanism of curing is that of the apparent resin. These coatings may provide both barrier and cathodic protection to steel. They do not require as clean a steel surface and are easier to topcoat than inorganic zinc coatings.

Advantages	Limitations
Provides excellent protection	Requires skilled applicator to steel under many conditions
Surface preparation less stringent than inorganic zincs	High cost
Easier to topcoat than inorganic zincs	Constant agitation required during application
	Unsuitable for acid or alkali service unless topcoated

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7.6 SURFACE PREPARATION FOR PAINTING. Surface preparation is recognized as being one of the most important factors in coating performance and is about 45% of the total painting costs. Preparing a surface includes removing the contaminants that inhibit coating adhesion and providing a surface profile for tight bonding of the coatings.

Grease and oil will prevent tight bonding of coatings, as will loose dirt, dust, rust, scale, and chalk from old paint. Salt remaining on metal surfaces after cleaning may accelerate osmotic blistering. Salt can become trapped in metal pits and crevices where it is difficult to remove.

Mill scale is a bluish, somewhat shiny oxide residue that forms on steel surfaces during hot rolling. Although initially rather tightly adhering, it soon cracks, pops, and disbonds. Unless completely removed before painting, mill scale will later cause the coating to crack and expose the underlying steel.

While smooth surfaces may prevent a tight bonding of coatings, too great a surface profile may present coating difficulties for relatively thin primers. Pinpoint rusting occurs soon when peaks of blasted metal profiles receive only thin films of coating. The surface profile (distance between peaks and valleys) should be that recommended by the coating supplier. For metal structures requiring coating, this is normally 0.5 to 2.5 mils (thousandth of an inch) and never more than one-half the thickness of the primer. The profile height can be varied by changing the abrasive used in blasting.

    7.6.1 <u>Preparation Before Cleaning.</u> Before actual cleaning and painting, all welds, edges, bends, and other sharp projections should be ground smooth and all crevices filled. Sharp edges cause coatings to draw thin. Crevices are also difficult to coat and are sources of early corrosion (crevice corrosion). Weld spatter must also be removed because it is loosely held.

All old loose paint must also be removed. A heavy build up of paint can produce a rigid system ("dead paint") that is poorly bonded to the substrate.

There are many different methods of cleaning metal surfaces. The most commonly used cleaning methods are: solvents, hand and power tools, flames (thermal), steam cleaners, chemicals, abrasive blasting (wet and dry), and water blasting.

    Solvent Cleaning. Is used to remove grease and oil that are difficult to remove by other methods. In some cases, solvent containing coatings can dissolve thin deposits of oil and incorporate them in the coating without adverse effects. This is never the case with heavy oil deposits or grease. The solvent is usually applied on rags. Change the rags when they become contaminated. The final rinse is always made with fresh solvent. The organic solvents used should not come into contact with the eyes or skin, be used

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near sparks or flames, or be inhaled unnecessarily. Solvent cleaned metals may require further cleaning before coating.

Hand and Power Tool Cleaning. Removes only loosely adhering paint, rust, and mill scale. It is slow and produces a burnished rather than a textured surface that permits only limited coating adhesion. Thus, it is used mostly for spot cleaning. Hand tools include scrapers, wire brushes, and sanders.

Power tools (electrical and pneumatic) clean much faster than comparable hand tools and are essentially a duplication of them in power-driven equipment. They include sanders, grinders, wire brushes, chipping hammers, scalers, and needle guns. They clean by impact, abrasion, or both. Cleaning of metal surfaces is less expensive using power tools than using hand tools, and less particulate contamination occurs than when abrasive blasting. Thus, they are used mostly for spot cleaning, where contamination of adjacent areas by abrasive blasting is unacceptable, and when a surface tolerant coating, such as an oil-based paint is used.

Flame (Thermal) Cleaning. Flames and electric heating guns are use only to remove loose scale or rust from metal surfaces. The surface is then cleaned to achieve the desired level of cleanliness. Extreme caution must be used to keep open flames away from flammable materials.

Steam Cleaning. Steam cleaners may be used to clean dirt and grime from coated surfaces, so that repainting may be unnecessary. High temperature and velocity wet steam can also remove heavy oil and grease. Commercial detergents can be added to the wet steam to improve the cleaning power. Steam-cleaned steel is then further cleaned by other methods before coating.

Chemical Cleaning. Chemicals can often be used to clean metals for coating. Alkaline cleaners remove grease, oil, and oil-based coatings from steel but can damage other metals. Solvent strippers are appropriate for removing other coatings. Baths can be used for dip cleaning of some metals. Chemicals can also be used to treat metal surfaces (e.g., phosphating) to promote coating adhesion.

Abrasive Blasting. Abrasive blasting is usually the preferred method of preparing steel and some other metal surfaces for cleaning. The impact of high velocity abrasive particles can completely remove all rust, scale, dirt, and old coating, but not grease or oil. It also roughens the surface to produce a texture that promotes tight coating adhesion. Aluminum and other softer metals require softer abrasives (e.g., plastic beads) for removing old coatings and not damage the metal. Because of the importance of abrasive blasting of steel, it is discussed in considerable detail in Paragraph 7.6.3.

Wet and Water Blasting. Water is sometimes added to the abrasive by using a ring water sprayer at the nozzle to reduce the amount of particulate dust produced in blast cleaning of steel. Chemical corrosion inhibitors such as sodium, potassium dichromate, or phosphate must be dissolved in the water to prevent flash rusting of steel before coating. The possible adverse effects of inhibitor residue on coating performance has not been established.

Water blasting, sometimes called "hydroblasting" is sometimes used to clean metal surfaces for coating. The water may be heated and detergent may be added to help with the cleaning. Power washing with pressures up to about 2,000 psi is effective in removing dirt and mildew on coated metals and is generally safe on adjacent wood and concrete/masonry. Bare steel can be cleaned with water pressures over 30,000 psi and water volumes of only 2 to 15 gallons per minute. Ultrahigh waterblasting begins at 20,000 psi. Abrasives can be added to the stream of water or used separately later to roughen the metal surface to achieve good coating adhesion. Extreme caution must be maintained with these high pressures. Again, corrosion inhibitors must be used in the water.

7.6.2 Recommended Cleaning Methods

Steel. The preferred method of cleaning uncoated steel is washing it with a solvent followed by abrasive blasting. The preferred method of cleaning coated steel is also by abrasive blasting followed by a solvent cleaning, if the coating is to be removed. Other cleaning methods such as hand or power tools are more practical for spot repair of coatings. The standards for different levels of abrasive blasting of steel and for alternative methods of cleaning are discussed in Paragraph 7.6.3.

Galvanized Steel. The recommended method of cleaning galvanized steel varies with the condition of its surface. Simple solvent cleaning is usually adequate for new, clean galvanized steel. If loose zinc corrosion products or coatings are present, they should be removed by bristle or wire brushing only as heavy as necessary for complete removal. If rust is present on older steel, it should be spot removed by abrasive blasting or wire brushing so as not to disturb remaining in-tact galvanizing. A thin coat (0.3 to 0.5 mils) of wash primer (see MIL-P-15328) is often used on new galvanized steel to promote adhesion of oil-based or latex coatings.

Aluminum and Other Soft Metals. New, clean aluminum and other soft metals may be cleaned for coating by solvent washing. Detergent washing may be required for removing dirt. Abrasive blasting with plastic beads or other soft abrasive may be necessary to remove old coatings. These metals, like galvanized steel, are sometimes wash primed to promote adhesion of oil-based or latex coatings.

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7.6.3 **Standards for Cleaning Steel Surfaces.** The most frequently used written standards for cleaning steel surfaces are from the Steel Structures Painting Council (SSPC). They include standards for all common methods of cleaning. Volume I of SSPC's Steel Structures Painting Manual contains all the available standards, as well as other useful information. The National Association of Corrosion Engineers (NACE) has a set of standards for blasted steel surfaces similar to those of the SSPC. Pictorial standards NACE standard steel specimens encased in plastic are also available for determining the level of abrasive blasting. However, the written standards constitute the legal requirements for contract work.

The four grades of blast-cleaned steel are:

White Metal Blast -	100% free of oil, mill scale, rust, and paint SSPC SP-5; NACE Specification 1
Near White Blast -	95% free of residual stain and discoloration SSPC SP-10; NACE Specification 2
Commercial Blast -	Two-thirds free of stain and discoloration SSPC SP-6; NACE Specification 3
Brush-off Blast -	Only tight mill scale, rust, or paint remaining SSPC SP-7; NACE Specification 4

Before using the pictorial standards, you must first determine the grade of steel blasted, since different grades of steel blast cleaned to the same level will not look the same.

Rust Grade A - Adherent mill scale (tight scale with little rust)

Rust Grade B - Rusting mill scale (rusting started; scale flaking)

Rust Grade C - Rusted (mill scale easily removed; little pitting)

Rust Grade D - Pitted and rusted (no mill scale; visible pitting)

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SSPC standards for steel surfaces cleaned by methods other than blasting are:

Method	SSPC No.	Intended Use
Solvent Cleaning	SP-1	Removes oil and grease before further cleaning by another method
Hand Tool Cleaning	SP-2	Removes loose mill scale, rust, and coating
Power Tool Cleaning	SF-3	Removes loose mill scale, rust, coatings faster
Flame Cleaning	SP-4	Preliminary removal of loose mill scale and rust from new steel before further cleaning
Pickling	SP-8	Removed mill scale and rust

Different types of coatings require different levels of cleaning. The most commonly agreed upon levels are:

Coating Type	Minimum Surface Preparation
Drying oil	Hand or power tool cleaning
Alkyd	Commercial blast
Coal tar	Commercial blast
Asphaltic	Commercial blast
Latex	Commercial blast
Vinyl lacquer	Commercial or near white blast
Chlorinated rubber	Commercial or near white blast
Epoxy	Commercial or near white blast
Coal tar epoxy	Commercial or near white blast
Urethane	Commercial or near white
Organic zinc	Commercial or near white
Inorganic zinc	Near white or white blast

For immersion or other severe environments, the higher level of two options should be used.

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7.6.4 Abrasive Blasting Equipment and Procedures.

Conventional Blasting Equipment. Conventional, abrasive blasting equipment has five basic components: the air compressor, air hose, blasting machine, blast hose, and nozzle.

Air Compressor. The air compressor takes in, compresses, and then releases large volumes of air by piston or rotary action. The continuous and constant supply of high pressures and volumes of air to propel abrasives from the blasting pot and through the blasting hose and nozzle to the metal surface is one of the most critical parts of the blasting operation. The capacity of a compressor as measured in cubic feet per minute (cfm) is directly related to its horsepower rating. A flow of 170 to 220 cfm of 90 to 100 psi nozzle pressure air necessary for blast cleaning steel plate can be obtained with a 50 or 60 horsepower compressor. The rate of blast cleaning is directly related to the nozzle air pressure and volume. Sources of pressure loss include worn compressor parts, small diameter or long hoses (frictional losses), and couplings joining lengths of hose. A 10 psi drop in pressure will reduce the cleaning rate by 15%.

Oil and water traps are used to remove these contaminants originating at the compressor or other components that would otherwise be transferred to cleaned surfaces. These traps need to be inspected and cleaned frequently. Detection of oil and water contaminants cab be achieved with a simple blotter test. A clean, dry, white blotter is held 18 inches in front of the nozzle with only the air flowing for 1 to 2 minutes. Stains on the blotter indicate the presence of contaminants. A simple test to detect for oil contamination of an abrasive is to place a small amount of it in a glass jar, fill the jar with clean water and then shake the jar. A sheen that rises to the surface of the water indicates oil contamination. Such abrasives should be discarded.

Air Hose. The air hose delivering air from the compressor to the blasting machine need not be as durable as the blasting hose, because it is not eroded by abrasives or dragged along the ground. The air hose should have a large diameter (about 1-inch-ID when under 50 feet long) and short length. Exterior couplings are preferred to interior couplings; they effectively reduce hose diameters and increase frictional losses. Use as few couplings as possible to minimize possible air leaks.

Blasting Machine. The blasting machine or "sand pot" holds the abrasive. A valve on the bottom controls the amount of abrasive fed into the blast hose. The chief parts of a gravity-fed blasting machine are the: moisture separator, exhaust valve, filling head, metering valve, and hose/tank coupling. A continuous, uniform flow of abrasive (from an automatic metering valve) is required for efficient cleaning. Blasting machine capacities vary from 50 pounds to several tons of abrasive. Smaller machines require more filling time.

<u>Blast Hose</u>. The blast hose carrying the air and abrasive from the blasting machine to the nozzle must be sturdy, flexible, and treated to prevent electrical shock. A 4-ply blast hose with a 1.25 ID is sold in short, joinable sections to minimize frictional loses.

ID hose called a "whip" is sometimes joined at the nozzle. It is easier to handle, particularly in tight areas, but is not recommended, because its reduced diameter causes frictional losses of pressure.

<u>Nozzles</u>. Nozzles are available with several lengths, designs, sizes of openings (throats), and lining materials. Nozzle lengths of 5 to 8 inches are generally used for removing tightly adhering rust and scale. Shorter nozzles, 3 inches or less, are appropriate for behind beams and in other inaccessible places when a whip might be used.

The tapered shape of the venturi nozzle is more efficient than the cylindrical shape of the straight bore nozzle. The venturi creates a larger, more uniform blast pattern and can increase cleaning rates by 30 to 50%.

The orifice size is chosen according to the available volume of air. The largest practical size that does not permit loss of pressure is usually best. A 1/2-inch nozzle with proper air supply can clean four times the area of a 1/4-inch nozzle.

The lining, particularly at the orifice, is gradually worn away by the abrasive. Since enlarged openings reduce efficiency, the liner is usually replaced after the original diameter has increased by 50%. Tungsten, carbide, and Norbide liners may have service lives of 300, 750 to 1,000 hours, respectively, as compared to 6 to 8 hours for cast iron liners. Dropping or banging the more brittle tungsten, carbide, and Norbide nozzles can reduce their service lives. Nevertheless, they are much more economical to use in the long term.

All nozzles are equipped with "deadman valves" that permit blasting when they are depressed. If the operator drops the nozzle, the flow of air and abrasive is immediately stopped.

A hypodermic needle gage is used to measure nozzle pressure. It is inserted into the blast hose immediately in front of the nozzle in the direction of abrasive flow to minimize damage to it from the flowing abrasive.

Alternative Approaches to Blasting. Automatic cleaning by centrifugal blasting can be achieved in shops in a controlled environment. It utilizes machines with motor-driven, bladed wheels to hurl abrasive at high speed by centrifugal force. Its advantages over conventional blasting include: (1) savings of time, labor, energy, and abrasives; (2)

a superior, more uniform cleaning; (3) reduces blasting waste by recycling the abrasive several times; and (4) protects the environment.

A centrifugal blast cabinet with four 25-hp wheels can throw 2,400 pounds of abrasive per minute. The amount of abrasive throw requires 33 conventional blasters. Portable centrifugal blasting equipment is also available for regular steel surfaces like the decks of ships or sides of storage tanks.

Vacuum blasting systems are now available which collect, clean, and recycle abrasives. Production is slow but very effective in eliminating blasting dust, cleaning welds, and reducing hazardous waste from toxic paints.

Another approach of avoiding contamination of the environment with blasting dust is to conduct the blast cleaning in an enclosed building where particulates are trapped and collected and the abrasive can be cleaned and recycled.

Blasting Procedures

Choosing Abrasives. Abrasives are available in a variety of sizes, shapes, hardnesses, and breakdown characteristics. The proper abrasive for a particular coating is one that provides the necessary cleaning and profile at a good rate, and permits the coating to perform well.

A larger size abrasive will cut deeper than a smaller size abrasive, but the greatest rate of cleaning is achieved with as small a size as possible to give the desired surface. Particles in the 40- to 50-mesh range are commonly used today. Those larger than 16- to 18-mesh have a slow clean rate and may gouge the surface; those 100-mesh or finer may not be able to give the desired profile.

The size and shape of the abrasive is responsible for the type of blasted profile produced. Round shot tends to peen the steel surface to a wavy profile. It is effective in removing brittle deposits, such as mill scale. Grit is angular and so produces a more jagged finish, generally preferred for tight coating adhesion. The variety of grit materials available produces a variety of surface patterns. Sand and slag abrasives are semiangular and produce surface patterns somewhere between those for shot and grit.

Hard abrasives cut faster and deeper than softer or more brittle ones. A hard, but brittle abrasive tends to shatter on impact, which reduces its cleaning rate.

The manner in which abrasive particles fracture and change shape upon impact is called their breakdown characteristic. It limits the number of times recycling is possible, the amount of particulate dust emitted into the air, and the amount of dust that must be removed from the cleaned surfaces before coating.

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The four types of abrasives used are:

     1. <u>Natural Oxides.</u> Silica, the most widely used oxide, is readily available, cheap, and effective, but health concerns are greatly restricting its use. Starblast, another natural oxide, is fast cutting, has less breakdown and dusting, and may be recycled.

     2. <u>Metallic Abrasives</u>. Steel shot and grit abrasives are efficient, hard, and dust free. Care must be taken to keep them dry during storage to prevent rusting. Indeed, all abrasives should be stored in their original sealed bags on pallets off the ground until ready for use. Impacting steel shot may cause small slivers called "hackles" to form on steel surfaces. They may extend up to 6 mils and so must be removed by grinding or sanding before coating to prevent later pinpoint rusting.

     3. <u>Slag Abrasives</u>. Copper and nickel slags, by-products of the ore smelting industry, are fast cutting but have a high breakdown and cannot be recycled.

     4. <u>Synthetic Abrasives.</u> Aluminum oxide and silicon carbide are non-metallic abrasives with cleaning properties similar to those of metallics but without the rust problem. They are hard, fast cutting, and low dusting but expensive and must be recycled to be economical.

     <u>Blast Cleaning Techniques.</u> Some of the important items to remember are:

     1. <u>Angle of Attack.</u> The nozzle to surface angle may range between 45 and 90 degrees depending on the work. An 80- to 90-degree angle is suitable for removing rust and mill scale and cleaning pits. A slight downward angle will direct the dust away from the blaster and permit better visibility. A 45- to 60- degree angle is best for peeling away heavy layers of coating or rust. General cleaning is best done at 60 to 70 degrees.

     2. <u>Nozzle-to-Surface Distance</u>. The closer the nozzle is to the work, the denser the abrasive will be, but the blast pattern will be smaller. While a close distance (e.g., 6 inches) may be necessary for removing tight scale, 18 inches or more may be more appropriate for removing old paint and for general cleaning.

     3. <u>Straight Line Passes</u>. Each pass with the blast nozzle should be in a straight line at the same distance from the surface. Arcing or varying the distance from the work will produce non-uniform cleaning.

     4. <u>Coating Cleaned Surfaces.</u> No more steel should be blasted than can be coated that day, since rusting can occur overnight. On hot humid days, flash rusting may

occur in a few hours. If this occurs, the rust must be removed by brush blasting before coating.

It only takes one spray painter to keep up with four blasters, so the work must be properly scheduled.

7.7 APPLICATION OF COATINGS. The basic choices for applying coatings are brush, roller, and spray. Selecting the most appropriate method for a particular job is not so easy today, because the modern high-performance, VOC-conforming coatings are more difficult to apply than coatings previously used. The following considerations must be made before selecting the application method:

Application methods appropriate for the particular coating.

Desired appearance.

Ease and speed of application.

Simplicity of equipment and required operator skills.

Safety/environmental requirements.

Economics of application.

If the coating like inorganic zincs can only be applied by spray, the application choices will be limited. Such coatings are also likely to require highly skilled operators for specialized equipment. Ease and speed of application will affect the ability to provide not only an economical but also a quality, cosmetically acceptable finished product. Safety and environmental restraints may limit the available methods to those with high transfer efficiencies or require safety gear than will slow operations. Some of these factors may be much more important than others.

The relative rates of different application rates are given below:

Application Method	Square Feet Applied in 8-Hour Day
Brush	1,000
Roller	2,000 to 4,000
Conventional Air Spray	4,000 to 8,000
Airless Spray	8,000 to 12,000

In contract painting, the contractor is usually given his choice of application method. We, however, should be aware of the problems associated with the particular method he chooses for his work plan and advise him of any concerns we may have about this method.

7.7.1 <u>Brush Application.</u> Brushing is an effective, relatively simple coating application method. It is particularly good for priming, since it works the paint into the surface's irregularities. Because it is slow, brushing is used primarily for touch-ups, small areas (e.g., trim), complex configurations, or where overspray may be a serious problem. It does not produce a very uniform thickness.

Natural brush bristles of good quality are preferred for paint brushes, but synthetic filaments resistant to strong solvents may be also be satisfactory. Bristles that are naturally or artificially flagged (with split tips) are preferred, because they hold more paint. Nylon and polyester filaments are more water resistant than natural fibers and so are preferred for latex paints.

Brushes can leave brush marks in paints that do not level well. They may also leave areas of low thickness. Thus, a second coat should be applied at right angles to the first in order to minimize overlap of brush marks or thin areas. Additional coats should be applied at right angles to the previous coat.

Tips for painting with brushes are:

Shake loose any unattached bristles by spinning the brush between the palms of the hand.

Remove any stray bristles with a putty knife.

Dip the brush to cover one-half the bristle length. Too much paint may wet the heel of the brush and run down the handle.

Remove excess paint by tapping the brush on the edge of the can.

Apply paint with a light touch. Use the bristle tips rather than pressing down hard; this will minimize brush marks.

Work from the dry to the wet surface; this will minimize lap marks.

Hold the brush at a 75-degree angle to the surface; this produces the best results.

7.7.2 Roller. A roller is best used on large, relatively flat areas that do not require the smooth surface or uniformity received from spraying and in interior areas where overspray may present a masking or cleaning problem. The nap fiber length normally varies between 1/4 to 3/4 inch. A longer nap holds more paint but does not give as smooth a finish. Thus, it is used on rougher surfaces. Rollers with extra long naps (1-1/4 inches) are used to coat chain link fences. Handle extensions 10 feet or longer allow the painter to reach high areas but usually at a reduction in application quality.

The roller cannot penetrate pores, cracks, or other surface irregularities as well as a brush. Also, rolling can mix air into the paint to permit moisture to penetrate the cured film. Lacquers are difficult to apply by roller because of their rapid solvent evaporation, particularly on warm days.

Tips for painting with a roller are:

For thick-bodied coatings, dip the roller directly in the paint container; for thin-bodied coatings, use a roller tray.

Load the roller uniformly for even application at the desired thickness. Too little or too much coating may cause tracking or skidding.

Do not apply heavy pressure to the roller.

Apply the second coat at right angles to the first to avoid areas of low thickness or holidays.

7.7.3 Spray.

Conventional Air Spray. Air spray features the finest atomization and finish and the greatest versatility. The basic parts of conventional air spray equipment are: air compressor, paint tank, hoses for air and fluid, and spray gun.

The air compressor powers the conventional air spray equipment. It must continuously supply both adequate air pressure for paint atomization and uniform flow of paint to the spray gun. Air pressure and flow are directly related to each other. If one drops, so does the other. The air flow, measured in cfm, must be great enough that the pressure does not drop during triggering to give short bursts rather than a continuous stream of atomized paint. Pulsation indicates an inadequate air supply. The air supply must also provide power for agitators or other accessories. Data sheets of paint suppliers provide information on recommended spraying pressures (and thus necessary compressor capacities), air caps, and fluid tips. Oil and water in the air supply must be removed by separator or extractor attachments to provide clean air.

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The tank that holds the paint material (usually in a paint pail) has an air compressor to control the operational pressure. Some tanks have agitators that continuously mix the paint to prevent settling of heavy pigments. When large quantities of material are required, a pressure pump can be used directly in the paint container.

The air hose carries the compressed air, and the fluid hose carries the paint to the gun. An air hose with too small an ID can cause the air line pressure to drop and starve the gun. As with blasting hoses, frictional losses of pressure can be minimized by using relatively large diameter and short hoses. Avoid kinking or compressing these hoses. A large diameter may be necessary on a long hose to maintain adequate air pressure. The ID of the hose from the compressor to the pressure tank is usually at least 3/8 inch and the ID of the hose from the pressure pot to the gun should be at least 5/16 inch.

The ID of the fluid hose is determined by the necessary volume and pressure of the particular paint at the gun. Heavy paint may require as large an ID as 1/2 or 3/4 inch. Small guns often use a 1/4 inch ID fluid hose. The hoses must be resistant to the paints and solvents that flow through them.

The conventional spray gun is relatively complex and requires a great deal of skill to operate. The basic parts of a spray gun are: air nozzle or cap, fluid nozzle or tip, fluid needle, trigger, fluid adjustment valve, air valve, side port control, gun body and handle, air inlet, and fluid inlet. Supplier instructions provide much information on their operation.

Most spraying problems are related to improper or inadequate cleaning of guns. Recommended maintenance items include:

Lubricate the air gun daily.

Wash the gun body with a rag dipped in solvent. (Only wet the front end of the gun with solvent. The solvent will remove lubricants and dry out the packing.)

Unclog nozzle by washing it separately in solvent. Use only a pipe cleaner, broom bristle, or match in cleaning the hole to prevent damage.

Never use oils or lubricants containing silicone.

With conventional air spray, outer jets of air atomize the paint. The external mix air nozzle is almost always used. The external mix nozzle is used for production work that does not require a fine finish. They are not used with catalyzed or fast drying paints, these paints tend to clog the nozzle.

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A proper spray pattern when the trigger is fully depressed may be round or "fan" shaped (a long oval). As long as the fluid and air pressure remain the same, the amount of sprayed paint will remain the same. Increasing the pattern size decreases the paint thickness and vice versa. The ideal spray pattern for production work is a long oval with clearly defined edges and little overspray or rebound. The individual particles of atomized paint should be uniform in shape, size, and distribution. Spray pressures should be kept as low as possible for such a pattern.

Special spray equipment may be designed to apply thick paints. This includes heating accessories to reduce paint viscosities and components for mixing of metered components at the gun. Guns on extension arms permit spraying in difficult to reach places. It is considered a better technique to use scaffolding to get to such areas, if at all possible.

Airless Spray. Airless spray features the greatest production rate and consequently the greatest economy. The basic parts of airless spray equipment are: high-pressure paint pump, fluid hose, and airless spray gun.

A high pressure pump forces paint from the container to the spray gun and atomizes it into a spray. It is rated according to the ratio of paint pressure produced to the air pressure that produced it. Thus, a pump that delivers a paint pressure of 30 psi for each psi of air pressure from the compressor has a 30:1 ratio. There must be sufficient pressure and material flow to produce a constant spray of paint.

The fluid hose must be able to withstand the high pressures necessary to deliver the paint to the gun and atomize it. While pressures of 1,800 to 3,500 psi are commonly used, most air hoses can handle pressures as high as 5,000 psi. A 1/8- to 1/4-inch ID hose is used for medium viscosity paints, and 3/8- to 1/2-inch ID for high viscosity paints.

The airless spray gun is basically a fluid nozzle with a valve. **A** spray tip filter screens out particles that might clog the tip. Each spray tip is designed for a particular spray pattern. Indeed, changing tips is the only way to change the spray pattern. The orifice size (0.007 to 0.0072 inch) controls the atomization and the amount of fluid delivered. The tip angle (10 to 80 degrees) controls the fan width. Tips with the same orifice size but different angles will deliver the same amount of paint but at different fan widths and thicknesses. A large spray pattern is required for a high application rate. Paint viscosity is the chief factor in selecting a particular tip.

Airless spray guns may be powered by electricity, gasoline, or compressed air. As with conventional air spray, a good pattern will have a smooth oval outline, clearly defined edges, and a uniform distribution of paint particles. However, a round pattern is not acceptable. To correct a faulty airless spray pattern tips, filters, or atomization pressures may need to be replaced or adjusted.

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Air-Assisted Airless Spray. Air-assisted airless spray uses compressed air to assist in the atomization of paint from an airless system. It makes it easier to apply heavy products.

Electrostatic Spray. Electrostatic spray can apply coatings to hard-to-coat conductive surfaces with minimum loss of paint. This ability to paint "around corners" permits a painter to coat very complex configurations. It can be used for airless or conventional air application. A charged probe is used for external ionization of the atomized paint, which is attracted to a grounded surface. It presents no safety hazard to properly trained personnel. Electrostatic spray has the following features: ability to wrap around edges and irregular surfaces; increased transfer efficiency (lower material usage), more uniform paint application, and less overspray.

Thermal Spray of Metals. Equipment and techniques are available for the thermal (flame or electric arc) spraying of metal coatings on steel. The metals are melted, and the molten metal is sprayed to produce a porous coating that protects by cathodic protection. For longer protection, they may be sealed with a thin conventional organic coating or silicone. Aluminum and zinc are the most frequently used thermal sprayed metals. Zinc presents a health hazard and so is seldom sprayed by the Navy. A very clean steel surface is required for coating. Metal spray coatings are normally very abrasion resistant.

Powder Coatings. Organic polymers (e.g., epoxies and acrylics) in powder form can be applied to a conductive (usually metal) surface and fused to it by heating in an oven at a predetermined temperature to form a tough, corrosion resistant coating. Application is done by electrostatic spray to a preheated metal component to permit the powder to stick to it before fusing. Application can also be done in a fluidized bed. In addition to being free of organic solvent, the system has a high transfer efficiency. Any powder not sticking to the metal surface can be collected and blended with virgin powder and used again.

7.7.4 <u>Recommended Spraying Procedures.</u> The recommended aspects of paint spraying, for both airless and conventional air spray are described below.

Stroking. Stroking during spraying should be done with the gun, wrist, arm, and shoulder at right angles to the work and moving parallel to it. This prevents "'arcing," varying the distance of the gun to the work, which results in variation of the paint thickness. For large, flat surfaces, each stroke should overlap the previous one by 50%. This produces a relatively uniform surface and eliminates holidays at the ends of the fan.

The stroke length should be from 18 to 36 inches, depending on the sprayer's arm length and comfort. Long areas should be divided up into smaller sections of appropriate length. Each section should slightly overlap the adjacent ones.

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Triggering. The stroke of the spray gun should begin before the gun is triggered and continue briefly after releasing the trigger. This produces a smooth, continuous film without a heavy build up of paint at the start and end of each stroke. It also helps keep the fluid nozzle or airless tip clean.

Distance. The amount of material delivered and the atomization pressure determine the proper gun-to-surface distance for a uniform, wet film. It is usually about 6 to 12 inches for conventional air spraying and 12 to 15 inches for airless spraying. If the gun is held too close to the surface, the paint can sag or run. If the gun is held too far from the surface, a dry spray with a sandy finish and holidays (pinhole or skip areas) may result.

Corners. Each side of inside corner should be sprayed separately. A vertical stroke on one side, followed by a short horizontal stroke on the other will usually result in a relatively uniform coating. Spraying directly into the corner will produce a film of varying thickness, thinner in the corner and heavier on the sides.

An outside corner is sprayed directly when the sides are sprayed. This results in uniform paint thickness, without lap marks.

7.7.5 Storing and Mixing of Coatings Before Application.

Storing Coatings. Proper storage of coatings will protect these costly products from premature deterioration and minimize fire hazard. Long term storage should be in a room or building isolated from other work areas. The room or building should be dry, well-ventilated, and protected from sunlight, sparks, and flames. Shelves or pallets should be used to keep the cans up away from the dampness of floors. Labels should be kept in tact and free of paint to permit easy identification. Material safety data sheets (MSDSs) should be available for each coating and solvent stored, as required by law. Stocks of coating should be rotated and used so that old ones are used first, and no coating should be kept more than 1 year after manufacture. Once opened, the contents of a can should be used before opening up another can of the same coating. Coatings stored for more than 1 year should be checked for quality, as described in Paragraph 7.8, before using.

No more coating should be taken to the job site than is actually required. It should also be protected from the weather. Water-borne coatings can freeze in cold weather and can be damaged permanently.

Mixing Coatings. During storage, the coating's heavy pigments tend to settle and cake at the bottom of cans. These coatings must be reblended to their original uniform consistency before applying to obtain complete curing and satisfactory film properties. Mixing of coatings may be done either manually or mechanically, the latter usually

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being preferred, especially with volumes of 5 gallons or more, in order to insure thorough blending.

1. <u>Mixing Single-Component Coatings.</u> Single-package coatings are mixed as follows.

Pour the thin upper portion of settled paint into a clean container the same size as the original can.

Stir the settled portion of paint with a strong, clean paddle to break up the pigment and lift it from the bottom.

Break up paint clumps by rubbing them against the inside wall of the can.

Use a "figure 8" movement to mix the paint thoroughly.

Change the mixing to a lifting and beating motion.

Gradually return the thin, upper portion of paint to the original container, stirring continuously.

When the paint appears to be well mixed, "box" the paint by pouring it back and forth between the two containers until it reaches a smooth, uniform consistency.

Avoid excessive mixing of latex paints. Excessive mixing may entrap air and cause foaming.

No more paint should be mixed than can be used that day. Unused portions of paint should be combined and stored in a single, covered container. It should be mixed again before using.

2. <u>Mixing Two-Component Coatings</u>. Two-component coatings must be mixed in the correct proportions and in the manner specified by the supplier in order to achieve optimum film properties. Most suppliers package the kits in the correct mixing ratio. The chemical reaction that starts when the two components are mixed and continues long after curing to a solid film. Some two-component products require an induction period, such as 30 minutes, to allow the reaction to achieve a necessary reaction stage before applying the coating. The curing reaction is greatly accelerated by higher temperatures thus greatly reducing the pot life (the time period during which the coating can be successfully applied). The larger the batch size mixed, the greater will be the exotherm (temperature rise), and the shorter will be the pot life. If pot life is exceeded,

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the coating may harden in the pot, lines, or gun. Mixed coatings not used at the end of the day cannot be kept over night. The mixed coatings must be discarded.

Two-component are mixed as follows.

> Stir the base component (usually Package A) with a clean paddle to disperse pigment lumps that may have settled. (Five minutes is usually adequate.)

> While continuing to stir, <u>slowly</u> add all of Package B (usually called the catalyst, co-reactant, or curing agent) which is frequently unpigmented. (The mixing container must be large enough to hold both components.)

> Agitate the two mixed components with a manual or power stirrer until smooth.

Note: Vary these instructions if specified by the supplier.

Environmental Conditions and Thinning (Reducing) Mixed Coatings. Properly formulated coatings seldom require mixing when applied in the recommended temperature range. Most coatings should be applied between 50 and 90°F. However, the best temperature range for conventional spraying is 60 to 80°F, and airless spraying can be used at 90°F. Lacquers such as vinyls and chlorinated rubbers can be applied at temperatures as low as 35°F. The coating's temperature being applied should always be as high as that of the surface being coated but not significantly higher, unless formulated for hot application.

The coating being applied should have a viscosity level for proper application. Three factors may affect viscosity: (1) solvent/solids ratio; (2) coating temperature: and (3) mixing of thixotropic coatings.

The solvent/solids ratio is established by the coating supplier, so that no thinning is usually necessary. The colder the coating, the greater will be its viscosity. Thus, it is generally best to warm cold paints rather than thin them to achieve proper application viscosity. Should thinning be necessary, the type and amount of thinner specified by the supplier should be used. The amount is not ordinarily more than 1 pint per gallon of coating and should not cause the coating to exceed the VOC limits discussed in Paragraph 7.4.1. With two-component coatings, viscosity of the mixed products is important, not the viscosities of the original components.

Some coatings called "thixotropic" or "false-bodied" reach the desired viscosity after being stirred or agitated. They seem very thick in the can but when stirred become

more fluid, so that they can be applied. On further standing, the viscosity will increase until the coating reaches its previous gel-like stage. Thus, thixotropic coatings may require continual agitation during application.

In order to prevent condensation of moisture from the air on wet paint, it should be applied only when the temperature is at least 5°F above the dew point and rising. Also, coating should never be applied when the prevailing wind is blowing 15 mph or greater or when the temperature is expected to fall below freezing, before the coating is fully cured.

7.8 INSPECTION OF PAINTING. Inspecting contract painting work is done to verify that the requirements of the specification are met in full and that a quality product has been obtained. Obviously, the latter requires that the specification has been properly prepared. Any apparent errors, omissions, or potential problems should be brought to the attention of the contract officer. Before work has begun, there should be a pre-construction conference to be sure that there is a complete understanding of what is expected. At this time, the inspector should become aware of the times when critical items of inspection must be made and that the areas to be inspected will be accessible and checked before the work proceeds further. The inspector's daily reports must be complete and clearly written, since they may become legal evidence. Any field changes must be written and approved by the contracting officer.

7.8.1 Inspection of Materials. The coating materials must be inspected before work is started to insure that there are sufficient quantities of each product to fulfill all requirements and that they are of the specifications or brands required. The amount of each material required can be determined from the coverage rate given on the supplier's data sheet or by calculation. Use the 16,000 ft^2/gal as the wet film covering rate of paints, if the volume of solids in the wet paint is known. Along with the data sheet and label identification, each material must have a material data safety sheet. The material should be stored off the ground or floor, protected from the weather, and away from a source of sparks or flame. If laboratory testing of products is required, it should be verified that each product meets its specification requirement. If testing was not required, two l-quart authentic samples of each product should be taken and stored during the warranty period, normally 1 year, to be tested should a problem arise.

7.8.2 Inspection of Surface Preparation. Industrial standards should be used for surface preparation, whenever they are available. For steel surfaces, the standards are normally those of the Steel Structures Painting Council (SSPC). These include:

SSPC-SP 1 - Solvent Cleaning
SSPC-SP 2 - Hand Tool Cleaning
SSPC-SP 3 - Power Tool Cleaning

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SSPC-SP 5 - White Metal Blast Cleaning
SSPC-SP 6 - Commercial Blast Cleaning
SSPC-SP 7 - Brush-Off Blast Cleaning
SSPC-SP 8 - Pickling
SSPC-SP 10 - Near-White Blast Cleaning

The standard chosen should be the one appropriate for the coating and the environment, as recommended by the coating supplier or by the guide specification used. SSPC-SP 5 or 10 are normally specified for high-performance coatings. All four blast cleaning standards require solvent cleaning (SSPC-SP 1) to remove grease and oil before blasting. Visual standards are available from SSPC and others to assist in verifying the level of blast cleaning. Different visual standards are available for different conditions (extent of rusting) of the steel. Hand and power tool cleaning are most frequently used for touch-up or when abrasive blasting cannot be used.

The supplier of the primer or the guide specification may also recommend a particular abrasive for blasting or a particular profile for the blast cleaned surface. The latter is obtained by selecting an appropriate abrasive. To verify that the specified profile height has been received, it will be necessary to use a comparitor, profilometer, or test paper.

7.8.3 **Inspection of Coating Application.** It is customary to test for appropriate weather conditions before starting to apply any coating. Temperature can easily be checked with a thermometer and humidity with a sling psychrometer to determine if they meet specification requirements. The temperature should always be at least 5°F above the dew point and rising, to prevent condensation of moisture on the wet paint. Also, exterior spray painting should not be started, if the wind affects the spray's pattern.

By determining the wet film thickness of a coating, you can determine if the specified dry film thickness will be received. Several types of wet film gages are available. Since such measurements disturb the wet film, it will have to be repaired before continuing.

Several types of magnetic gages are available for determining if the dry film thickness meets specification requirements. They should all be checked for calibration before using. The Tooke gage is a destructive gage (cuts into the coating film) for determining dry film thickness on any substrate surface.

Electrical holiday detectors are used to locate holidays or other imperfections in coatings on metal or other conductive surfaces. The low holiday detector (e.g., 67 volts) is normally used on coatings less than 10 mils thick, and the high voltage detector on thicker coatings such as those used on underground piping.

7.8.4 Final Acceptance Inspection. A thorough inspection should be made to determine if all specification requirements have been met before final acceptance. All previously noted deviations should be corrected.

7.9 PREMATURE COATING FAILURES. All coatings eventually fail. Of great concern are those that occur within the warranty period (normally 1 year) or well before expected. Obviously, problems should be corrected as soon as found to minimize the extent of damage. There are two general types of early failures: those that affect the surface coating only and those that expose the underlying substrate surface.

7.9.1 Topcoat Failures. Topcoat failures may be only cosmetic, if they occur on the surface of the coating. Examples of such failures are blushing, bleeding, and fading. They can be corrected by properly applying an additional coat of the topcoat.

Failures that completely penetrate the topcoat are more serious. Examples of these are intercoat peeling and blistering. If the failure is not extensive, the areas of damage may be removed and the spot repaired.

7.9.2 Failures That Expose Substrate Surface. Failures that expose the underlying metal are very serious, since the metal may corrode and undercut the surrounding film. Examples of this failure are cracking and peeling to the metal.

Corrective actions depend on the severity of the problem. For limited or localized damage, spot cleaning and repair may be suitable. Cleaning is best accomplished by abrasive blasting but hand or power tool cleaning may be adequate. For extensive damage (e.g., 20% or greater), it is ordinarily best to remove all the existing coating by abrasive blasting and completely recoat.

7.10 MAINTENANCE PAINTING. Most painting operations consist of maintenance painting. Because of the great expense of total repainting and disposal of old paint, it is best to use and maintain high-performance coating systems as long as possible. Coating systems should be selected for easy maintenance.

7.10.1 Compatibilities. The maintenance painting of existing coated metal structures requires that a compatible coating be applied. If it is incompatible, early coating failure may occur. Cause of incompatibility include strong topcoat solvents lifting existing coatings, strong topcoat solvents causing bleeding of existing bituminous coatings, and inability of new rigid topcoat to expand and contract with flexible undercoat. It is best to topcoat existing paint with the same type of coating as already on the structure. If this is not possible, the topcoat should be of the same generic type or cure by the same mechanism. The one exception to this rule is repair of inorganic zinc systems. Zinc rich-organic coatings are used to obtain good adhesion to both exposed steel and surrounding organic topcoat. If there is any concern about incompatibility of the new

coating, it is wise to apply a test patch about 1 ft^2 in size over the existing paint and check for incompatibility problem that should occur within a few days.

7.10.2 Spot Repairing. Spot repairs require cleaning of exposed metal and surrounding tightly adhering topcoat(s). The coating edges at damaged areas should be "feathered" (beveled) to achieve good adhesion of the patch and provide an attractive finish. Primer and topcoats used in these repairs should completely cover the metal and overlap onto the existing coating system to prevent weak joints of new to old coating.

7.11 PAINTING SPECIAL STEEL STRUCTURES.

7.11.1 Fuel and Water Storage Tanks.

Interiors. Interiors of steel fuel and water tanks should be cleaned for coating by abrasive blasting to a white or near white metal finish (i.e., SSPC-SP 5 or 10). The cleaned steel should then be coated with three coats of the epoxy-polyamide (see MIL-P-24441) each applied at 3 mils dry film thickness. Formula 150 green primer should be followed by Formula 156 red intermediate coat (Formula 151 gray is also suitable for fuel tanks but not potable water tanks) and Formula 152 white finish coat.

Exteriors. Exteriors of steel fuel and water tanks should be coated as described for their interiors except that the finish coat of Formula 152 should be replaced by 1-1/2 mils dry film thickness of white (see MIL-C-85282) aliphatic polyurethane. The latter provides good exterior weathering.

7.11.2 Piping.

Underground. Underground piping can be coated with a variety of thick coatings or wraps. These include extruded and fusion-bonded coatings and plastic and heat-shrinkable tapes. Coal tar and asphalt materials are not applied very much any more because of health and safety concerns. They are best applied in a shop under controlled conditions. They should be checked for holidays both immediately after application and above the ditch before burial. Required properties include: good electrical insulation, good moisture (barrier) resistance, easy application and field repair, good adhesion, resistance to damage during handling, and resistance to cathodic disbonding.

Above Ground. Coating piping located above ground should be done as previously described above for steel fuel and water tank exteriors.

Underwater. Coating piping located underwater, should be done as previously described for steel fuel and water storage tank interiors.

7.11.3 Waterfront Structures. Steel waterfront structures (e.g., piling and other pier structures) are normally coated with the epoxy-polyamide system previously described for steel fuel and water tanks interiors. An alternative system is two coats of SSPC Paint 16 (coal tar epoxy-polyamide) applied to a total of 16 mils dry film thickness over a near-white (SSPC-SP 10) abrasively blasted surface.

7.11.4 Antenna and Other Tall Towers and Supporting Equipment.

Towers. Because of the extreme expense of repainting steel antenna towers, it is best to apply and maintain a high-performance coating system. If possible, the primer or the total system should be applied in a shop under controlled conditions and touch up the damaged coating areas after erection in the field. A recommended coating system consists of one coat of zinc-rich epoxy (SSPC Paint 20, Type II), one coat of epoxy-polyamide (MIL-P-24441) Formula 150 green primer, and one coat of white aliphatic polyurethane (MIL-C-85285).

Anchors and Guys. Anchors and guys can be protected by applying a petrolatum paste that encapsulates the metal. A special applicator has been developed for remote application of steel guy lines with petrolatum paste. Alternatively, anchors may be coated as described for the exteriors of steel fuel and water storage tanks.

7.12 PAINTING GALVANIZED SURFACES. Because new galvanized steel is smooth and may contain oil to protect it during storage, it is difficult to get coatings to bond well to it. Weathered galvanizing that has developed a surface texture is much easier to coat. Historically, galvanizing has been wash primed and coated with two coats of alkyd or latex coating. Because wash primer and the recommended alkyd coating are no longer considered environmentally acceptable, this method is no longer applicable. Latex coatings may, however, be applied to weathered galvanizing. A much better performance will be received from one coat of epoxy-polyamide Formula 150 green primer and one coat of aliphatic polyurethane (MIL-P-85285). New galvanizing should always be solvent washed (SSPC-SP 1) before coating. Weathered galvanizing should be washed to remove all loose surface contamination before coating.

7.13 PAINTING ALUMINUM AND OTHER NONFERROUS METALS. In the past, aluminum and other nonferrous metals were frequently wash primed and coated with alkyd. Because this system is no longer environmentally acceptable, a two or more coat epoxy (MIL-P-24441) is recommended.

7.14 PAINTING SAFETY. Because coating operations are frequently hazardous, special safety precautions must be taken. Local safety offices can provide detailed information and safety equipment.

7.14.1 <u>**High Places (Scaffolding, Lifts, Nets, and Lines).**</u> Workers in high places should be protected by life lines or nets. Scaffolding should be the required design, and instructions on their use should be followed.

7.14.2 <u>**High Pressures.**</u>

Abrasive Blasting Respirators/Training/Physicals. Abrasive blasters should have the necessary safety training, equipment, and physical examinations to meet all prevailing safety requirements.

Waterblasting. Waterblasting equipment must have a safety certificate and must be used as described in the instructions.

Airless Spraying. Airless spray guns should always be used with safety guards. Back flushing with solvents should be done only when special adapters for this purpose are used.

7.14.3 <u>**Flammable Materials.**</u> Flammable paint materials should be stored in accordance with local safety requirements and used in enclosed areas only with grounded equipment and structures and with nonsparking electrical fixtures. Proper ventilation of vapors is required.

7.14.4 <u>**Toxic Materials.**</u> Toxic paint materials must be stored in accordance with local safety requirements. Clothing and respirators should be used to avoid contact and inhalation. Exposure time should be limited as much as practical.

7.14.5 <u>**Caustic Materials (Acids, Alkalis, Steam).**</u> Acids, alkalis, and steam can cause serious burns. Gloves, face shields, and protective clothing should be used when working with them.

7.14.6 <u>**Safety Plan.**</u> All shops conducting cleaning or application operations should have a safety program. This program should include first-aid and safety training related to these operations to keep all workers aware of hazardous conditions and methods to provide protection from the hazards.

CHAPTER 8. CORROSION RESISTANT METALS

8.1 SELECTING METALS FOR CORROSION RESISTANCE. Selecting metals for their resistance to corrosion should be considered as a part of the overall material selection process. Corrosion resistance as well as strength, ductility, fabricability, availability, and cost are all factors that must be considered in selecting a material. In this chapter, the corrosion resistance and applications of many of the metals that are commonly used in shore facilities will be described. However, in order to make specific materials selections, detailed information on the corrosion properties as well as other materials properties must be obtained and evaluated.

8.2 APPLICATION OF CORROSION PERFORMANCE DATA TO SELECTION OF MATERIALS. Materials performance data, whether based on the analysis of previous successful or unsuccessful application or on corrosion testing must be carefully integrated into the design process. Only through an understanding of how the type and amount of corrosion that is likely to occur in specific locations in a system will affect the function of the system can corrosion failures be avoided.

     8.2.1 Materials Selection as Part of the Design Process. Material selection is often performed only toward the end of the design process. In some cases, due to material availability, fabrication problems, or even after initial use or test has shown that the originally specified material is unsatisfactory, the first attempt to solve the problem is to change the material without changing the design. This often results in a less than optimum match between material properties and the requirements of the application. In some cases, this process results in a materials "overkill" that has an adverse impact on cost, fabrication difficulties, and use of non-standard components with attendant problems in obtaining spares.

     8.2.2 Designing to Fit Available Materials. In many cases, it is appropriate to identify those materials that have suitable corrosion properties for a specific application, then design a system based on the properties of the available materials. This is often more effective than selecting materials that have the properties required by a given design.

     8.2.3 Use of Corrosion Data. Corrosion data. whether from experience or from testing, must be used in a systematic manner. Corrosion data are used to quantitatively predict the amount and distribution of corrosion that will occur on a given component in a given application. Whether the design is performed in a "materials first" or "design first" manner, some quantitative corrosion data must be used. It is important to understand how the data were obtained in order to best apply it to design.

8.2.4 <u>Definition of Required Material Properties.</u> In order to select materials, limits for material performance must be established. While requirements for such properties as strength and ductility are relatively easy to define, requirements for such properties as corrosion resistance and fabricability are often less easy to define quantitatively. For corrosion resistance, high levels of resistance to certain forms of attack such as crevice corrosion, can be identified as a specific requirement with resistance to other forms of attack being less important. A list of specific critical properties for a specific application with "desirable" and "acceptable or threshold" requirements for these critical properties is often useful in selecting materials for specific applications.

8.2.5 <u>Determination of Acceptable Performance.</u> In many cases, a material will be selected that will perform adequately for a given service life but will deteriorate significantly during that service period and will either have to be repaired or replaced if the application is repeated. In this case, the performance could be considered adequate but not desirable. In many cases this is appropriate. In cases where repetitive or extended application is anticipated, select a more corrosion resistant material that will not require repair or replacement for re-use.

8.2.6 <u>Sources of Corrosion Data.</u> Corrosion data are available from a wide variety of sources. However, it is not available from any single source. Data from similar service performance, corrosion testing, or corrosion theory can all be used if properly interpreted and applied.

Service Performance. Data from previous service performance often address many of the anticipated corrosion related factors but are often qualitative in nature. As discussed in Chapter 3 of this manual, in-service material performance must be properly evaluated in order to be useful in design.

Corrosion Testing. Data from corrosion tests are usually very quantitative in nature but often does not address many of the factors anticipated in a given application. Most marine corrosion data are obtained from the exposure of small samples of isolated materials. Information on galvanic interactions and the effects of crevices is more limited and is often semi-quantitative or qualitative. Care must be taken to verify that the quantitative data presented are appropriate to the form of corrosion that was experienced. Corrosion rates based on weight loss should not be used to assess non-uniform corrosion attack. Corrosion data are usually more useful in comparing the performance of materials with similar performance than in comparing the performance of materials with widely different corrosion behavior. In many cases, data from corrosion testing are difficult to use in the quantitative prediction of long term system performance of complex systems.

Corrosion Theory. Corrosion theory is useful in evaluating the causes of corrosion damage but is difficult to apply to the prediction of corrosion performance. If there are no data from either corrosion testing or from in-service performance of a given material it is likely that some aspect of its performance has made it unfit for marine service. The market for marine materials is highly competitive and if a material has not been used or tested in the marine environment it should be used only with great caution.

8.3 GENERAL CATALOG OF CORROSION DATA. The following can be used as a general guide for preliminary evaluation of materials for marine service. Additional details on material properties and performance should be obtained for design purposes.

8.3.1 Irons and Steels. Irons and steels are the most commonly used materials for shore facilities. They are subject to uniform corrosion at a low rate and can be protected by protective coatings and/or cathodic protection. Due to the experience with using irons and steels in a wide variety of environments, there are large amounts of data from corrosion testing and much in-service performance data available for the irons and steels. Irons and steels are low in cost and are easy to form and fabricate.

Carbon Steels. Steels with a total alloy content less than 3% corrode uniformly in a wide variety of environments including atmospheric and immersion service. The corrosion of carbon steels in marine environments varies widely and is dependent on local conditions. Rates as low as 1 MPY and as high as 250 MPY have been experienced. For immersion service in seawater, the rates of uniform attack are less dependent on local conditions and rates from 5 to 10 MPY are common. Carbon steel is seldom exposed to aggressive environments without coatings or cathodic protection. It is the performance of these systems rather than the corrosion rates of the unprotected material that govern the life of carbon steel marine equipment. Temporary localized failure of protective systems does not result in high rate localized attack. Carbon steel is anodic with respect to most other materials.

High Strength-Low Alloy Steels. High strength-low alloy steels show improved corrosion resistance over carbon steels in rural and mild industrial environments. In marine atmospheres and in immersion services, however, the difference in performance between carbon and low-alloy steels is minor. The primary advantage of these materials is their higher strength. But remember that the same amount of material loss will usually have a greater impact on the load carrying capacity of a high strength material than on a low strength material. The high strength-low alloy steels should be protected when used in marine environments. They are somewhat more cathodic than carbon steels.

8.3.2 Alloy Steels. Steels with a higher alloy content are more susceptible to pitting attack than steels with lower alloy content. Pitting is common in alloys with more than 5% total alloy content. Corrosion rates are similar to carbon and low alloy

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steels with pitting being only three to five times the rate calculated from weight loss. Alloy steels are selected for their higher strength but can be susceptible to hydrogen embrittlement or stress corrosion cracking at yield strengths in excess 100 ksi. The alloy steels are somewhat more cathodic than carbon steels.

Cast Irons. "Cast iron" refers to a wide variety of materials. Commonly, they are ferrous alloys that contain more than 2% carbon that is found in the alloy such as graphite or large carbide aggregates. These alloys are used primarily for their formability by casting rather than their mechanical properties or corrosion resistance. Many of the low alloy cast irons are subject to graphitization. This occurs fairly uniformly with a penetration rate of 0.010 to 0.020 inches per year in seawater immersion or in many soil environments. Alloy cast irons containing 20% nickel have improved corrosion resistance and corrode uniformly at a low rate. The potential of graphitized cast iron can be very cathodic with respect to most other materials and can approach that of graphite. Thus, when graphitized, cast irons can cause corrosion when electrically coupled to most other metals. Alloy cast irons are somewhat more cathodic than carbon steels.

8.3.3 Stainless Steels. Stainless steels can be defined as a ferrous alloys that contain more than 11% chromium and are resistant to general rusting in mild atmospheric conditions. They are generally subject to non-uniform attack in chloride containing environments with crevice corrosion and pitting attack being common on many alloys. Due to the high rate of localized attack that occurs at the start of the attack, the incubation time for attack is often a more significant measure of corrosion resistance than penetration rates. The stainless steels exhibit two potential states: (1) active and (2) passive. The passive state is substantially cathodic to the active state. It is this potential difference that drives non-uniform attack, such as pitting and crevice corrosion on these alloys. For purposes of evaluating possible galvanic corrosion between the stainless steels and other alloys, the potential of the passive state should be used. As these alloys polarize readily, their potentials can have a wide range in some conditions and may be of little value in assessing galvanic corrosion problems based on field measurements.

200 Series Stainless Steels. This group of alloys is similar to the more common 300 Series alloys described below as they are non-magnetic and have an austenitic structure. The basic alloy contains 17% chromium, 4% nickel and 7% manganese. Although these alloys are somewhat more resistant to attack than the more common 300 series stainless steels, their overall performance is similar. Some proprietary grades related to the 200 series, have performance equal or superior to the best 300 series stainless steels. These alloys are, however, not immune to attack and are very susceptible to concentration cell and pitting attack. When corrosion starts they usually corrode rapidly and non-uniformly. In seawater immersion, the incubation time for these alloys is in the range of 1 to 3 months with some of the Nitronic grades having incubation times of up to 1 year.

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300 Series Stainless Steels. This group of alloys are non-magnetic and have an austenitic structure. The basic alloy contains 18% chromium and 8% nickel. These alloys are subject to crevice corrosion and pitting. They have a range of incubation times in seawater ranging from essentially zero in the case of the free machining grades, such as Type 303, to 6 months to 1 year for the best alloys, such as Type 316. They have been widely used in facilities with mixed results. If used in an application where chloride levels are low or where concentration cell corrosion has been prevented through design, they are likely to perform well. When chloride levels are high and where concentration cells can occur, the performance of these alloys is often poor. They must always be selected with care for a specific application and the effect of potential non-uniform attack on system performance must be addressed.

400 Series Stainless Steels. This group of alloys are magnetic and have a martensitic structure. The basic alloy contains 11% chromium and 1% manganese. These alloys can be hardened by heat treatment but have poor resistance to corrosion. They are subject to both uniform and non-uniform attack in seawater. The incubation time for non-uniform attack in chloride containing environments is very short, often only hours or a few days. Unless protected, using these alloys in seawater or other environments where they are susceptible to corrosion is not recommended.

600 Series Stainless Steels. This series of stainless steels is commonly referred to as "Precipitation Hardening" stainless steels. These steels can be heat treated to high strength levels. They are subject to crevice corrosion and pitting in chloride containing environments and are also subject to stress corrosion cracking and hydrogen embrittlement. The incubation time for crevice corrosion and pitting in seawater is relatively short, often only a few days. The incubation time for stress corrosion cracking can be very short, sometimes measured in hours. The use of these alloys in chloride containing environments is not normally recommended unless they are carefully selected, their heat treatment is carefully specified and controlled, and the effect of pitting and crevice corrosion is properly addressed.

Miscellaneous Cast and Wrought Stainless Steels. Alloy 20, a proprietary cast and wrought stainless steel has superior corrosion resistance to Type 316 stainless steel. Many newly developed proprietary stainless steels have given good service in many applications and have corrosion resistance superior to Type 316 stainless steel. The use of these alloys must be evaluated based upon their specific corrosion properties. While the resistance of these alloys is superior to many other grades of stainless steels, the benefits of using these alloys in critical applications instead of more corrosion resistant or corrosion immune alloys must be balanced against the consequences of failure.

8.3.4 Aluminum Alloys. Aluminum alloys are used primarily because of their low weight, the ease with which they can be formed and fabricated, and their corrosion

resistance in many atmospheric and immersion environments. They are not, however, resistant to corrosion in many marine environments and are subject to crevice corrosion, pitting, and in some alloys, stress corrosion cracking. The alloys are also very subject to galvanic corrosion as they have an anodic potential with respect to most other metals.

1000 Series Aluminum Alloys. This series of alloys are essentially unalloyed aluminum. While they have fairly good corrosion resistance as compared to other aluminum alloys, they have relatively low strength. They are subject to crevice corrosion and pitting.

2000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and copper. These alloys are relatively high in strength and are widely used in the aerospace industry. The corrosion resistance of these alloys is inferior to most other aluminum alloys.

3000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and manganese. Their corrosion performance is roughly comparable to the 1000 series alloys.

5000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and magnesium. The are relatively low in strength and cannot be heat treated to obtain higher strengths. Their corrosion performance in most environments is superior to other aluminum alloys with the exception of the 1000 series. They are, however,, subject to both pitting and crevice corrosion, particularly in marine applications.

6000 Series Aluminum Alloys. This series of alloys are alloys of aluminum, magnesium, and silicon. They are relatively high in strength and can be heat treated to obtain higher strengths. Their corrosion performance in most environments is somewhat inferior to the 5000 series alloys but is acceptable in many applications. They are subject to both pitting and crevice corrosion.

7000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and zinc. They are heat treatable to obtain high strengths. Their corrosion performance in chloride containing environments application is inferior to other aluminum alloys. If they are used, care must be used to control crevice and pitting attack unless the effects of these forms of attack are not functionally significant. Some of the 7000 series alloys are subject to stress corrosion cracking when heat treated to high strength levels.

Cast Aluminum Alloys. Of the cast aluminum alloys, alloy A-356 has the best overall balance between mechanical properties, castability, and corrosion resistance and is the most commonly used aluminum casting alloy for corrosion service. Its corrosion performance is comparable to the 6000 series wrought alloys.

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8.3.5 Copper. Although copper has a relatively low strength, its electrical and thermal conductivity make it an appropriate material for some marine applications. Copper corrodes uniformly at a low rate in many environments. Copper is subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices. Copper and copper alloys are cathodic to steel and many other commonly used alloys.

Bronzes. Bronzes are copper-tin, copper-aluminum, or copper-silicon alloys. Many of these alloys corrode uniformly at a relatively low rate. Some of the alloys, particularly the aluminum bronzes with aluminum contents in excess of 10%, are subject to dealloying and should not be used if this form of attack is functionally significant. Nickel-aluminum bronzes are widely used as casting alloys and, if properly heat treated, can give excellent service. Most bronzes are subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices.

Brasses. Brass is a copper-zinc alloy. Unless the zinc content is below 10% or inhibitors are added to the alloy, brasses are subject to dealloying in immersion service, particularly in seawater. The use of other copper alloys such as the aluminum bronzes or copper-nickel alloys in lieu of brass is recommended for most applications where resistance to corrosion in immersion conditions is important.

Copper-Nickel Alloys. The nickel content of the most common copper-nickel alloys ranges from 10% to 30%. They are most commonly used for heat exchanger tubes. The resistance of the alloys to velocity attack is good with the limiting velocity for the 10% nickel alloy being about 8 feet per second and for the 30% nickel alloy being about 20 feet per second. They also have good resistance to low flow conditions. The alloys corrode uniformly below their limiting velocities. Both alloys are subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices.

Beryllium Copper. Beryllium copper alloys can have very high strengths of up to 200 ksi. They corrode uniformly at a low rate. Beryllium copper is subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices. Beryllium copper is widely used as a spring and electrical contact material.

8.3.6 Nickel Alloys. Many nickel alloys have been developed specifically for their high resistance to corrosion. The alloys in this group are among the most corrosion resistant materials in many environments and some of the alloys are essentially immune to attack.

Nickel. Nickel, as usually applied as a plating material, is resistant to corrosion in mildly corrosive environments but is not resistant to corrosion in chloride containing

environments. Except in chemical processing, nickel is seldom used as a structural material.

Nickel-Copper Alloys. The most common nickel-copper alloy is Monel 400, which is nominally 70% nickel and 30% copper. Monel 400 is highly resistant to corrosion in many environments but is not totally resistant to corrosion in seawater. It is subject to pitting attack in seawater if exposed without coupling to other metals. The incubation time for pitting in seawater is rather long and ranges from 1 to 2 years. Monel 400 is subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices. Monel is cathodic to most other common alloys. Monel K-500 is an age hardenable nickel-copper alloy and has higher strength than Monel 400 but has comparable corrosion characteristics.

Other Nickel Alloys. Nickel alloys such as Inconel 625 and Hastelloy C-276 are essentially immune to corrosion in many environments. Inconel alloy 718 has high strength in the order of 150 ksi and has good resistance to corrosion in many environments and usually only exhibits small amounts of crevice attack. A-286 is a nickel-chromium-titanium-molybdenum alloy that is widely used as a high strength fastener alloy. While subject to crevice corrosion with initiation times and propagation rates similar to Type 316 stainless steel, it has been successfully used in many applications. Its practical corrosion resistance is improved due to its cathodic potential with respect to many materials and the significant improvement in its corrosion resistance when coupled to more anodic materials.

8.3.7 Titanium Alloys. Titanium alloys are high in cost and difficult to form and fabricate. Many of the alloys are, however, essentially immune to corrosion in a wide variety of environments.

General Corrosion Performance. Titanium alloys are essentially resistance to general corrosion in most environments at ambient temperature. They are essentially immune to crevice attack and pitting. At elevated temperatures they can be subject to pitting and crevice corrosion in some environments.

Stress Corrosion Cracking. Some of the titanium alloys are subject to stress corrosion cracking. The commercially pure (CP) alloys and Alloy 6Al-4V are the most commonly used alloys and are resistant to stress corrosion cracking in most environments. Use of these alloys is recommended unless higher strength is specifically required. Other alloys may be resistance to stress corrosion cracking but must be evaluated for each specific application.

8.3.8 Other Alloys and Materials. Several materials that are either effectively immune to corrosion in many environments or have other unique properties are available for use in special applications.

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Cobalt Alloys. Stellite 6 is a cobalt based alloy that is widely used for a combination of abrasion and corrosion resistance. It is difficult to form and fabricate but can be used when its relatively high yield strength (90 ksi), abrasion resistance, and immunity to corrosion are required. MP-35N is another cobalt based alloy that is widely used as an aerospace fastener material. Its combination of extremely high yield strength (285 ksi) and immunity to corrosion are unique. The potential of cobalt alloys are cathodic to most other metals.

Noble Metals. Gold and platinum are essentially inert in most environments. Gold is sometimes used as a plating on copper alloys to improve electrical contact resistance. Platinum is primarily used as an anode material for impressed current cathodic protection. It is either used as wire anodes or is bonded to titanium or niobium supports. Platinum and gold are cathodic to most other metals.

Lead Alloys. Lead and lead alloys corrode uniformly at a low rate in many environments where the protective film of corrosion products formed on their surface is insoluble. However, in the presence of nitrates, acetates, or chlorides, lead alloys can corrode non-uniformly as the corrosion products formed are not protective. Lead-tin solder corrodes in a similar manner.

CHAPTER 9. SYNTHETIC ORGANIC MATERIAL (PLASTICS) AND ORGANIC MATRIX COMPOSITES (REINFORCED PLASTICS)

9.1 GENERAL PROPERTIES OF PLASTIC MATERIALS.

9.1.1 Definition. A plastic is any one of a large and varied group of materials that contain, as an essential ingredient, an organic resin substance of large molecular weight. Although the material is solid in the finished state, at some stage in its manufacture it has been or can be formed into various shapes by flow, usually through application or together with heat and pressure.

An organic matrix composite or reinforced plastic is any one of a large and varied group of materials that use a plastic or combination of plastics as the matrix material combined with any number of reinforcing materials to provide a composite with improved properties over the individual parts.

9.1.2 Classification. Organic plastic materials may be classified into four groups:

Thermoplastic - can be physically transformed and change shape by heat, repeatedly.

Thermosetting Plastic - chemically transformed by heat, chemical action, catalysts or ultraviolet light or other forms of radiation leading to a relatively infusible state.

Elastomers - synthetic polymerized, stretchable, rubber-like properties.

Thermoplastic Elastomers - has the characteristics of both plastics and elastomers.

9.1.3 Physical Properties. All corrosion-resistant materials must be selected on the basis of their ability to out perform all other products when evaluated under identical conditions. High molecular weight organic materials are used to advantage by forming into useful shapes. The physical properties listed should be considered when selecting plastic materials:

Stress/strain characteristics under service conditions
Creep
Strength (tensile, impact, flexural, compressive)
Heat distortion
Specific gravity
Flammability

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Resistance to weather
Resistance to sunlight
Hardness

9.1.4 Chemical Resistance Versus Molecular Structure. Natural macromolecules frequently have some inconvenient or undesirable properties. This problem has been approached on the basis of: (a) modification of the natural macromolecules; and (b) the synthesis of other new types, often from natural macromolecules. In selecting a plastic material, the following characteristics should be considered: Polar and nonpolar classification, resistance to specific environments, resistance to specific chemicals, service tests under specific conditions, and toxicity.

9.1.5 Laboratory Tests. Methods of testing plastics are outlined in the following specifications:

Plastics, Organic: General Methods of Testing. Federal
Specification L-P-406

Rubber: Sampling and Testing, Federal Test Method. Standard No.
601

Paint, Varnish, Lacquer, and Related Materials: Methods of
Inspection, Sampling, and Testing. Federal Specification TT-P-141

1988 Book of ASTM Standards. ASTM Volumes 08.01, 08.02, 08.03,
08.04, 09.01, 09.02, and 10.01

Tentative specifications. Society of the Plastics Industry

9.1.6 Organic Matrix Composites (Reinforced Plastics). Composites have high tensile strength and impact resistance. The reinforcement can be embedded in the matrix or external. The composites design structure can be fiberglass, honeycomb, single to multiple plys, or any number of other construction designs.

The majority of organic matrix composites uses the first two types of plastics as the matrix material but there are still many uses for the elastomers where flexibility may be a requirement, as in flexible fuel hoses.

9.1.7 Fiber Reinforced Plastics (FRP). A broad group of composite materials composed of fibers embedded in a plastic resin matrix. In general, they have high strength-to-weight ratios and excellent corrosion resistance compared to metals. They can be formed economically into virtually any shape and size.

In size, FRP products range from tiny electronic components to large boat hulls. In between these extremes, there is a wide variety of FRP gears, bearings, bushings, housings, and parts used in all product industries.

Glass is by far the most used fiber in FRPs. Glass-fiber-reinforced plastics are often referred to as GFRP or GRP. Asbestos fiber has some use, but is limited in applications where maximum thermal insulation or fire resistance is required. Other fibrous materials used as reinforcements are paper, sisal, cotton, nylon, and Kevlar. For high performance parts and components, fibers, such as boron and graphite, can be used.

Although a number of different plastic resins are used as the matrix for reinforced plastics, thermosetting polyester resins are the most common. The combination of polyester and glass provides a good balance of mechanical properties as well as corrosion resistance, low cost, and good dimensional stability. In addition, curing can be done at room temperature without pressure, thus making for low processing equipment costs. For high volume production, special sheet-molding compounds are available in continuous sheet form. Resin mixtures of thermoplastics with polyesters have been developed to produce high quality surfaces in the finished molding. The common thermoplastics used are acrylics, polyethylenes, and styrenes.

Other glass-reinforced thermosets include phenolics and epoxies. GRP phenolics are noted for their low cost and good overall performance in low strength applications. Because of their good electrical resistivity and low water absorption, they are widely used for electrical housings, circuit boards, and gears. Since epoxies are more expensive than polyesters and phenolics, GRP epoxies are limited to high performance parts where their excellent strength, thermal stability, chemical resistance, and dielectric strength are required.

Initially, GRP materials were limited to thermosetting plastics. Today, however, more than 1,000 different types and grades of reinforced thermoplastics are commercially available. Leaders in volume use are nylon and styrenes; others include sulfones and ABS. Unlike thermosetting resins, GRP thermoplastic parts can be made in standard injection-molding machines. The resin can be supplied as pellets containing chopped glass fibers. As a rule, a GRP thermoplastic with chopped fibers at least doubles the plastic's tensile strength and stiffness. Glass-reinforced thermoplastics are also produced as sheet materials for forming on metal stamping equipment.

9.1.8 Polymerization. Most synthetic organic materials (plastics) are produced by adding small unsaturated molecules together to form long chains that can be straight or branched and with or without cross-linking. This process is usually carried out under pressure, under heat, chemical action, radiation, or any combination of these catalysts known as curing agents.

9.2 THERMOPLASTIC APPLICATIONS.

9.2.1 Acetal Resins. Highly crystalline resins that have the repeating group $(OCH_2)_x$. The resins are polyformaldehyde. The natural acetal resin is translucent white and can be readily colored. There-are two basic types: homopolymer (Delrin) and copolymer (Ceclon). In general, the homopolymers are harder, more rigid, and have higher tensile flexural and fatigue strength, but lower elongation. The copolymers are more stable in long term, high temperature service and have better resistance to hot water. Special types of acetals are glass filled, providing higher strengths and stiffness, and tetrafluoroethylene (TFE) filled, providing exceptional frictional and wear properties.

Acetals are among the strongest and stiffest of the thermoplastics. Their tensile strength ranges from 8,000 to about 13,000 lb/in.^{2} (55 to 89 MPa), the tensile modules of elasticity is about 500,000 lb/in.^{2} (3,445 MPa), and fatigue strength at room temperature is about 5,000 lb/in.^{2} (34 MPa). Their excellent creep resistance and low moisture absorption (less than 0.4%) give them excellent dimensional stability. They are useful for continuous service up to about 220°F (104°C). Acetals' low friction and high abrasion resistance, though not as good as nylon's, rates them high among thermoplastics. Their impact resistance is good and remains almost constant over a wide temperature range. Acetals are attacked by some acids and bases, but have excellent resistance to all common solvents. They are processed mainly by molding or extruding. Some parts are also made by blow and rotational molding. Parts and products made of acetal include pump impellers, conveyor links, drive sprockets, automobile instrument clusters, spinning reel housings, gear valve components, bearings, and other machine parts. Delrin, of DuPont, is used for mechanical and electrical parts. It has a specific gravity of 1.425, a tensile strength of 10,000 lb/in.^{2} (68 MPa) with elongation. of 15%, dielectric strength of 500 volts per mil (19.6 x 10^6 volts per meter), and Rockwell hardness of M94. It retains its mechanical strength close to the melting point of 347°F (175°C). Celcon, of the Celeanese Corp., is a thermoplastic linear acetal resin produced from trioxane, which is a cyclic form of formaldehyde. The specific gravity is 1.410, flexural strength of 12,000 lb/in.^{2} (82 MPa), Rockwell hardness of M76, and dielectric strength of 1,200 volts per mil (47 x 10^6 volts per meter). It comes in translucent white pellets for molding.

9.2.2 Acrylic Resins. Colorless, highly transparent, thermoplastic, synthetic resins made by the polymerization of acrylic derivatives, chiefly from the esters of acrylic acid, CH_2:CH"COOH, and methacrylic acid, CH_2:C(CH$_3$)"COOH, ehtyl acrylate and methyl acrylate. Glacial acrylic acid is the anhydrous monomer with less than 2% moisture. It can be esterified directly with an alcohol. Vinyl acrylic acid, CH_2:CHCH:CHCOOH, with a melting point of 80°C, is made from acrolein and malonic acid. It polymerizes on heating.

The resins vary from soft, sticky semi-solids to hard, brittle solids, depending on the constitution of the monomers and on the polymerization. They are used for adhesives, protective coatings, finishes, laminated glass, transparent structural sheet, and molded products. Acrylic resins, or acrylate resins, are stable and resistant to chemicals. They do not cloud or fade in light when used as laminating material in glass and are used as air-curing adhesives to seal glass to metals or wood. Water-based acrylics are also used for caulks and sealants. They have better adhesion and weather resistance than butyl rubbers and dry more quickly. The sealants usually contain about 80% solids.

Most acrylic plastics are based on polymers of methyl methacrylate, which can be modified by copolymerizing or blending with other monomers. Noted for excellent optical properties, they have a light transmission of about 92%. Besides the transparent grades, they come in translucent or opaque colors as well as the natural water white color. Moldings have a deep luster and high surface gloss, and for this reason are widely used for decorative parts. Acrylic plastics have excellent weathering characteristics. Because they are hardly affected by sunlight, rain, and, corrosive atmospheres, they are well suited for outdoor use. In general, the majority of grades can be used up to about 200°F (100°C). Thermal expansion is relatively high.

Acrylic plastics are hard and stiff. They are a relatively strong plastic; their tensile strength ranges from 5,000 to about 11,000 lb/in.^{2} (34 to about 75 MPa). However, regular grades are somewhat brittle. High impact grades are produced by blending with rubber stock. The high strength is useful only for short term loading, For long term use, to avoid crazing or surface cracking, tensile stresses must be limited to about 1,500 lb/in.^{2} (10 MPa).

Acrylic plastics are available as cast sheets, rods, tubes, and blocks. They are also processed by injection or compression molding. Sheets are produced in thicknesses from 1/8 to 3/8 inch (0.32 to 0.95 cm) and in sizes up to 10 by 12 feet (3 by 4 meters). A special process that produces molecular orientation in the cast product is used to make crack-resistant aircraft cabin windows and fighter plane canopies. Acrylic moldings as large as 1 yd^2 (1 m^2) have been produced. A lead-filled acrylic sheet, produced by Kyowa Gas Chemical Industry Co., Japan, is used as a radiation shielding material. It is transparent and has better impact strength and fabricability than leaded glass. Moldings include knobs, handles, escutcheons, parts for vending machines, and a wide variety of lenses for light control, signal lamps, etc. the like.

Tough molding resins are made by copolymerizing methyl methacrylate with styrene.

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Product	Manufacturer	Remarks
Zerlon 150	Dow Chemical Co,	A molding resin with a flexural strength of 17,600 lb/in.^{2}(123 MPa).
Thiacril	Thiokol Chemical Corp.	An acrylate rubber having a tensile strength of 2,500 lb/in.^{2}(16 MPa) and an elongation of 350%. Used for gaskets, wire insulation, and hose.

Allyl methacrylate is a liquid of the empirical formula $C_7H_{10}O_2$ boiling at 145°F (63°C), and insoluble in water. It can be polymerized to form liquid or hard solid resins, but is used chiefly as a cross-linking agent for other resins to raise the softening point and increase hardness.

Product	Manufacturer	Remarks
Gafite	General Aniline & Film Corp.	A polymethyl alphachloroacrylate $(CH_2CClCOOCH_3)_x$. A transparent and crack-resistant resin used for aircraf windows. The heat distortion point is 260°F (127°C), and has higher tensile and flexural strength than other acrylics. Cyclohexyl methacrylate has optical properties similar to crown glass, and is used for cast lenses, where its softness and low softening point, 160°F (71°C), are not objectionable.
Lucite	E.I. du Pont de Nemours & Co., Inc.	A methyl methacrylate marketed as molding powder and in rods, tubes, and cast and molded sheets. Lucitone, which is this material, is used for making dentures (pink) and can be translucent.
Lucite HM-140	E.I. du Pont de Nemours & Co., Inc.	A Lucite material compounded for high temperature injection molding.

Product	Manufacturer	Remarks
Acrylic syrup	E.I. du Pont de Nemours & Co., Inc.	A liquid Lucite for use as a low pressure laminating resin. Produces strong, stiff tough laminates adaptable to translucent or bright colors. Reinforced with glass fibers, a panel with contact cure has a flexural strength of 25,000 lb/in.^{2} (172 MPa), elongation 1.5%, distortion point at 233°F (112°C), Rockwell hardness of R121, and light transmission up to 65%.
Crystalite	Rohm & Haas Co.	An acrylic molding powder used for aircraft windows.
Plexiglas	Rohm & Haas Co.	A transparent methyl methacrylate in sheets and rods. Also used for aircraft windows.
Perspex	Rohm & Haas Co.	A similar English acrylic resin used for aircraft windows.
Plexiglas V	Rohm & Haas Co.	An injection molding.
Plexiglas VM	Rohm & Haas Co.	A molding powder that resists heat distortion to 174°F (79°C).
Vernonite	Rohm & Haas Co.	An acrylic denture resin.
Acryloid Resins	Rohm & Haas Co.	Acrylic copolymer solid resins, and the acrysol resins are solutions for coatings.
Plexene M	Rohm & Haas Co.	A styrene-acrylic resin for injection molding. The specific gravity of the molded resin is 1.08, the dielectric strength is 350 volts per mil (14 x 10^6 volts per meter), and tensile strength 15,000 lb/in.^{2} (103 MPa).
Rhoplex Resin	Rohm & Haas Co.	Acrylic resin emulsions for paints, textile finishes, and adhesives.
Crilicon Resin	Jersey State Chemical Co.	Acrylic resin emulsions for paints, textile finishes, and adhesives.

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Product	Manufacturer	Remarks
Polyco 296	American Polymer Corp.	A water-soluble acrylic copolymer used for thickening natural or synthetic rubber latex for paper and textile coatings.

Coatings made with acrylics have good adhesion and gloss, are resistant to oils and chemicals, and have good dielectric strength.

Product	Manufacturer	Remarks
Carboset 511	B.F. Goodrich Chemical Co.	A water solution of acrylic resin for protecting polished metal surfaces and precision parts against scratching. It is resistant to water, but can be washed off with soap and water.
Cavalon	Du Pont	A polyacrylic resin for coatings that has high hardness and resistance to abrasion.

9.2.3 Cellulosic Resins. Cellulose is the main constituent of the structure of plants, which when extracted, is used for making paper, plastics, and in many combinations. Cellulose is made up of long chain molecules in which the complex unit $C_6H_{10}O_5$ is repeated as many as 2,000 times. It consists of glucose molecules with three hydroxyl groups for each glucose unit. These OH groups are very reactive, and an almost infinite variety of compounds may be made by grafting on other groups, either repetitively or intermittently, such as reaction with acetic or nitric acids to form acetates or nitrates, reaction with ethylene oxide to form hydroxyethyl cellulose, reaction with acrylonitrile to form cyanoethylated cellulose, or reaction with vinyls.

Ethyl Cellulose. A colorless, odorless ester of cellulose resulting from the reaction of ethyl chloride and cellulose. The specific gravity is 1.07 to 1.18. It is non-flammable, very flexible, stable to light, and forms durable alkali-resistant coatings. It is used as a thin wrapping material, for protective coatings, as a hardening agent in resins and waxes, and for molding plastics. Ehtyl cellulose plastics are thermoplastic and are noted for their ease of molding, light weight, and good dielectric strength, 400 to 520 volts per mil (15 to 20.5 x 10^6 volts per meter), and retention of flexibility over a wide range of temperatures from -75 to 150°F (-57 to 66°C), the softening point. They are the toughest, lightest, and have the lowest water absorption of the cellulosic plastics. But they are softer and lower in strength than cellulose-acetate plastics.

Product	Manufacturer	Remarks
Lumarith EC	Celanese Corp.	An ethyl cellulose in the form of sheets, films, and molding powder. Celcon is a name applied by Celanese to ethyl cellulose plastics.
Hercocel E	Hercules, Inc.	A compounded ethyl cellulose molding powder in several formulations to give tensile strengths from 3,750 to 7,400 lb/in.^{2} (26 to 51 MPa), with elongation from 6 to 16%.
Ethocel	Dow Chemical Co.	An ethyl cellulose. Stripcoat is a solution of ethyl cellulose used for dipping automotive and aircraft parts or other metal products to form a thin, waterproof protective coating to prevent corrosion. The coating strips off easily when the part is ready to use.

The same material is marketed by a number of other companies for the same purpose under a variety of trade names.

Cellulose Acetate. An amber colored, transparent material made by the reaction of cellulose with acetic acid or acetic anhydride in the presence of sulfuric acid. In Germany it was made by treating beechwood pulp with acetic acid in the presence of an excess of zinc chloride. It is used for lacquers and coatings, molding plastics, rayon, and photographic film. Cellulose acetate may be the triacetate $C_6H_7O_2(OOOCCH_3)_3$, but may be the tetracetate or the pentacetate, or mixtures. It is made in different degrees of acetylation with varying properties, Unlike nitrocellulose, it is not flammable, and it has better light and heat stability. It has a refractive index of 1.47 to 1.50, and a sheet 1/8-inch (0.32 cm) thick will transmit 90% of the light. The specific gravity is 1.27 to 1.37, hardness 8 to 15 Brinell, tensile strength 3,500 to 8,000 lb/in.^{2} (24 to 55 MPa), compressive strength up to 20,000 lb/in.^{2} (137 MPa), elongation 15 to 80%, dielectric strength 300 to 600 volts per mil (12 to 24 x 10^6 volts per meter), and softening point 122 to 205°F (50 to 96°C). It is thermoplastic and is easily molded. The molded parts or sheets are tough, easily machined, and resistant to oils and many chemicals. In coatings and lacquers the material is adhesive, tough, and resilient, and does not discolor easily.

Cellulose acetate fiber for rayons can be made in fine filaments that are strong and flexible, nonflammable, mildewproof, and easily dyed. Standard cellulose acetate for molding is marketed in flake form.

Cellulose triacetate, with 60 to 61.5% combined acetic acid, is more insoluble, has higher dielectric strength, and is more resistant to heat and light than other types. It is cast into sheets and is also used for resistant coatings and textile fibers.

Cellulose acetate lacquers are sold under many trade names. They are the acetate in solvents with plasticizers and pigments.

Product	Manufacturer	Remarks
Vimlite	Celanese Corp.	Saran screen filled with cellulose acetate. Transmits ultraviolet light and is used for glazing.
Miramesh	National Research Corp.	Material with one side coated with a film of aluminum. Used for light diffusers and radiant-heat reflectors.
Masuron	John W. Masury & Son	Cellulose acetate material.
Nixonite	Nixon Nitration Works	Cellulose acetate material.
Plastacele	Du Pont	Cellulose acetate material.
Acele	Du Pont	Du Pont's name for acetate yarns.
Celanese	Celanese Corp.	Cellulose acetate yarns and fabrics.
Celairese	Celanese Corp.	Fluffy acetate fiber used for interlinings.
Lanese	Celanese Corp.	Fine fluffy acetate fiber used to blend with wool.
Fortisan	Celanese Corp.	Specially processed strong acetate fiber of extreme fineness [0.0001 inch (0.00025 cm) in diameter], originally developed for parachutes, but now also used in fine fabrics.

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Product	Manufacturer	Remarks
Forticel	Celanese Corp.	Cellulose propionate plastic used in injection molding. Has a flow point at (161°C), has high impact resistance, and requires less plasticizier than cellulose acetate.
Arnel	Celanese Corp.	Cellulose tricetate fiber resistant to shrinkage and wrinkling in fabrics.
Arnel 60	Celanese Corp.	Cellulose acetate fiber with a circular cross section instead of the normal crenelated cross section for higher strength and better spinning qualities.
Hercocel A	Hercules, Inc.	Cellulose acetate molding powder that will produce moldings with tensile strengths from 4,000 to 7,000 lb/in.^{2} (27 to 186 MPa) and elongations from 14 to 22%. The flow temperatures ranges from 285 to 355°F (140 to 179°C), depending on the form.
Avcovel	American Viscose Corp.	By-product of cellulose production used as a filler in plastics to increase impact strength. It contains 50% cellulose and 50% white cotton.

Cellulose acetate butyrate is made by the esterification of cellulose with acetic acid and butyric acid in the presence of a catalyst. It is used for coatings, insulation, varnishes, and lacquers. Called butyrate or CAB, is somewhat tougher, has lower moisture absorption, and a higher softening point than acetate. Special formulations with good weathering characteristics plus transparency are used for outdoor applications, such as signs, light globes, and lawn sprinklers. Clear sheets of butyrate are available for vacuum-forming applications. Other uses include: transparent dial covers, television screen shields, tool handles, and typewriter keys. Extruded pipe is used for electric conduits, pneumatic tubing, and low pressure waste lines.

Cellulose acetate propionate is similar to butyrate in both cost and properties. Some grades have slightly higher strength and modulus of elasticity. Propionate has better molding characteristics but lower weatherability than butyrate. Cellulose acetate

propionate is used to make steering wheels, fuel filter bowls, and appliance housings. Transparent sheeting is used for blister packaging and food containers.

Product	Manufacturer	Remarks
Tenite III		A cellulose acetate propionate used for extrusion rod and moldings of high impact strength.
Hercose C	Hercules, Inc.	A cellulose acetate butyrate used for cable coverings and coatings. It is more soluble than cellulose acetate and more miscible with gums. It forms durable and flexible films.
Ester EAB-171	Eastman	A liquid cellulose acetate butyrate for glossy lacquers, chemical-resistant fabric coatings, and wire-screen windows. Contains 17% butyl with one hydroxyl group per four anhydroglucose units. Transmits ultraviolet light without yellowing or hazing and is weather resistant.

9.2.4 Chlorinated Polyether. A high priced, high molecular weight thermoplastic used chiefly in the manufacture of process equipment. Crystalline in structure, it is extremely resistant to the thermal degradation at molding and extrusion temperatures. The plastic is resistant to more than 300 chemicals at temperatures up to 250°F (120°C) and higher, depending on environmental conditions.

Along with the mechanical capabilities and chemical resistance, chlorinated polyether has good dielectric properties. Loss factors are somewhat higher than those of polystyrenes, fluorocarbons, and polyethylenes, but are lower than many other thermoplastics. Dielectric strength is high and electrical values- show a high degree of consistency over a range of frequencies and temperatures.

The material is available as a molding powder for injection molding and extrusion applications. It also comes in sheets, rods, tubes, pipes, and blocks for lining tanks and other equipment, and for machining gears, plugs, etc. Rods, sheets, tubes, pipes, blocks, and wire coatings can be extruded on conventional equipment and by normal production techniques. Parts can be machined from blocks, rods, and tubes on conventional metal working equipment.

Sheets can be used to convert carbon steel tanks into vessels capable of handling highly corrosive liquids at elevated temperatures. Using a conventional adhesive system and hot gas welding, sheets can adhere to sandblasted metal surfaces.

Coatings of chlorinated polyether powder can be applied by several processes. Using the fluidized bed process, pretreated and preheated metal parts are dipped in an air-suspended bed of finely divided powder to produce coatings, which after baking are tough, pinhole free, and highly resistant to abrasion and chemical attack. Parts clad by this process are protected internally and externally against corrosion.

9.2.5 Fluoroplastics (also known as fluorocarbon resins and fluorine plastics). A group of high performance, high price engineering plastics. They are composed basically of linear polymers in which some or all of the hydrogen atoms are replaced with fluorine, and are characterized by high crystallinity and molecular weight. All fluoroplastics are natural white and feel waxy. They range from semi-rigid to flexible. As a class, they rank among the best of the plastics in chemical resistance and elevated temperature performance. Their maximum service temperature ranges up to about 500-F (260°C). They also have excellent frictional properties and cannot be wet by many liquids. Their dielectric strength is high and is insensitive to temperature and power frequency. Mechanical properties, including tensile creep and fatigue strength, are only fair, although impact strength is high.

There are three major classes of fluoroplastics. In order of decreasing fluorine replacement of hydrogen, they are: fluorocarbons, chlorotrifluoroethylene, and fluorohydrocarbons. There are two fluorocarbons: tetrafluoroethylene (PTFE or TFE) and fluorinated ethylene propylene (FEP). PTFE is the most widely used fluoroplastic. It has the highest useful service temperature, 500°F (260°C), and chemical resistance. FEP's chief advantage is its low melt viscosity, which permits it to be conventionally molded.

Product	Manufacturer	Remarks
Teflon	Du Pont	A tetrafluoroethylene of specific gravity up to 2.3. Tensile strength: up to 3,500 lb/in.^{2} (23.5 MPa). Elongation: 250 to 350%. Dielectric strength: 1,000 volts per mil (39.4 x 10^6 volts per meter). Melting point: 594°F (312°C). Is water and chemical resistant.

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Product	Manufacturer	Remarks
Teflon S	Du Pont	A liquid resin of 22% solids. Can be sprayed by conventional methods and is curable at low temperatures. Gives a hard, abrasion-resistant coating. Temperature service range is up to 400°F (204°C). Is used as conveyors and chutes.
T-film	Eco Engineering Co.	A thin Teflon film for sealing pipe threads.
Teflon Fiber	Du Pont	Plastic in extruded monofilament, down to 0.01 in. (0.03 cm) in diameter. Oriented to give high strength. Used for heat- and chemical-resistant filters.
Teflon Tubing	Du Pont	Made in fine sizes down to 0.10 inch (0.25 cm) in diameter with wall thickness of 0.01 in. (0.03 cm).
Teflon 41-X	Du Pont	A colloidal water dispersion of negatively charged particles of Teflon. Used for coating metal parts by electrodeposition.

Teflon FEP is fluorinated ethylenepropylene in thin film, down to 0.0005 inch (0.001 cm) thick, for capacitors and coil insulation. The film has a dielectric strength of 3,200 volts per mil (126 x 10^6 volts per meter), tensile strength of 3,000 lb/in.^{2} (20 MPa), and elongation of 250%.

Chlorotrifluoroethylene (CTFE or CFE) is stronger and stiffer than the fluorocarbons and has better creep resistance. Like FEP and unlike PTFE, it can be molded by conventional methods.

There are two kinds of fluorohydrocarbons: polyvinylidene fluoride (PVF_2) and polyvinyl fluoride (PVF). While similar to the other fluoroplastics, they have a lower heat resistance, and considerably higher tensile and compressive strength.

Except for PTFE, the fluoroplastics can be molded, extruded, and formed by other conventional methods. However, processing must be carefully controlled. Because PTFE cannot exist in a true molten state, it cannot be conventionally molded. The common method of fabrication is by compacting the resin in powder form and then sintering.

Product	Manufacturer	Remarks
Whitcon	Whitford Chemical Corp.	A fluorocarbon powder of 1-m particle size. Used as a dry lubricant or added to rubbers, plastics, and lubricating greases.
Plaskon Halon (Grade G80)	Allied Chemical Co.	A tetrafluoroethylene powder 25 to 30 m fine particles. Molded parts have tensile strengths to 6,500 lb/in.^{2} (44.5 MPa).
Fluorothene Plastic	Union Carbide	Has the formula $(CF_2" CFCl)_n$, which is different from Teflon. It has one chlorine atom on every unit of the polymer chain, replacing the fourth fluorine atom. It is transparent and molded parts have a specific gravity of 2.1, a tensile strength of 9,400 lb/in.^{2} (65 MPa), a high dielectric strength, and will withstand temperatures to 300°F (149°C).
KEL-F	3M	A chlorotrifluoroethylene used for moldings, gaskets, seals, liners, diaphragms, and coatings. The molded parts have high chemical resistance. The compressive strength is 30,000 lb/in.^{2} (210 MPa), but can be heat treated to increase the compressive strength to 80,000 lb/in.^{2} (560 MPa). The tensile strength of the molded material is 5,000 lb/in.^{2} (34 MPa), but oriented fibers have a tensile strength to 50,000 lb/in.^{2} (344 MPa).
Fluorocarbon Rubber	3M	A saturated fluorocarbon polymer containing 50% fluorine. Is used for tubing, gaskets, tank linings, paints, and protective clothing. Clothing has a tensile strength of 3,000 lb/in.^{2} (20 MPa), elongation of 600%, heat resistance to 400°F (204°C), and a high resistance to oils and chemicals.

Product	Manufacturer	Remarks
Aclar	Allied Chemical Co.	A chlorotrifluoroethylene transparent packaging film that is exceptionally resistant to oils and chemicals, has a moisture-barrier efficiency 400 times that of polyethylene film, has good strength to 390°F (199°C), and retains its flexibility to -300°F (-184°C). It is also used for wire covering.

9.2.6 Polyamide Resins (Nylon). A group of polyamide resins that are long-chain polymeric amides in which the amide groups form an integral part of the main polymer chain and have the characteristic that when formed into a filament, the structural elements are oriented in the direction of the axis.

Nylon was originally developed as a textile fiber, and high strengths (above 50,000 lb/in.2 (344 MPa)) are obtainable in the fibers and films. But this high strength is not obtained in the molded or extruded resins because of the lack of oriented stretching. When nylon powder, which has been precipitated from the solution is pressed and sintered, the parts have high crystallinity and very high compressive strength, but they are not as tough as molded nylon.

Nylons are produced from the polymerization of a dibasic acid and a diamine. The most common one of the group is that by the reaction of adipic acid with hexamethylenediamine. The nylon molding and extruding resin of Du Pont's Elvamide 8042, formerly Zytel 42, has a tensile strength of 12,500 lb/in.^{2} (106 MPa) with elongation above 100%, a flexural strength of 13,800 lb/in.^{2} (95 MPa), Rockwell hardness of R118, a flow temperature of 480°F (249°C), and a dielectric strength of 350 volts per mil (14 x 10^6 volts per meter).

All of the nylons are highly resistant to common solvents and to alkalies, but are attacked by strong mineral acids. Molded parts are light weight, with a specific gravity of about 1.14, good shock-absorbing ability, good abrasion resistance, very low coefficient of friction, and high melting point, up to about 482°F (250°C). One disadvantage of nylon is its high water absorption and the resulting dimensional changes in moldings in service. Nylon is used to make gears, bearings, cams, and linkages. The electrical characteristics are about the same as those of the cellulosic plastics. As a wire insulation, nylon is valued for its toughness and solvent resistance.

Nylon fibers are strong, tough, elastic, and have a high gloss. The finer fibers are easily spun into yarns for weaving or knitting either alone or in blends with other fibers, and they can be crimped and heat set.

9-16

Product	Manufacturer	Remarks
Nyloft Fiber	Firestone Tire & Rubber Co.	Is used in carpets. The nylon is staple fiber, lofted, or wrinkled to give the carpet a bulky texture resembling wool.
Caprolan Tire Cord	Firestone Tire & Rubber Co.	Made from Nylon 6 of high molecular weight, has the yarn drawn to four or five times its original length to orient the polymer and give one-half twist per inch.
Nylon Film	Du Pont	Made in thicknesses down to 0.002 in. (0.005 cm) for heat-sealed wrapping, especially for food products where tight impermeable wrap is needed.
Nylon Sheet	Du Pont	Comes in colors or is transparent in thicknesses from 0.005 to 0.06 in. (0.013 to 0.152 cm). Is used for gaskets and laminated facings
Nylon Monofilament	Du Pont	Filament and fiber, when stretched, have a low specific gravity down to 1.068, and a tensile strength above 50,000 lb/in.^{2} (344 MPa). Is used for brushes, surgical sutures, tennis strings, and fishing lines. Nylon fibers made by condensation with oxalic acid esters have high resistance to fatigue when wet.
Nylon 6	Du Pont	Is made from caprolactam, which has the empirical formula $(CH_2)_5 N H C:O$, with a single 6-carbon ring. Molded parts have a tensile strength of 11,700 lb/in.^{2} (79 MPa) elongation 70%, dielectric strength 440 volts per mil (17.3 x 10^6 volts per meter), and a melting point of 420°F (216°C).

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Product	Manufacturer	Remarks
Nylon Foam or Cellular Nylon	Du Pont	Is made from Nylon 6 and comes in slabs, rods, and sheets. Densities range from 1 to 8 lb/ft^3(16 to 128 kg/m^3). The low density material is flexible, but the high density material is rigid with a load carrying capacity about the same as balsa wood. The foam is used in light weight buoys and flotation products.
Nylon 6/10	Du Pont	Is tough, heat resistant, and has a very low brittleness temperature. Can absorb about one-third as much moisture as Nylon 6 and half as much as Nylon 6/6.
Nylon 9	Du Pont	Is made from soybean oil by reacting with ozone. It has better water resistance than other nylons and is used for coatings.
Nylon 11	Du Pont	Is a polycondensation product of aminoun-deconoic acid which is made by a complex process from the recinoleic acid of castor oil. This type of nylon has superior dimensional stability and is used for injection moldings. Nylon 11 was originally marketed in France as Rilsan.
Nylon 12	Du Pont	Is similar to Nylon 11. Is a lauro lactam synthesized from butadiene. Has a low water absorption and good strength and stability. Is used for packaging film, coatings for metals, and moldings.
Nylon 4	Du Pont	Is a polypyrrolidine used for textile fibers. The molecular chain has more amide groups than do the chains of other nylons. Its ability to absorb moisture is about the same as cotton. Fabrics made from this nylon do not have the hot feel that is common with other synthetic fibers, and they press better and are static free.

Product	Manufacturer	Remarks
Alrac Nylon	Radiation Research Corp.	Is Nylon 4.
Nylon 6/6	Du Pont	Has a specific gravity of 1.14 and a tensile strength of 11,500 lb/in^2 (78 MPa). Is used for gears and mechanical parts, and its physical properties can be further enhanced by adding glass fibers or spheres as fillers.
Nylatron G	Polymer Corp.	Graphite-impregnated nylon in rods and strips for making gears, bearings, and packings.
Nylasint	Polymer Corp.	Sintered nylon impregnated with oil. Used for bearings
Flalon	Burgess-Berliner Assoc.	Nylon flanned of 15-denier crimped fibers carded on both faces. Looks like cotton flannel, but is superior in heat and wear resistance.
Raynile	Hewitt-Robbins, Inc.	Rayon-nylon fabric with nylon traverse threads. Is flexible and has about twice the strength of cotton fabric.
Fiberthin	U.S. Rubber Co.	Thin waterproof fabric used to replace heavier tarpaulins for protective coatings. Is woven of nylon and coated with plastic. Weighs 5 oz/yd^2 (0.17 kg/m^2) and has a tensile strength of 175 lb/in. (31 kg/cm) of width.
Facilon	Sun Chemical Corp.	Caprolan nylon fabric impregnated with vinyl resin. Used for facing wall panels and flexible floor coverings. Comes in colors and embossings.

9.2.7 **Polycarbonate Resins.** Made by reacting bisphenol and phosgene, or by reacting a polyphenol with methylene chloride and phosgene. The monomer may be $OC_6H_4C(CH_3)_2C_6H_4OC:O$. The molecular structure is in double-linked zigzag chains that give high rigidity. The resin is thermoplastic. It is crystalline with rhombic crystals.

Polycarbonate is a linear, low crystalline, transparent, high molecular weight plastic. It is considered the toughest of all plastics. In thin sections, up to 3/16 inch (0.478 cm) thick, its impact strength is as high as 16 ft"lb (24 kg"m). In addition, polycarbonate is one of the hardest plastics. It also has good strength and rigidity, and because of its high modulus of elasticity, is resistant to creep. These properties, along with its excellent electrical resistivity, are maintained over a temperature range of -275 to 250°F (-170 to 121°C). It has negligible moisture absorption, but it has poor solvent resistance, and, in a stressed condition, will craze or crack when exposed to some chemicals. It is unaffected by greases, oils, and acids. Polycarbonate plastics are easily processed by extrusion, by injection, blow, rotational molding, and vacuum forming. They have very low and uniform mold shrinkage. With a white light transmission of almost 90% and high impact resistance, they are good glazing materials. They have more than 30 times the impact resistance of safety glass. Other applications are safety shields and lenses. Besides glazing, polycarbonate's high impact strength makes it useful for air-conditioner housings, filter bowls, portable tool housings, marine propellers, and housings for small appliances and food-dispensing machines.

Product	Manufacturer	Remarks
Lexan Resin	General Electric	Has a molecular weight of 18,000, a tensile strength of 10,500 lb/in.^{2} (71 MPa), with an elongation of 60%, dielectric strength to 2,500 volts per mil (98 x 10^6 volts per meter), and a Rockwell hardness of M70. The deformation temperature under load is 290°F (143°C), and the specific gravity is 1.20. Is transparent and the 1/8-inch (0.318-cm) transmits 85% of the light. This material is called Makrolon in Germany.
Merlon	Mobray Chemical Co.	Polycarbonate resin.
Plestar Film	Ansco	Polycarbonate.

Product	Manufacturer	Remarks
Lexan 145	General Electric	Polycarbonate powder for use in emulsion coatings that have high strength, are tough, and nontoxic. When this resin is compounded with 40% glass fiber, its tensile strength is doubled and its coefficient of thermal expansion is greatly reduced.
Lexan FL 1800	General Electric	Structural foam resin with high resistance to combustion, meets both service performance requirements and flammability standards for materials used in enclosures for large data process systems.
Cycolac KM	Borg-Warner Corp.	A carbonate resin that is used in mixtures with an acrylonitrile-butadiene-styene copolymer with copolymerization. It retains the general characteristics of the carbonate with added flexural strength.

9.2.8 Polyester Resins. A large group of synthetic resins produced by condensation of acids such as maleic, phthalic, or itaconic with an alcohol or glycol, such as allyl alcohol or ethylene glycol to form an unsaturated polyester. When polymerized the resins will give a cross-linked, three-dimensional molecular structure, which in turn will copolymerize with an unsaturated hydrocarbon such as styrene or cyclopentadiene to form a copolymer of complex structure of several monomers linked and cross-linked. At least one of the acids or alcohols of the first reaction must be unsaturated. The polyesters made with saturated acids and saturated hydroxy compounds are called alkyd resins, and these are largely limited to the production of protective coatings and are not copolymerized.

The resins undergo polymerization during cure without releasing water, and do not require high pressure for curing. Through the second modification stage with hydrocarbons, a wide range of characteristics can be obtained. The most important use of the polyesters is as laminating and molding materials, especially glass-fiber-reinforced plastic products. The resins have high strength, good chemical resistance, high adhesion, and capacity to take bright colors. They are also used, without fillers, as casting resins, for filling and strengthening porous materials, such as ceramics and plaster of Paris, and for sealing the pores in metal castings. Some of the resins are tough and are used to produce textile fibers and thin plastic sheets and film. Other resins are used with fillers to produce molding powders that cure at low pressures of 500 to 900 lb/in.^{2} (3 to 6 MPa) with fast operating cycles.

Product	Manufacturer	Remarks
Mylar Film	Du Pont	Polyester made by condensing terephthalic acid and ethylene glycol. The extremely thin film, 0.00025 to 0.0005 in. (0.00063 to 0.0013 cm) is used for capacitors and for insulating motors and transformers. The film has: a high dielectric strength, up to 6,000 volts per mil (236×10^6 volts per meter); a tensile strength of 20,000 lb/in^2 (137 MPa) with elongation of 70%; is highly resistant to chemicals and has low water absorption; is thermoplastic, with a melting point at about 490°F (254°C).

Polyester fibers are widely used in clothing fabrics. The textile fiber produced from dimethyl terephthalate is known as Dacron. The English textile fibers called Teron and Terylen are similar materials. Melinex is the English name for the film.

Product	Manufacturer	Remarks
Mylar 50T	Du Pont	Used for magnetic sound-recording tape. The 0.005-in. (0.013-cm) tape has breaking strength of 120 oz (3.4 kg) per 1/4 in. (0.64 cm) of width.
Urylon		Japanese fiber that has a low specific gravity, 1.07, and a high melting point, 482°F (250°C). The fiber is produced from azelaic acid.

Product	Manufacturer	Remarks
Terefilm	Acme Backing Corp.	Polyester film that is a cyclohexylene dimethylene terephthalate. Film has a dielectric strength of the 0.0005-in. (0.0013-cm), is 8,000 volts per mil (315×10^6 volts per meter), with tensile strength of 20,000 lb/in^2 (137 MPa), and heat distortion temperature of 340°F (171°C). Is used for insulation and magnetic tape.

Electronic tape can also have a magnetic-powder coating on the polyester. But where high temperature may be encountered, as in a spacecraft, the magnetic coating is applied to metal tapes.

Product	Manufacturer	Remarks
Densimag	Whittaker Corp.	Magnetic coating on a nonmagnetic stainless-steel tape. Has a combined thickness of 0.00105 in. (0.00267 cm). Tape will operate at temperatures to 600°F (316°C).
Koplac Resins	Koppers Co., Inc.	Polyesters based on styrene.
Vibrin 135	Naugatuck Chemical Co.	Polyester resin made with triallyl cyanurate and modified with maleic anhydride. Moldings reinforced with glass fiber have a tensile strength of 38,000 lb/in^2 (261 MPa), and retain a strength of 23,000 lb/in.^{2} at 500°F (260°C).
Vibrin 136A	Naugatuck Chemical Co.	Another polyester resin made with triallyl cyanurate and modified with maleic anhydride with a higher strength and very high radar transparency. Its used for radomes and nose cones.

Transparent thermoplastic polyester resins are made by copolymerizing esters of itaconic acid with vinyl chloride, methacrylate, or acrylonitrile. Itaconic acid, $CH_2:CCH_2(COOH)_2$, is made from anhydrous glucose. Pimelic acid, $HO_2C(CH_2)CO_2H$, is made from petroleum as a white crystalline solid, and is used for making polyester and polyamide resins. Another acid used for these resins is glutaric acid, $HO_2C)CH_2)_3CO_2H$, produced from acrylein. Glutaric anhydride, $O:HC(CH_2)_3HC:O$, is also used, and its cross-linking ability is used for insolublizing starches and proteins to give water resistance to paints and paper coatings.

Het acid, made by Hooker Chemical, is a complex chlorinated phthalic acid produced by hydrolyzing the product of the condensation of maleic anhydride hexachlorocyclopentadiene made from pentane. This acid reacts with glycols and maleic anhydride that forms a hard polyester resin that is cross-linked with styrene to give the liquid hetron resin, which will cure with heat and a catalyst to an insoluble solid. The resin contains 30% chlorine. It is used for making laminated or reinforced plastics.

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Another chlorinated polyester resin is RF resin made by Interchemical Co. This resin is flame resistant, cures at normal temperatures, and is used in lay-up lamination work, such as boat building and tank construction.

Some of the polyester type resins have rubber-like properties, with higher tensile strengths than the rubbers and superior resistance to oxidation.

Product	Manufacturer	Remarks
Vulcollan	Goodyear Tire & Rubber Co.	Resin with higher wear resistance and chemical resistance than GRS rubber. It is made by reacting adipic acid with ethylene glycol and propylene glycol and then adding diisocyanate to control the solidifying action. Can be processed like rubber, but solidifies more rapidly.
Chemigum SL	Goodyear Tire & Rubber Co.	Polyester rubber.

Polyesters also offer a great variety of possibilities in textile fibers.

Product	Manufacturer	Remarks
Kodel	Eastman Chemical Products, Inc.	A white polyester fiber that is easy to dye. Is resistant to piling, which is the tendency of surface fibers to form balls, has high dimensional stability, and is heat resistant.
Trevira 271	Hoechst Fibers Industries	A flame resistant polyester fiber made from polyethylene terephthalate polymers that have been modified by including a flame retardant in the polymer structure. If subjected directly to a flame, the fabrics made of this fiber melt and shrink away. When the flame is removed, the fabrics self-extinguish.

9.2.9 Polyethylene Resins. A group of polyolefin polymers derived from ethylene by polymerization by heat and pressure. Polyethylene plastics are one of the lowest cost and most widely used plastics. As a group, they are noted for their toughness, excellent dielectric strength, and chemical resistance. Another outstanding charac-

teristic is their low water absorption and permeability. This is the reason for their wide use in sheet form as moisture barriers. The resins are white in thick sections, but otherwise the range varies from translucent to opaque. They feel waxy. There are many available types, ranging from flexible to rigid materials, are classified by density (specific gravity) into three major groups: Low density = 0.910 to 0.925, medium density = 0.926 to 0.940, and high density = 0.941 to 0.959.

The variations in properties among these three groups are directly related to density. As density increases, polymer cross-bonding or branching and crystallinity increase. Thus stiffness, tensile strength, hardness, and heat and chemical resistance increase with density in polyethylenes. Low density polyethylenes are flexible, tough, and less translucent than high density grades. High density grades, often called linear polyethylene grades, are stronger, more rigid, and have high creep resistance under load, but they have lower impact resistance. Low density polyethylenes are used in blow-molded bottles and containers, gaskets, paintbrush handles, and flexible film packaging. High density grades are used in wire insulation, beverage cases, dishpans, toys and the film is used in boil-in-bag packaging. In general, polyethylenes are not used in load bearing applications because of their tendency to creep. However, a special type, high molecular weight polyethylene is used for machine parts, bearings, bushings, and gears.

Polyethylenes can be blended or combined with other monomers -- propylene, ethyl acrylate, and vinyl acetate -- to produce copolymers to improve such properties as stress-crack resistance and clarity and to increase flexibility. They can also be modified by exposure to high energy radiation, which produces cross-linking and, thereby, increases heat resistance and stiffness.

Product	Manufacturer	Remarks
Zetafax Resin	Dow Chemical Corp.	An ethyleneacrylic resin that has good adhesion to metals and a high chemical resistance. Zetabon is a Zetafax-coated metal tape for cable shielding.
Ultrathene UE630-81A	U.S. Industrial Chemicals Co.	An ethylene vinyl acetate copolymer for for rubber-like packaging film.
Aircoflex Resins	Air Reduction Co.	Similar copolymers for use as pigment binders, paper and textile coatings, and adhesives. Have higher molecular weight and better stability than polyethylene.

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Product	Manufacturer	Remarks
Polythene and Alathon	Du Pont	Names for polyethylene. Used in the forms of molding powder, rod, sheet, tubes, and foil for packaging and paper coatings.
Agilene	American Agile Corp.	Is a polyethylene. The plastic can be cross-linked by irradiation. Irradiated polyethylene parts become thermoset and have increased strength, toughness, and higher heat resistance.
Irrathane	General Electric Co.	Irradiated polyethylene. The plastic can be cross-linked chemically by heating with carbon black and a diperoxide. When used as piping this method increases strength, improves weather resistance, and eliminates stress cracking.
Irrathene Tape SPT	General Electric Co.	A flexible irradiated polyethylene self-sealing insulating tape for corona-resistant electric cables. This tape can withstand temperatures to 260°F (127°C).
Fortiflex A	Celanese Corp.	A polyethylene with a specific gravity of 0.96 and a linear crystalline structure. Has a tensile strength of 4,500 lb/in^2 (30 MPa), flexural strength of 5,500 lb/in^2 (37 MPa), Rockwell hardness of R40, and will withstand operating temperatures above 400°F (204°C). Is used for rigid chemical piping. If used for piping and wire covering, small amounts of carbon black can be added to increase its resistance to the weather.
Fortiflex F-087	Celanese Corp.	Has a specific gravity of 0.938 and transfer elongation of 600%. Is used for packaging film and takes printing ink well.

Product	Manufacturer	Remarks
Microthene	U.S. Industrial Chemical Co.	A high density powder of 350 mesh for rotational molding of thin-walled parts.
Dylan	Koppers Co.	A low pressure linear polyethylene used for polyethylene fibers. Has a density of 0.95, a tensile strength of 3,500 lb/in.^{2} (23 MPa), elongation of 225%, and a softening point at 255°F (123°C).

The fibers and fabrics are marketed under trade names. One such trade name is Reevon, by Reeves Brothers, Inc. The fibers and fabrics are used as upholstery fabric woven of polyethylene monofilament.

Polyethylene foam is light weight, has negligible water absorption, and is used in sheet and film for thermal insulation, and for wire insulation.

Product	Manufacturer	Remarks
Orthofoam and Metafoam	Ludlow Papers	Polyethylene foam. Comes in sheets from 0.016 to 0.035 in. (0.041 to 0.089 cm) thick. The low density material has a tensile strength to 1,500 lb/in.^{2} (9 MPa). The high density material has a tensile strength to 12,000 lb/in.^{2} (82 MPa) with elongation of 2.5 to 5%.
Polyethylene DGDA-2580	Union Carbide Corp.	Foam is used for extruded insulation coatings on electric cables. Gives uniformly dispersed closed cells so that the material has about 30% gas by volume. Extruded coatings have a smooth surface, a tensile strength of 2,800 lb/in.^{2} (18 MPa), and a dielectric constant of 15 to 1.7.

Polyethylene film is resistant to oils, greases, and fatty acids; also has good tear strength and fold endurance, and the light weight gives a large area per pound. It is widely used for packaging.

Product	Manufacturer	Remarks
Tenite 161M	Eastman Chemical Products, Inc.	An extruding grade film that has a density of 0.923, tensile strength of 2,200 lb/in.^{2} (14 MPa), and elongation of 600%. When film is irradiated and stretched biaxially, it can be shrunk as much as 20% in all directions by applying a blast of hot air or dipping into water (180°F (82°C)). Films are used for packaging meats and poultry where a tight, close fit is desired.
Cryovac L	W.R. Grace & Co.	Is similar to Tenite 161M film. Is a high density polyethylene that has a high concentration of hydrogen atoms that are capable of slowing down or stopping fast neutrons. Sheets made with a small amount of boron to stop the low energy neutrons are used for atomic shielding where light weight is necessary.
Panelyte Sheet	St. Regis Paper Co.	Is a sheet film made for this purpose. Made of Petrothene 100, U.S. International Chemicals Co., a polyethylene containing 2% boron.

Polyethylene rubbers are rubber-like materials made by cross-linking with chlorine and sulfur, or they are ethylene copolymers. Chlorosulfonated polyethylene is a white spongy material. It has chlorine atoms and sulfonyl chloride groups spaced along the molecule. It is blended with rubber to add stiffness, abrasion resistance, and resistance to ozone, and also for wire covering.

Product	Manufacturer	Remarks
Hypalon S-2	Du Pont	Is a chlorinated polyethylene.
Plaskon CPF200	Allied Chemical Corp.	A chlorinated polyethylene containing containing about 73% chlorine. Is used for coatings and has a high resistance to acids and alkalies.

Product	Manufacturer	Remarks
Ethylene-propylene rubber	Various companies	A chemically resistant rubber of high tear strength.
Ethylene butadiene resin	Phillips Petroleum Co.	Can be vulcanized with sulfur to increase hardness and widen temperature range. For greater elongation a terpolymer with butene can be made.

Polyethylene of low molecular weight is used for extending and modifying waxes. Is also used in coating compounds to increase toughness, gloss, and heat-sealing properties.

Product	Manufacturer	Remarks
Epolene N-11	Eastman Chemical Products, Inc.	For blending with waxes. Has a molecular weight of 1,500, a density of 0.925, and a softening point at 103°C.
Epolene N	Eastman Chemical Products, Inc.	Used in paste polishes. Has a molecular weight of 2,500 to 3,000.
Epolene LVE	Eastman Chemical Products, Inc.	Used in paper and textile coatings. Is a low density polyethylene with a molecular weight of 1,500.
Epolene HDE	Eastman Chemical Products, Inc.	Used for self-polishing floor waxes to add hardness to the film. Has a molecular weight of 1,500, but a high density of 0956.

Such materials are called polyethylene wax, but they are not chemical waxes. They can be emulsified by oxidation, and they can be given additional properties by copolymerization with other plastics.

Product	Manufacturer	Remarks
Elvax	Du Pont	Is a copolymer of ethylene with vinyl acetate. Is compatible with vegetable and paraffin waxes. When added to these waxes it increases adhesiveness, gloss, toughness, and heat sealing.
Ladcote	LA. Dreyfus Co.	Is a copolymer of ethylene with vinyl acetate.
Chemetron 100	Chemetron Corp.	Is a modified ethylene wax. Is an ethylene stearamide and comes in powder or beads. Improves luster, pigment dispersion, and mar resistance in lacquers.

Polymethylene waxes are microcrystalline and have sharper melting points than the ethylene waxes. They are more expensive, but have high luster and durability.

Polybutylene plastics are rubber-like polyolefins with superior resistance to creep and stress cracking. Films of this resin have high tear resistance, toughness, and flexibility, and are used widely for industrial refuse bags. Chemical and electrical properties are similar to those of the polyethylene and polypropylene plastics.

Polymethyl pentene is a moderately crystalline polyolefin plastic resin that is transparent even in thick sections. Almost optically clear, it has a light transmission value of 90%. Parts molded of this plastic are hard and shiny with good impact strength down to -20°F (-29°C). Specific gravity (0.83) is the lowest of any commercial solid plastic. A major use is for molded food containers for quick frozen foods that are later heated by the consumer.

9.2.10 **Polypropylene Resins.** An important group of synthetic plastics used for molding resins, film, and texture fibers. Developed in 1957 in Italy and Germany, they are produced as polypropylene by catalytic polymerization of propylene, or may be copolymers with ethylene or other material. Propylene is a methyl ethylene ($CH_3CH:CH_2$) produced in the cracking of petroleum, and also used for making isopropyl alcohol and other chemicals. The boiling point is 48.2°C. It belongs to the class of unsaturated hydrocarbons known as olefins, which are designated by the word ending **ene.** These unsaturated hydrocarbons tend to polymerize and form gums, and thus are not used in fuels although they have anti-knock properties.

In polyproplyene plastics the carbon atoms linked in the molecular chain between the CH_2 units each have a CH_3 and an H attached as side links, with the bulky side

groups spiraled regularly around the closely packed chain. The resulting plastic has a crystalline structure with increased hardness and toughness and a higher melting point. This type of stereosymmetric plastic has been called isotactic plastic. It can also be produced with butylene or styrene, and the general term for the plastics is polyolefins. Copolymers of propylene are termed polyallomers.

Polyproplyene is low in weight. The molded plastic has a density of 0.910, a tensile strength of 5,000 lb/in.^{2}(34 MPa), with elongation of 150%, and Rockwell hardness of R95. The dielectric strength is 1,500 volts per mil (59 x 10^6 volts per meter), dielectric constant 2.3, and a softening point at 150°C. Blown bottles of polypropylene have good clarity and are nontoxic. The melt flow is superior to that of ethylene. A unique property is that thin sections of polyproplyene can withstand prolonged flexing. This characteristic has made polypropylenes popular for "living hinge" applications. In tests, they have been flexed over 70 million times without a failure.

The many different grades of polypropylenes fall into three basic groups: (1) homopolymers, (2) copolymers, and (3) reinforced and polymer blends. Properties of the homopolymers vary with molecular weight distribution and the degree of crystallinity. Commonly, copolymers are produced by adding other types of olefin monomers to the propylene monomers to improve properties, such as low temperature toughness. Copolymers are also made by radiation grafting. Polypropylenes are reinforced with glass or asbestos fibers to improve mechanical properties and increase resistance to deformation at elevated temperatures.

Product	Manufacturer	Remarks
Tenite	Eastman Chemical Products, Inc.	A polypropylene used for molded parts, film, fiber, pipe, and wire covering.
Olefane	Avisun Corp.	A polypropylene film used for packaging, has a specific gravity of 0.89. Is resistant to moisture, oils, and solvents. Is crystal clear and flexible. Can withstand temperatures to 250°F (121°C). The 0.001-in. (0.003-cm) film has 31,000 ft/lb (20,830 m/kg).
Dynafilm 200	U.S. Industrial Chemicals Co.	A polypropylene laminated with polyethylene for easy heat sealing for packaging. The 0.001-in. (0.003-cm) film has a strength of 3,000 lb/in.^{2}(20 MPa) and 400% elongation.

Product	Manufacturer	Remarks
Dynafilm 300	U.S. Industrial Chemicals Co.	Has the appearance, feel, and machine handling properties of a Cellophane film. Consists of oriented polypropylene coated on both sides with vinyl acetate. The film ranges in thicknesses of 0.0008 to 0.0012 in. (0.0020 to 0.0030 cm) and heat seals at 100°F (38°C).

Polypropylene fiber was originally produced in Italy under the name of Merkalon. Unless modified, it is more brittle at low temperatures and has less light stability than polyethylene, but it has about twice the strength of high density linear polyethylene. Monofilament fibers are used for filter fabrics. They have a high abrasion resistance and a melting point at 310°F (154°C).

Multifilament yarns are used for textiles and rope. Polypropylene rope is used for marine hawsers, will float on water, and does not absorb water like Manila rope. It has a permanent elongation, or set, of 20%, compared to 19% for nylon rope and 11% for Manila rope. The working elasticity is 16% compared to 25% for nylon and 8% for Manila. The tensile strength of the rope is 59,000 $lb/in.^2$ (406 MPa). Fine denier multi-filament polypropylene yarn used for weaving and knitting dyes easily and comes in many colors.

Chlorinated polypropylene is used in coatings, paper sizing, and adhesives. It has good heat and light stability, and high abrasion and chemical resistance.

9.2.11 Polystyrene. Often referred to as styrene resin, it is used for molding, in lacquers, and for coatings formed by the polymerization of monomeric styrene, which is a colorless liquid of the composition $C_6H_5CH:CH_2$, specific gravity 0.906, and boiling point at 145°C. It is made from ethylene, and is ethylene with one of the hydrogen atoms replaced by a phenyl group. It is also called phenyl ethylene and vinyl benzene. As it can be made by heating cinnamic acid, $C_6H_5CH:CHCO_2H$, an acid found in natural balsams and resins, it is also called cinnamene. In the form of vinyl toluene, which consists of mixed isomers of methyl styrene, the material reacts with drying oils to form alkyd resins for paints and coatings.

The polymerized resin is a transparent solid, very light in weight with a specific gravity of 1.054 to 1.070. The tensile strength is 4,000 to 10,000 lb/in^2 (27 to 68 MPa), a compressive strength of 12,000 to 17,000 $lb/in.^2$ (82 to 117 MPa), and a dielectric strength of 450 to 600 volts per mil (18 to 24 x 10^6 volts per meter). It is also tougher and stronger at low temperatures than most other plastics. It is valued as an electrical insulating material, and the films are used for wrapping cable.

When produced from methyl stryene, parts have a hardness to Rockwell M83, with tensile strengths to 8,900 lb/in^2(61 MPa), and a stiffness that makes them suitable for such products as cabinets and housings. Dielectric strength is also high, above 800 volts per mil (32 x 10^{6}volts per meter). The resin is also used for electronic parts. The heat distortion temperature is 215°F (101°C).

Styrenes are subject to creep. Therefore, the long term bearing strength (over 2 weeks) is only about one-third the short time tensile strength. Since their maximum useful service temperature is about 160°F (71°C), their use is restricted to room-temperature applications. Because of their low cost and ease of processing, polystyrenes are widely used for consumer products. The impact gradesand glass-filled types are used for engineering parts and semi-structural applications. Also, polystyrene foams are used more than all of the foam plastics. Because of good processing characteristics, polystyrenes are produced in a wide range of forms. They can be extruded, injection-, compression-, and blow-molded, and thermo formed. They are also available as film sheets and foam.

Polystyrenes can be divided into the following major types: general purpose grades, the lowest in cost, are characterized by clarity; colorability; and rigidity. They are applicable where appearance and rigidity, but not toughness, are required. Common uses are: wall tiles, compact cases, knobs, brush backs, and container lids. Impact grades of polystyrenes are produced by physically blending styrene and rubber. Grades are generally specified as medium, high, and extra high. As impact strength increases, rigidity decreases.

Medium impact grades are used where a combination of moderate toughness and translucency is desired. For example, products such as containers, closures, and small radio cabinets.

High impact grades have improved heat resistance and surface gloss. They are used for refrigerator door liners and crisper trays, containers, toys, and heater ducts in automobiles.

Extra high impact grades are quite low in stiffness. Their use is limited to parts subject to high speed loading.

Styrene can be polymerized with butadiene, acrylonitrile, and other resins. The terpolymer, acrylonitrile-butadiene-styrene (ABS) is one of the common combinations. Styrene-acrylonitrile (SAN) has excellent resistance to acids, bases, salts, and some solvents. It also is among the stiffest of the thermoplastics, with a tensile modulus of 400,000 to 550,000 lb/in^2(2,757 to 3,791 MPa). Styrene resins for molding are now marketed under a wide variety of trade names, with or without fillers and reinforcing

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agents. Many of these are copolymer resins, or are modified with plasticizers or cross-linking agents.

Product	Manufacturer	Remarks
Victron	U.S. Rubber Ro.	A clear transparent polystyrene.
Lustron	Monsanto	A polystyrene in various grades.
Stymer	- - -	A polystyrene resin for sizing textiles.
Piccotex	Pennsylvania Industrial Chemical Corp.	A styrene copolymer in solid form soluble in mineral spirits for use in paints, coatings, and adhesives.
Styron and Styraloy	Dow Chemical Co.	Polystyrene molding resins.
Tyril	Dow Chemical Co.	Originally called Styrex, is a styrene-acrylonitrile copolymer.
Loalin	Catalin Corp.	A polystyrene with a specific gravity of 1.05 to 1.07. Is crystal clear and will take light pastel colors. In the clear form it transmits 90% light. Is water-resistant and has a dielectric strength of 500 to 700 volts per mil (1,970 to 2,758 volts per meter). It is not affected by alcohol, acids, or alkalies, but is soluble in aromatic hydrocarbons. It is preferably injection molded.
Exon 860	Firestone Plastics Co.	A soft grade polystyrene that molds easily into products of high flexibility. The molded material has a tensile strength of 6,000 lb/in.^{2} (41 MPa) with elongation of 50%, Rockwell hardness of R100, and a dielectric strength of 510 volts per mil (20 x 10^6 volts per meter).

Product	Manufacturer	Remarks
Fibertuff	Koppers Co.	Marketed in pellets for injection molding. Is 60% polystyrene and 40% glass fiber. Molded parts have a specific gravity of 1.33, a tensile strength of 11,000 lb/in.^{2} (75 MPa), heat distortion point of 220°F (104°C), and high impact resistance.

Styrene-butylene resins are copolymers that mold easily and produce thermoplastic products of low water absorption and good electrical properties. They have strength equal to the vinyls with greater elongation. Foamed polystyrene is available in blocks and heavy sheets for thermal insulation. It weighs about 1 lb/ft^3 (16 kg/m^3) and is rigid. Flexible styrene foam is also made into very thin sheets for wrapping frozen foods. It is grease resistant and a good insulator, and is low in cost. Styrene is now best known for its use in synthetic rubbers, but the difference between resins and rubbers is flexibility.

9.2.12 <u>Urethanes (also known as polyurethanes).</u> A group of plastic materials based on polyether or polyester resin. The chemistry involved is the reaction of a diisocyanate with a hydroxyl-terminated polyester or polyether to form a higher molecular weight prepolymer, which in turn is chain-extended by adding difunctional compounds containing active hydrogens, such as water, glycols, diamines, or amino al-cohols. The urethanes are block-polymers capable of being formed by a literally indeter-minate number of combinations of these components. The urethanes have excellent tensile strength and elongation, good ozone resistance, and good abrasion resistance. Combinations of hardness and elasticity not available with other systems are possible in urethanes, ranging from Shore hardness of 15 to 30 on the "A" scale for most industrial or mechanical goods applications, to the 70 to 85 Shore "D" scale. Urethanes are fairly resistant to many chemicals, such as aliphatic solvents, alcohols, ether, certain fuels, and oils. They are attacked by hot water, polar solvents, and concentrated acids and bases.

Urethane elastomers are made with various isocyanates, the principal ones being tolylene diisocyanate (TDI) and 4,4'-diphenylmethane diisocyanate (MDI) reacting with linear polyols of the polyester and polyether families. Various chain extenders, such as glycols, water, diamines, or aminoalcohols, are used in either a prepolymer or a one-shot of system to form the long-chain polymer.

Urethane textile fibers were first made in Germany under the name of Igamide. The Fiber K, or Lycra, of Du Pont, and the Vyrene, of the U.S. Rubber Co., are flexible urethane fibers used for flexible garments. They are more durable than ordinary rubber fibers or filaments, and are 30% lighter in weight. They are resistant to oils and to wash-ing chemicals, and also have the advantage that they are white in color. Spandex fibers

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are stretchable fibers produced from a fiber forming substance in which a long chain of synthetic molecules are composed of a segmented polyurethane. Stretch before break of these fibers is from 520 to 610%, compared to 760% for rubber. Recovery is not as good as rubber. Spandex is white and dyeable. Resistance to chemicals is good but is degraded by hypochlorides.

9.2.13 <u>Polyvinyl Resins.</u> A group of products varying from liquids to hard solids, made by the polymerization of ethylene derivatives, used in finishes, coatings, and molding resins, or it can be made directly by reacting acetic acid with ethylene and oxygen. In general, the term vinyl designates plastics made by polymerizing vinyl chloride; vinyl acetate, or vinylidene chloride, but may include plastics made from styrene and other chemicals.

The term is generic for compounds of the basic formula RCH:CR'CR". The simplest are the polyesters of vinyl alcohol, such as vinyl acetate. This resin is lightweight, with a specific gravity of 1.18, and is transparent, but it has poor molding qualities and its strength is no more than 5,000 lb/in.^{2} (34 MPa). The vinyl resins are brittle at low temperatures. Elvacet, of Du Pont, and Lemac, of the American Monomer Corp., are vinyl acetate molding resins. But the vinyl halides, CH_2:CHX also polymerize readily to form vinylite resins, which mold well, have tensile strengths to 9,000 lb/in.^{2} (62 MPa), high dielectric strength, and high chemical resistance, and a wide range of useful resins is produced by copolymers of vinyl acetate and vinyl chloride. Various grades of Bakelite, Geon, Tygon, and other resins are these chloride acetate copolymers.

Vinyl alcohol, CH_2:CHOH, is a liquid boiling at 96°F (35.5°C). Polyvinyl alcohol is a white, odorless, tasteless powder, which when dry forms a colorless and tough film. The material is used as a thickener for latex, in chewing gum, and for sixes and adhesives. It can be compounded with plasticizers and molded or extruded into tough and elastic products. Hydrolized polyvinyl alcohol has greater water resistance, higher adhesion, and its lower residual acetate gives lower foaming. Soluble film, for packaging detergents and other water-dispersible materials to eliminate the need of opening the package, is a clear polyvinyl alcohol film. Textile fibers are also made from polyvinyl alcohol, either water-soluble or insolubilized with formaldehyde or another agent. Vinal, manufactured by the Air Reduction Chemical Co., is a polyvinyl alcohol textile fiber that is hot-drawn by a semi-melt process and insolubilized after drawing. The fiber has a high degree of orientation and crystallinity, which gives good strength and is resistant to water. Polyvinyl alcohol fibers are called Vinylon in Europe and Kuravilon in Japan.

Vinyl alcohol reacted with an aldehyde and an acid catalyst produces a group of polymers known as vinyl acetal resins, and separately designated by type names, as polyvinyl butyral and polyvinyl formal. The polyvinyl alcohols are called Solvars, and the polyvinyl acetates are called Gelvas. The vinyl ethers range from vinyl methyl ether, CH_2:CHOCH$_3$, to vinyl ethylhexyl ether, from soft compounds to hard resins. Vinyl

ether is a liquid which polymerizes, or can react with hydroxyl groups to form acetal resins. Gantrez M, of General Aniline & Film Corp., is a water-soluble polyvinyl methyl ether for use in paints, inks, and adhesives. Alkyd vinyl ethers are made by reacting acetylene with an alcohol under pressure, producing methyl vinyl ether, ethyl vinyl ether, or butyl vinyl ether. They have reactive double bonds that can be used to copolymerize with other vinyls to give a variety of physical properties.

Polyvinyl formals, Formvars, are used in molding compounds, wire coatings, and impregnating compounds. It is one of the toughest of the thermoplastics. Formvar, of the Shawinigan Products Corp., has a specific gravity of about 1.3, a tensile strength up to 12,000 lb/in^2 (82 MPa), elongation from 5 to 20%, Rockwell hardness of M85, and dielectric strength of 450 volts per mil (17 x 10^6 volts per meter). This type of plastic is resistant to alkalies but is attacked by acids.

A plastisol is a vinyl resin dissolved in a plasticizer to make a pourable liquid without a volatile solvent for casting. The poured liquid is solidified to increase viscosity. The polyvinyl acetals, Alvars, are used in lacquers, adhesives, and phonograph records. The transparent polyvinyl butyrals, Butvars, are used as interlayers in laminated glass. They are made by reacting polyvinyl alcohol with butyraldehyde, C_3H_7CHO. Vinal is a general name for vinyl butayl resin used for laminated glass.

Vinyl acetate is a water-white mobile liquid with a boiling point of 70°C, usually shipped with a copper salt to prevent polymerization in transit. The composition is $CH_3:COO:CH:CH_2$. It may be polymerized in benzene and marketed in solution, or in water solution for use as an extender for rubber, and for adhesives and coatings. The higher the polymerization of the resin, the higher the softening point of the resin. The formula for polyvinyl acetate resin is given as $(CH_2:CHOOCCH_3)_x$. It is a colorless, odorless thermoplastic with a density of 1.189, unaffected by water, gasoline, or oils, but soluble in the lower alcohols, benzene, and chlorinated hydrocarbons.

Polyvinyl acetate resins are stable to light, transparent to ultraviolet light, and are valued for lacquers and coatings because of ther high adhesion, durability, and ease of compounding with gums and resins. Resins of low molecular weight are used for coatings, and those of high molecular weight for molding.

Product	Manufacturer	Remarks
Darex and Everflex	W.R. Grace &	Paint and coating resins.
Vinylite and Vinyloid	Union Carbide	Vinyl acetate resins for molding.

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Product	Manufacturer	Remarks
Wood Glu	Paisley Products, Inc.	A milky water dispersion of polyvinyl acetate used as an adhesive for wood and paper. Vinyl acetate will copolymerize with maleic acrylonitrile, or acrylic esters. With ethylene it produces a copolymer latex of superior toughness and abrasion resistance for coatings.
Aircoflex 500	Air Reduction Co.	A vinyl acetate ethylene copolymer latex.

Vinyl chloride, CH_2CHCl, also called ethenyl chloride and chloroethylene, produced by reacting ethylene with oxygen from the air and ethylene dichloride, is the basic material for the polyvinyl chloride resins. It is a gas. The plastic was produced originally in Germany under the name of Igelite for cable insulation and as Vinnol for tire tubes. The tensile strength of the plastic may vary from the flexible resins with about 3,000 lb/in.^{2} (20 MPa) and Shore hardness of 90. The dielectric strength is high, up to 1,300 volts per mil (52 x 10^6 volts per meter). It is resistant to acids and alkalies. Polyvinyl chloride usually comes as a white powder for molding or extruding, but PVC pearls, of the Escambia Chemical Corp., is the material made by a water-suspension process in the form of white porous particles capable of easily absorbing a high proportion of plasticizer.

Product	Manufacturer	Remarks
Polvin and Opalon	Monsanto	Polyvinyl chloride resins.
Ultron	Monsanto	Polyvinyl chloride film.

Unplasticized polyvinyl chloride is used for rigid chemical-resistant pipe.

Product	Manufacturer	Remarks
Kraloy D-500	Kraloy Plastic Pipe Co.	Polyvinyl chloride in rigid pipe.
Carlon V	Carlon Products	Polyvinyl chloride in rigid pipe.
Vyflex Sheet	Kaykor Industries, Inc.	Rigid unplasticized polyvinyl chloride in sheets of making acid tanks, ducts, and flumes.

Polyvinyl chloride sheet, unmodified, may have a tensile strength of 8,200 lb/in.^{2} (57 MPa), flexural strength of 12,600 lb/in^2 (86 MPa), and a light transmission of 78%. But in bends or comers of moldings, or in folds of a sheet, the resin shows opaque whitening. This can be eliminated by modifying the resin with an acrylic. The resins have improved processing qualities and flexibility, especially for blown bottles and extruded parts, but the light transmission is reduced.

Product	Manufacturer	Remarks
Acryloid KM-607	Rohm & Haas	A white acrylic powder. When used in polyvinyl sheet to a content of 20%, it gives a tensile strength of 6,700 lb/in^2 (46 MPa) and a light transmission of 72%.

Vinylidene chloride plastics are derived from ethylene and chlorine polymerized to produce a thermoplastic with softening point of 240 to 280°F (116 to 138°C). The resins are noted for their toughness and resistance to water and chemicals. The molded resins have a specific gravity of 1.68 to 1.75, tensile strength of 4,000 to 7,000 lb/in.^{2} (27 to 48 MPa), and flexural strength of 15,000 to 17,000 lb/in.^{2} (103 to 117 MPa).

Product	Manufacturer	Remarks
Saran	Dow Chemical Co.	A vinylidene chloride plastic extruded into tubes for handling chemicals, brines, and solvents to temperatures as high as 275°F (135°C). Is also extruded into strands and woven into a box-weave material as a substitute for rattan.
Saran Latex	Dow Chemical Co.	Water dispersion of the plastic, used for coating and impregnating fabrics. For coating food-packaging papers, it is waterproof and greaseproof, is odorless and tasteless, and gives the papers a high gloss. Saran is also produced as a strong transparent film for packaging.
Saranex	Dow Chemical Co.	A Saran film laminated with polyethylene sheet to give it heat-sealing qualities.

Product	Manufacturer	Remarks
Saran Bristles	Dow Chemical Co.	Bristles on brushes that are made in diameters from 0.10 to 0.20 in. (0.025 to 0.051 cm).
Velon	Firestone Tire & Rubber Co.	Material used for screens and fabrics.
Zetex	B.F. Goodrich Co.	A polyvinylidene cyanide.

Vinyl benzoate is an oily liquid of the composition $CH_2{:}CHOOCC_6H_5$, which can be polymerized to form resins with higher softening points than polyvinyl acetate, but are more brittle at low temperatures. These resins, copolymerized with vinyl acetate, are used for water-repellent coatings.

Vinyl crotonate, $CH_2CHOOCCH{:}CHCH_3$, is a liquid with a specific gravity of 0.9434. Its copolymers are brittle resins, but it is used as a cross-linking agent for other resins to raise the softening point and to increase abrasion resistance.

Vinyl formate, $CH_2{:}CHOOCCH$, is a colorless liquid which polymerizes to form clear polyvinyl formate resins that are harder and more resistant to solvents than polyvinyl acetate. The monomer is also copolymerized with ethylene monomers to form resins for mixing in specialty rubbers.

Methyl vinyl pyridine, $(CH_3)(CHCH_2)C_5H_3N$, is produced by the Phillips Chemical Co. for making resins, fibers, and oil-resistant rubbers. It is a colorless liquid with a boiling point of 64.4°C. The active methyl groups give condensation reactions, and will copolymerize with butadiene, styrene, or acrylonitrile.

Polyvinyl carbazole, under the name of Luvican, was used in Germany as a mica substitute for high frequency insulation. It is a brown resin that softens at 150°C.

An adhesive to replace rubber cement was made in Germany by combining Oppanol C, a high molecular weight polyvinyl isobutylene ether, with Igovin, a low molecular weight polyvinyl isobutyl ether, and compounding with zinc oxide and wool grease.

Product	Manufacturer	Remarks
Marvinol VR-10	Glenn L. Martin Co.	Coatings and impregnations produced by the reaction of acetylene and hydrogen chloride with a catalyst. It is also used for casting into films.
Marvinol Resins	U.S. Rubber Co.	Are polyvinyl chloride. The vinyl plastics are used for wall tile and sheet wall coverings. They are adaptable to bright colors, are nonstaining, and easily cleaned.
Kalitex	U.S. Plywood Corp.	A vinyl sheet wall covering with an embossed burlap-weave pattern with colors on the reverse side.
Vinyon	Union Carbide	A vinyl chloride-acetate fiber in various grades. Since it is resistant to strong acids and alkalies, Vinyon fiber is made into filter cloth for temperatures not above 160°C. It is also used in wool mixtures. It is produced by the copolymerization of vinyl chloride and vinyl acetate.
Vinyon N	Union Carbide	A vinyl chloride-acrylonitrile copolymer marketed as a fine, silk like textile fiber. The fiber has high strength, an elongation of 30%, and is nonflammable. It has a light yellow color and is easily dyed.
Carilan	- - -	A Japanese vinyl acetate fiber.

The possibility of variation in vinyl resins by changing the monomer, copolymerization, and difference in compounding is so great that the term vinyl resin is almost meaningless when used alone. The resins are marketed under a continuously increasing number of trade names. In general, each resin is designed for specific uses, but not limited to those uses.

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Product	Manufacturer	Remarks
Advagum	Advance Solvents & Chemical Corp.	A highly plasticized vinyl copolymer used as an extender for rubbers.
Pliovac	Goodyear Tire & Rubber Co.	A high molecular-weight vinyl chloride for coatings, tiling, and extrusions.
Victron	Naugatuck Chemical Co.	Vinyl acetal resins.
Saflex	Monsanto Co.	Vinyl acetal resins.
Butacite	Du Pont	A clear polyvinyl butyral for laminated glass.
Formex	General Electric Co.	A vinyl formal resin for insulating wire.
Boltaron 6200	Bolta Products, Inc.	A rigid unplasticized polyvinyl chloride in sheets, rods, and pipes. Can resist thermal distortion below 175°F (80°C).
Ingerin	---	A German polyvinyl ether.
Cosal	---	Made from vinyl isobutyl ether.
Mipolam	---	A German vinyl polymer for floor coverings.
Kynar	Pennwalt	A polymer of vinylidene fluoride, $CH_2:CF_2$, with a high molecular weight, about 500,000. It is a hard, white thermoplastic resin with a slippery surface, and has a high resistance to chemicals. It resists temperatures to 650°F (343°C), and does not become brittle at low temperatures. It extrudes easily, and has been used for wire insulation, gaskets, seals, molded parts, and piping.

9.3 THERMOSETTING APPLICATIONS.

9.3.1 Acrylonitrile-Butadiene-Styrene (ABS). Common trade names for these materials are Cycolac, Kralastic, and Lustran. They are opaque and distinguished by a good balance of properties, including high impact strength, rigidity, and hardness over a temperature range of -40 to 230°F (-40 to 110°C). Compared to other structural or engineering plastics, they are considered to fall at the lower end of the scale. Medium impact grades are hard, rigid, and tough, and are used for appearance parts that require high strength, good fatigue resistance, and surface hardness and gloss. High impact grades are formulated for similar products where additional impact strength is gained at some sacrifice in rigidity and hardness. Low impact grades have high impact strength down to -40°F (-40°C). Again, some sacrifice is made in strength, rigidity, and heat resistance. Heat resistant, high strength grades provide the best heat resistance -- continuous use up to about 200°F (93°C), and a 264 lb/in.^{2}(2 MPa) heat distortion temperature of around 215°F (102°C). Impact strength is about comparable to that of medium impact grades, but strength, modulus of elasticity, and hardness are higher. At stresses above their tensile strength, ABS plastics usually yield plastically instead of rupturing, and impact failures are ductile. Because of relatively low creep, they have good, long term load-carrying ability. This low creep plus low water absorption and relatively high heat resistance provide ABS plastics with good dimensional stability. ABS plastics are readily processed by extrusion, injection molding, blow molding, calendering, and vacuum forming. Resins have been developed especially for cold forming or stamping from extruded sheets. ABS plastics are used in helmets, refrigerator liners, luggage tote trays, housings, grills for hot air systems, and pump impellers. Extruded shapes include tubing and pipe. ABS plated parts are now in wide use, replacing metal parts in the automotive and appliance field.

9.3.2 Alkyd Resins. A group of thermosetting synthetic resins known chemically as hydroxycarboxylic resins, of which the one produced from phthalic anhydride and glycerol is representative. They are made by the esterification of a polybasic acid with a polyhydric alcohol, and have the characteristics of homogeneity and solubility that make them especially suitable for coatings and finishes, plastic molding compounds, caulking compounds, adhesives, and plasticizers for other resins. The resins have high adhesion to metals; are transparent, color easy, tough, flexible, heat- and chemical-resistant; and have good dielectric strength. They vary greatly with the raw materials used and with varying percentage compositions, from soft rubbery gums to hard brittle solids. Phthalic anhydride imparts hardness and stability. Maleic acid makes a higher melting point resin. Azelaic acid gives a softer and less brittle resin. The long chain dibasic acids, such as adipic acid, give resins of great toughness and flexibility. In place of glycerol the blycols yield soft resins, and sometimes the glycerol is modified with a proportion of glycol. The resins are reacted with oils, fatty acids, or

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other resins, such as urea or melamine, to make them compatible with drying oils and to impart special characteristics.

Since alkyd resins are basically esterification products of innumerable polybasic acids and polyhydric alcohols, and can be modified with many types of oils and resins, the actual number of different alkyd resins is unlimited, and the users' specification is normally by service requirements rather than composition. Short-oil alkyds, with 30 to 45% nonoxidizing oils, are used in baking enamels, while the long-oil alkyds, with 56 to 75% oxidizing oils, are soluble in mineral spirits and are used for brushing enamels.

Alkyd coatings are used for such diverse applications as air-drying water emulsion wall paints and baked enamels for automobiles and applicances.

The properties of oil-modified alkyd coatings depend on the specific oil used as well as the percentage of oil in the composition. In general, they are comparatively low in cost and have excellent color retention, durability, and flexibility, but only fair drying speed, chemical resistance, heat resistance, and salt spray resistance. The oil-modified alkyds can be further modified with other resins to produce resin-modified alkyds. The resin is sometimes added during manufacture of the alkyd and becomes an integral part of the alkyd, or the modifying resin is blended with the alkyd when the paint is formulated. When mixed with urea formaldehyde or melamine resin, harder and more resistant baked enamels are produced. Alkyds blended with ehtyl cellulose are used as tough flexible coatings for electric cable. Other resins blended with alkyds to produce special or improved properties include phenolic, rosin, vinyl, and silicone.

Alkyd plastics molding compounds are composed of a polyester resin and usually a diallyl phthalate monomer plus various inorganic fillers, depending on the desired properties. The raw material is produced in three forms: granular, putty, and glass-reinforced. As a class, the alkyds have excellent heat resistance up to about 300°F (150°C), high stiffness, and moderate tensile and impact strength. Their low moisture absorption combined with good dielectric strength makes them particularly suitable for electronic and electrical hardware such as switchgear, insulators and parts for motor controllers, and automotive ignition systems. They are easily molded at low pressures and cure rapidly. Amberlac and Duraplex, manufactured by Rohm & Haas Co., are alkyd resins that come in a wide range of formulations.

Paraplex resins are oil-modified soft resins used for coatings for textiles and paper, and for blending with cellulose plastics for better adhesion on lacquers. Paraplex, P-43HV, however, is a polyester-styene copolymer supplied as a clear liquid for laminating, molding, or casting at low pressure.

Product	Manufacturer	Remarks
Aquaplex	Rohm & Haas Co.	A group of oil-modified resins for use in water paints.
Teglac	American Cyanamid Co.	Resins used for indoor finishes and clear-coat varnishes, are hard alkyd resins made with natural resin acids as blending agents.
Cycopol	American Cyanamid Co.	An alkyd-styrene copolymer resing for fast drying enamels. Gives high gloss and durability.
Beckosol 1341	Reichhold Chemicals, Inc.	A phenol-modified alkyd resing for fast drying enamels.
Petrex Resin	Hercules, Inc.	A series of alkyd resins used in lacquers, varnishes, adhesives, and inks.
Arpolaz 1248-M	U.S. Industrial Chemicals, Inc.	A high gloss phthalic alkyd resin, soluble in mineral spirits, for industrial finishes.
Iso Burnok 32-0	T.F. Washburn Co.	A soybean oil isothalic alkyd used as a vehicle for thixotropic paints. Has high clarity and is odorless.
Dyal	Sherwin-Williams Co.	An alkyd resin for finishes.
Amalite and Amavar	American Alkyd	Alkyd resins for finishes.
Palaskon Alkyd	Allied Chemical Corp.	A mineral filled alkyd molding powder used for electrical parts having good arc resistance and heat resistance to 350°F (176°C).
Neolyn Resins	Hercules, Inc.	Alkyd resins produced from rosin. They are used as modifiers for nitro-cellulose and for vinyl resins in lacquers and adhesives to add toughness to the film.

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Product	Manufacturer	Remarks
Cellolyn 501	Hercules, Inc.	A lauric acid-penta-erythritol alkyd used in durable, color stable nitrocellulose lacquers.

A series of alkyd resins is produced when maleic anhydride or fumaric acid is reacted with rosin and then esterified with glycerol or other polyhydric alcohol. Isocyanate resins are linear alkyds lengthened by isocyanates and then treated with a glycol or a diamine to cross-link the molecular chain. Plastics made from these resins are noted for good abrasion resistance.

9.3.3 **Epoxy Resins.** A class of synthetic resins characterized by having in the molecule a highly reactive oxirane ring of triangular configuration consisting of an oxygen atom bonded to two adjoining and bonded carbon atoms. They are usually made by the reaction of epichlorohydrin with phenol compounds, but epoxidation is also done by the oxidation of a carbon-to-carbon double bond with an organic peracid such as peracetic. Epichlorohydrin is produced from ally1 chloride, and is a colorless liquid with a chlorine atom and an epoxide ring. The dipoxy resins made by the oxidation of olefins with peracetic acid have higher heat resistance than those made with bisphenol. Epoxidation is not limited to making plastic resins, and epoxidized oils, usually epoxidized with peracetic acid, are used as paint oils and as plasticizers for vinyl resins.

Epoxy resins are more costly than many other resins, but, because of their unusual combinations of high mechanical and electrical properties, they are important, especially for such uses as adhesives, resistant coatings, and for encapsulation of electron units. For encapsulation, they cast easily with little shrinkage. They have very high adhesion to metals and nonmetals, heat resistance from 350 to 700°F (177 to 260°C), dielectric strength to 550 volts per mil (22 volts per meter), and Rockwell hardness of M110. The tensile strength may be up to 12,000 lb/in^2 (82 MPa), with elongation to 2 to 5%, but some resilient encapsulating resins are made with elongation to 150% with lower tensile strengths. The resins have high resistance to common solvents, oils, and chemicals.

An unlimited variety of epoxy resins is possible by varying the basic reactions with different chemicals or different catalysts, or both, by combining with other resins, or by cross-linking with organic acids, amines, and other agents. To reduce cost when used as laminating adhesives they may be blended with furfural resins, giving adhesives with high strength and high chemical resistance. Blends with polyamides have high dielectric strength, mold well, and are used for encapsulating electrical components.

Product	Manufacturer	Remarks
Epon Resins	Shell Chemical Corp.	Epoxy resins made with epichlorohydrin and bisphenols.
Kern-Krete	Sherwin-Williams Co.	Coating for ceramic blocks.
Erkopon	Earl Paint Corp.	Coating for tanks based on ethoxyline resins or polyarly ethylene oxide condensates. Made from epichlorohydrin and bisphenol with an ethylenediamine catalyst.

By using a polyamide curing agent, an epoxy can be made water-emulsifiable for use in water-based paints. The water-soluble epoxy of General Mills, Inc., is a reaction product of Genepoxy M195, a bisphenol epichlorohydrin epoxy resin, and Versamid 265-WR70, an ethylene glycol ether acetate.

Product	Manufacturer	Remarks
Resin X-3441	Dow Chemical Co.	An epoxy resin with 19% bromine in the molecule. It is flame resistant. Another grade, with 49% bromine, is a semi-solid used for heat resistant adhesives and coatings.

Oxiron resins, of FMC Corp., are epoxidized polyolefins. They have five or more reactive epoxy groups along each molecule of the chain instead of the usual two terminal epoxy groups on each molecule. With dibasic acids or anhydrides they form strong, hard resins of high heat resistance; or resins of lower viscosity are made for laminating and casting.

Product	Manufacturer	Remarks
Novolac DEN 438	Dow Chemical Co.	An epoxy resin with a high distortion point of 570°F (299°C), made by the reaction of epichlorohydrin with a phenol-formaldehyde resin with an anhydride catalyst. Has a very high strength at elevated temperatures as an adhesive for laminates.

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Product	Manufacturer	Remarks
Narmco Adhesive	Whittaker Corp.	An epoxy adhesive with a sheer strength of 5,500 lb/in^2 (38 MPa).

Epoxies can be copolymerized with other resins. Epoxy-acrylate resin, used for glass-fiber laminates, combines the resistance and adhesiveness of the epoxy with the fast cure and strength of the acrylate.

Product	Manufacturer	Remarks
ERRA-0300	Union Carbide	An epoxy resin that has cyclopentyl oxide terminal groups instead of diglycidyl ether. Has a yield strength of 18,200 lb/in^2 (123 MPa) at 392°F (200°C), a heat deflection temperature of 434°F (223°C).
Aracast	Ciba-Geigy Corp.	Epoxy resins produced by a reaction of hydantoin with epichlorohydrin. Hydantoin is a nitrogen-containing heterocyclic compound. They have high mechanical properties, good dielectrical characteristics, and ultraviolet light resistance. They retain light transmission properties after thermal aging of several thousand hours at 302°F (150°C).

Novoloids are fibers that contain at least 85%, by weight, cross-linked novalac epoxies. Kynol is a novoloid noted for its resistance to exceptionally high temperatures. At 1,920°F (1,049°C) the fiber is virtually unaffected. The fiber also has high dielectric strength and excellent resistance to all organic solvents and nonoxidizing acids.

A family of one-component epoxy resins, named Arnox, are produced by General Electric Co. Suitable for compression, transfer, injection molding, filament winding, and pultrusion, they cure rapidly at temperatures of 250 to 350°F (121 to 177°C). The compression and transfer molding grade is a black, mineral-filled compound. The injection molding grade is a pelletized glass-fiber reinforced compound with a shelf life of 9 to 12 months below 80°F (27°C).

9.3.4 Melamine Resins. A synthetic resin of alkyd type made by reacting melamine with formaldehyde. The resin is thermosetting, colorless, odorless, and resistant to organic solvents. It is more resistant to alkalies and acids than urea resins, has

better heat and color stability, and is harder. The melamine resins are used as molding plastics, and are also valued for dishes for hot food or acid juices. They do not soften or warp when washed in hot water. Melamine, a trimer of cyanamide, has the composition $(N:C''NH_2)_3$.

Melamine may be made by reacting urea with ammonia at elevated temperatures and pressure. It has a specific gravity of 1.56 and melting point of 354°C. Melamine alone imparts to other resins a high gloss and color retention. The melamine resins have good adhesives but are too hard for use alone in coatings and varnishes. They are combined with alcohol-modified urea-formaldehyde resins to give coating materials of good color, gloss, flexibility, and chemical resistance.

Product	Manufacturer	Remarks
Uformite MU-56	Resinous Products & Chemical Co.	A urea-modified melamine-formaldehyde resin used for coatings and varnishes.
Melmac 1077	American Cyanamid Co.	A melamine-formaldehyde molding resin with cellulose filler. Has a tensile strength of 7,500 lb/in.^{2} (52 MPa) and dielectric strength of 325 volts per mil $(12.8 \times 10^6$ volts per meter).
Melmac 592	American Cyanamid Co.	Has a mineral filler. Has a dielectric strength of 400 volts per mil $(16 \times 10^6$ volts per meter) and will withstand temperatures to 300°F (149°C).
Melurac 300	American Cyanamid Co.	A melamine-urea-formaldehyde resin with a lignin extender used as an adhesive for water-resistant plywood.
Melmac 483	American Cyanamid Co.	A phenol-modified melamine-formaldehyde resin solution used for laminating fibrous materials.
Melmac 404	American Cyanamid Co.	A highly translucent melamine-formaldehyde resin for molding high-gloss buttons.

Product	Manufacturer	Remarks
Lanoset	- - -	A methylol-melamine made by alkylating a melamine-formaldehyde resin with methyl alcohol. It is used for shrinkproofing woolen fabrics.
Resimene 812	Monsanto	A colorless melamine-formaldehyde resin powder that can be dissolved in water or ethyl alcohol, for impregnating paper or fabrics, or for laminating.

9.3.5 Phenol-Formaldehyde Resin. A synthetic resin, commonly known as phenolic, made by the reaction of phenol and formaldehyde, and used as a molding material for making mechanical and electrical parts. It was the earliest type of hard, thermoset synthetic resins. It is the most widely used groups of plastics for a variety of products because of its combination of strength, chemical resistance, electrical properties, glossy finish, and nonstrategic abundance of low cost raw materials. The resins are also used for laminating, coatings, and casting resins.

The reaction was known as early as 1872 but was not used commercially until much later. A condensation product of 50 parts phenol and 30 parts 40% formaldehyde made under an English patent of 1905 was called Resinite, and was originally offered as a substitute for Celluloid. Various modifications were made by other inventors. Redmanol was not of the first of the American products by the Bakelite Corp. Juvelite was made in Germany by condensing phenol and formaldehyde with the aid of mineral acids. Laccain was made under an English patent by using organic acids as catalysts. A Russian phenol resin, under the name of Karbolite, used an equal amount of naphthalenesulfonic acid, $C_{10}H_7SO_3H$, with the formaldehyde.

The hundreds of different phenolic molding compounds can be divided into six groups on the basis of major performance characteristics. General purpose phenolics are low cost compounds with fillers such as food flour and flock, and are formulated for noncritical functional requirements. They provide a balance of moderately good mechanical and electrical properties, and are suitable in temperatures up to 300°F (149°C). Impact-resistant grades are higher in cost. They are designed for use in electrical and structural components subject to impact loads. The fillers are usually either paper, chopped fabric, or glass fibers. Electrical grades, with mineral fillers, have high electrical resistivity plus good arc resistance, and they retain their resistivity under high temperature and high humidity conditions.

Heat-resistant grades are usually mineral- or glass-filled compounds that retain their mechanical properties in the 375 to 500°F (190 to 260°C) temperature range. Some of

these, such as phenylsilanes, provide long term stability at temperatures up to 550°F (288°C). Special purpose grades are formulated for service applications requiring exceptional resistance to chemicals or water, or combinations of conditions such as impact loading and a chemical environment. The chemical-resistant grades, for example, are inert to most common solvents and weak acids, and their alkali resistance is good. Non-bleeding grades are compounded specially for use in container closures and for cosmetic cases.

The resins are marketed usually in granular form partly polymerized for molding under heat and pressure, which complete the polymerization, making the product infusible and relatively insoluble. They may also come as solutions, or compounded with reinforcing fillers and pigments. The tensile strength of a molded part made from a simple phenol-formaldehyde resin may be only about 6,000 lb/in.^{2} (41 MPa), with a specific gravity of 1.27 and dielectric strength of about 450 volts per mil (17.7 x 10^6 volts per meter). Reinforcement is needed for higher strength, and with a wood-flour filler the tensile strength may be as high as 10,000 lb/in^2 (68 MPa). With a fabric filler the flexural strength may be 15,000 lb/in^2 (103 MPa), or 18,000 lb/in.^{2} (124 MPa) with a mineral fiber. The specific gravity is also raised, and the mineral fillers usually increase the dielectric strength.

Proper balance of fillers is important, since too much may produce brittleness. Organic fillers absorb the resin and tend to cause brittleness and reduce the flexural strength, although organic fibers and fabrics generally give higher impact strength. Wood flour is the usual filler for general service products, but prepared compounds may have mineral powders, mica, asbestos, organic fibers of macerated fabrics, or mixtures of organic and mineral materials. The Resinox resins, of Monsanto, are in grades with fibrous and mineral fillers, and Moldarata, of the Westinghouse Electric Corp., is in various grades. Bakelite was the original name for phenol plastics, but trade names now usually cover a range of different plastics, and the types and grades are designated by numbers.

The specific gravity of filled phenol plastics may be as high as 1.70. The natural color is amber and, as the resin tends to discolor, it is usually pigmented with dark colors. Normal phenol resin cures to single-carbon methylene groups between the phenolic groups, and the molded part tends to be brittle. Thus, many of the innumerable various of phenol are now used to produce resins, and modem phenol resins may also be blended or cross-linked with other resins to give higher mechanical and electrical characteristics.

Furfural is frequently blended with formaldehyde to improve flow, lower specific gravity, and reduce the cost. The alkylated phenols give higher physical properties. Phenol-phosphor resin is a phenol resin modified with phosphonitrilic chloride. When cured the resin contains 15% phosphorous, 6% nitrogen, and less than 1% chlorine.

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The tensile strength is 7,000 lb/in^2 (48 MPa) and it will withstand continuous temperatures to 500°F (260°C).

Product	Manufacturer	Remarks
Flexiphen 160	Koppers Co.	Resin that has some of the single-carbon methylene linkages replaced by hydrocarbon chains, giving 30% higher flexural strength with 5% lower specific gravity.
Resinox 3700	Monsanto Chemical Co.	A mineral-filled-phenolic resin of high arc resistance and high dimensional stability for electrical parts.
Synvar	Synvar Corp.	Resin that comes in a number of grades.
Durez	Hooker Chemical Corp.	Resin that comes in a number of grades.

Phenol resins may also be cast and then hardened by heating. The cast resins usually have a higher percentage of formaldehyde and do not have fillers. In a syrupy state they are poured into lead molds and hardened in a slow oven.

Product	Manufacturer	Remarks
Crystallin	Crystallin Products Corp.	Phenol plastic.
Phenalin	Du Pont	Phenol plastic.
Catalin	American Catalin Corp.	Phenol plastic.
Ivoricast	West Cost Enterprises	A shock resistant cast phenolic plastic with wood-flour filler that cures at low heat.
Prystal	American Catalin Corp.	The name of water-clear Catalin.
Bois Glace	American Catalin	A Catalin-coated wood for desk tops.

Product	Manufacturer	Remarks
Fiberlon	Fiberloid Corp.	A cast phenol plastic.
Marblette	Marblette Corp.	A cast plastic.

9.3.6 Polyester Resins. Polyester laminates are usually made with high proportions of glass-fiber mat or glass fabric, and high strength reinforced moldings may also contain a high proportion of filler. A resin slurry may contain as high as 70% calcium carbonate or calcium sulfate, with only about 11% of glass fiber added, giving an impact strength of 24,000 lb/in^2 (165 MPa) in the cured-material.. Bars and structural shapes of glass-fiber reinforced polyester resins of high tensile and flexural strengths are made by having the glass fibers parallel in the direction of the extrusion. Glastrusions, of Hugh C. Marshall Co., in rods and tubes, are made by having the glass-fiber rovings carded under tension, then passing through an impregnating tank, an extruding die, and a heat-curing die. The rods contain 65% glass fiber and 35% resin. They have a flexural strength of 64,000 $lb/in.^2$ (441 MPa), and a Rockwell M hardness of 65.

Physical properties of polyester moldings vary with the type of raw materials used and the type of reinforcing agents. A standard glass-fiber-filled molding may have a specific gravity from 1.7 to 2.0, a tensile strength of 4,000 to 10,000 lb/in^2 (27 to 68 MPa), with elongation of 16 to 20%, a flexural strength to 30,000 lb/in^2 (206 MPa), a dielectric strength to about 400 volts per mil (16 x 10^6 volts per meter), and a heat distortion temperature of 350 to 400°F (177 to 204°C). The moldings have good acid and alkali resistance. But, since an almost unlimited number of fatty acids are available from natural fatty oils or by synthesis from petroleum, and the possibilities of by combining with alcohols, glycols, and other materials are also unlimited, the polyesters form an ever-expanding group of plastics.

9.3.7 Polyurethane Resins (Urethanes). Urethane foams are made by adding a compound that produces carbon dioxide or by reaction of a diisocyanate with a compound containing active hydrogen. Foams can be classified somewhat according to modulus as flexible, semi-flexible or semi-rigid, and rigid. No sharp lines of demarcation have been set on these different classes as the gradation from the flexibles to the rigids is continuous. Densities of flexible foams range from about 1.0 lb/ft^2 (16 kg/m^3) at the lightest to 4 to 5 lb/ft^2 (64 to 80 kg/m^3) depending on the end use. Applications of flexible foams range from comfort cushioning of all types, e.g., mattresses, pillows, sofa sets, backs and arms, automobile topper pads, and run underlay, to lightweight clothing interliners for increasing warmth. Densities of rigid urethane foams range from about 1.5 to 50 lb/ft^2 (24 to 800 kg/m^3).

There are six basic types of polyurethane coatings, or urethane coatings, as defined by ASTM Specification D16. Types 1, 2, 3, and 6 have long storage life and are formu-

lated to cure by oxidation, by reaction with atmospheric moisture, or by heat. Types 4 and 5 are catalyst-cured and are used as coatings on leather and rubber, and as fast curing industrial product finishes. Urethane coatings have good weathering characteristics as well as high resistance to stains, water, and abrasion.

9.3.8 Silicones. A group of resin like materials in which silicon takes the place of the carbon of the organic synthetic resins. Silicon is quadrivalent like carbon. But, while carbon has a valence of 2, silicon has only one valence of 4, and the angles of molecular formation are different. The two elements also differ in electronegativity, and silicon is an amphoteric element, having both acid and basic properties. The molecular formation of the silicones varies common plastics, and they are designated as inorganic plastics as distinct from the organic plastics made with carbon.

In the long chain organic synthetic resins, the carbon atoms repeat themselves, attaching on two sides to other carbon atoms, while in the silicones the silicon atom alternates with an oxygen atom so that the silicon atoms are not tied to each other. The simple silane formed by silicon and hydrogen corresponding to methane, CH_4 is also a gas, as is methane, and has the formula SiH_4 But in general, the silicones do not have the SiH radicals, but contain CH radicals as in the organic plastics. Basically, silicon is treated with methyl chloride and a catalyst to produce a gas mixture of silanes $(CH_3)_x(SiCl)_{4-x}$. After condensing, three silanes are fractioned, methyl chlorosilane, dimethyl dichlorosilane, and trimethyl trichlorosilane. These are the common building blocks of the siloxane chains, and by hydrolyzing them, cyclic linear polymer can be produced with acid or alkali catalysts to give fluids, resins, and rubbers.

Silicone resins have more heat resistance than organic resins, high dielectric strength, and are water resistant. Like organic plastics, they can be compounded with plasticizers, fillers, and pigments. They are usually cured by heat. Because of the quartz-like structure, molded parts have exceptional thermal stability. Their maximum continuous use service temperature is about 500°F (260°C). Special grades exceed this temperature and go as high as 700 to 900°F (371 to 482°C). Their heat deflection temperature for 265 lb/in.^{2}(1.8 MPa) is 900°F (482°C). Their moisture absorption is low, and resistance to petroleum products and acids is good. Nonreinforced silicones have only moderate tensile and impact strength, but fillers and reinforcements provide substantial improvement. Because silicones are high in cost, they are premium plastics and are limited to critical or high performance products, such as high temperature components in the aircraft, aerospace, and electronic fields.

A great variety of molecular combinations are available in the silicone polymers, giving resins varying characteristics, and those having CH radicals with silicon bonds are termed organosilicon polymers. Silicon tetramethyl, $Si(CH_3)$, is a liquid boiling at (26°C). Trichlorosilane, $HSiCl_3$, also called silicochloroform, corresponds in formation to chloroform. By replacing the hydrogen atom of this compound with an alkyl group,

the alkylchlorosilanes are made that have high adhesion to metals and are used in enamels. Methyl chlorosilane, $(CH_3)_2SiCl_2$, is a liquid used for waterproofing ceramic electrical insulators. The material reacts with the moisture in the ceramic, forming a water-repellent coating of methyl silicone resin and leaving a residue of hydrochloric acid that is washed off.

Product	Manufacturer	Remarks
Dry-Film 9977	General Electric Co.	A liquid mixture of dimethyl dichlorosilane and methyl trichlorosilane used for water-proofing ceramic electrical insulators.
Silicone SC-50	General Electric Co.	A sodium methyl siliconate used in concrete, in gypsum plaster, and in water paints to impart water repellency.
Velvasil	General Electric Co.	A dimethyl siloxane used in cosmetics as a water repellent and in lipsticks for smear resistance.

The dimethyl polysiloxanes are very stable fluids used widely in cosmetics, but valued also for use in shock absorbers, transformers, and in automatic control systems.

Product	Manufacturer	Remarks
Sun Filter Polish	Westley Industries	A dimethyl siloxane that is resistant to sunlight and alkaline chemicals. This material can withstand temperatures to 300°F (149°C).
Silcone cement	Charles Englehard Inc.	A polysiloxane with mineral fibers that gives strong, heat resistant bonds to metals, glass, and ceramics.

The strong cements developed by the Naval Ordnance Laboratory for making chemical bonds between glass fibers and resin in plastic laminates are made by reacting allyl trichlorosilane with phenon resorcinol, or xylenol.

Silcone insulating varnishes will withstand continuous operating temperatures at 350°F (177°C) or higher. Silicone enamels and paints are more resistant to chemicals than most organic plastics, and when pigmented with mineral pigments will withstand temperatures up to 1,000°F (538°C). For lubricants the liquid silicones are com-

pounded with graphite or metallic soaps and will operate between -50 and 500°F (-46 and 260°C).

Product	Manufacturer	Remarks
Thermocone	Joseph Dixon Crucible Co.	A black, chemical resistant paint that can withstand temperatures to 1,000°F (538°C). Thermocone is a liquid silicone containing graphite flakes.

Silicone liquids are stable at their boiling points, between 750 and 800°F (399 and 427°C), and have low vapor pressures, so that they are also used for hydraulic fluids and heat transfer media.

Silicone oils, used for lubrication and as insulating and hydraulic fluids, are methyl silicone polymers. They retain a stable viscosity at both high and low temperatures. As hydraulic fluids they permit smaller systems to operate at higher temperatures. In general, silicone oils are poor lubricants compared with petroleum oils, but they are used for high temperatures, 150 to 200°C, at low speeds and low loads.

Silicone resins are blended with alkyd resins for use in outside paints, usually modified with a drying oil. Resin XR-807, Dow Corning, is such a silicone-alkyd containing 25% silicone resin that is used to produce paints with high weather and sunlight resistance. A catalyst is added so that the paint can be air dried. Silicone-alkyd resins are also used for baked finishes, combining the adhesiveness and flexibility of the alkyd with the heat resistance of the silicone. A phenyl ethyl silicone is used for impregnating glass-fiber cloth for electrical insulation and it has about double the insulating value of ordinary varnished cloth.

Silicone rubber is usually a long chain dimethyl silicone that will flow under heat and pressure, but can be vulcanized by cross-linking the linear chains. Basically, it consists of alternate silicon and oxygen atoms with two methyl groups attached to each silicon atom. The tensile strength is 300 lb/in^2 (2 MPa), but with fillers it is raised to 600 lb/in.^{2} (4 MPa). It is usually compounded with silica and pigments. It is odorless and tasteless, is resistant to most chemicals but not to strong acids and alkalies, will resist heat to 500-F (260°C), and will remain flexible to -70°F (-57°C). The dielectric strength is 500 volts per mil (20 x 10^6 volts per meter).

Product	Manufacturer	Remarks
Silastic	Dow Corning	A silicone rubber. It is a white rubbery material with an elongation of 70 to 150% and had good adhesion to various materials. Used for electrical insulation, for coating fabrics, and for gaskets and other parts.
Silastic RTV 601	Dow Corning	Used to encapsulate electrical units. Has a specific gravity of 1.29, tensile strength of 300 lb/in.^{2}(2 MPa), elongation of 150%, and dielectric strength of 500 volts per mil (22 x 10^6 volts per meter). The hardness is Shore A40.

Ordinary silicone rubber has the molecular group (H"CH$_2$"Si"CH$_2$"H) in a repeating chain connected with oxygen linkages, but in the nitrile-silicone rubber, produced by General Electric, one of the end hydrogens of every fourth group in the repeating chain is replaced by a C:N radical. These polar nitrile groups have a low affinity for oils, and the rubber does not swell with oils and solvents. It retains strength and flexibility at temperatures from -100°F (-73°C) to above 500°F (260°C), and is used for such products as gaskets and chemical hose. This material, called N.S. Fluids in the form of water-white to yellow liquids having 3 to 23% nitrile content, is used for solvent-resistant lubricants and as antistatic plasticizers. As lubricants, they retain a nearly constant viscosity at varying temperatures. Fluorosilicones have fluoroalkyd groups substituted for some of the methyl groups attached to the siloxane polymer of dimethyl silicone. They are fluids, greases, and rubbers, incompatible with petroleum oils and insoluble in most solvents. The greases are the fluids thickened with lithium soap, or with a mineral filler.

9.4 ELASTOMERIC APPLICATIONS (NATURAL AND SYNTHETICS).

9.4.1 <u>Natural Rubbers (General).</u> A gum resin exudation of a wide variety of trees and plants, but especially of the tree Hevea brasiliensis and several other species of Hevea growing in all tropical countries and cultivated on plantations in southern Asia, Indonesia, Sri Lanka, Zaire, and Liberia, from which natural rubbers elastomers are made.

The gum resin was formerly referred to as India rubber and gum elastic. The first highly compounded rubber insulation, developed in 1867, was called Kerite. Brazilian rubber is sometimes called Para rubber. Caoutchouc was an early name for the crude rubber then cured over a fire into a dark, solid mass for shipment. Castilla rubber, or castilloa, is from the large tree Castilla elastica, and was the original rubber of the Carib

and Mayan Indians, but was cultivated only in Mexico and in Panama where it was called Panama rubber. The latex and rubber are identical with hevea rubber after purification. Euphorbia rubber is from vines of the genus Euphoria, of which there are 120 species in tropical Africa. Mangabeira rubber was formerly produced in the Amazon Valley. It is the latex of the mangabeira tree, which comprises various species of the genus Hancoria and yields the edible fruit mangaba The latex is coagulated with alum or sodium chloride, but the native Indians coagulated it with the latex of the caxiguba tree, Ficus anthelmintica, giving a better rubber. The rubber is softer than hevea rubber, but ages better. The low grade Assam rubber is from a species of ficus tree, F. elastica, of India and Malaya. Ceara rubber comes from the small, rapid growing tree, Manihot glaziovii, native to the semi-desert regions of Brazil, but now grown in India and Sri Lanka. The rubber is a good grade.

Rubber latex is a colloidal emulsion of the gathered sap, containing about 35% of rubber solids, blended from various sources to give average uniformity. The latex is coagulated with acid and milled into ribbed sheets called crepe rubber, or into sheets exposed to wood smoke to kill bacteria. These rubber sheets are known as smoked sheet rubber. These sheets constitute the commercial crude rubber, although rubber latex is used directly, especially for dipped goods such as gloves; toys; and balloons; for coatings, and for making foam rubber. Rubber can be vulcanized with sulfur and heat, removing the tackiness and making it harder and more elastic in the low sulfur compounds. All natural rubber, except adhesive rubbers, is vulcanized rubber.

Ordinary soft rubber contains only 3 to 6% sulfur, but also contains softners, fillers, antioxidants, or other compounding agents, giving varying degrees of elasticity, strength, and other qualities. When as much as 30% sulfur is added, the product is called hard rubber.

Vapor-cured rubber is rubber vulcanized by sulfur chloride fumes and neutralized with magnesium carbonate. This rubber is used for thin goods only. Acid-cured rubber is rubber cured in a bath of sulfur chloride in a solvent.

The tensile strength of rubber of low vulcanization is 800 to 1,200 lb/in^2 (6 to 8 MPa) of the original cross section. A good soft rubber can be stretched as much as 1,000% without rupturing, and will return close to the original length with little permanent set. The specific gravity is about 1.05, but with fillers may be as high as 1.30. When the term vulcanized rubber is now used, it refers to hard rubber vulcanized to a rigid but resilient solid. Vulcanized rubber is used in electrical parts and tool handles. Ace hard rubber, of the American Hard Rubber Co., has a specific gravity of 1.27, a tensile strength of 8,700 lb/in^2 (60 MPa), dielectric strength of 485 volts per mil (19 x 10^6 per meter), distortion temperature 172°F (78°C), and water absorption 0.04%. Vulcanite and Ebonite are old names for hard rubber.

Reclaimed rubber is produced largely from old tires and factory scrap. It is usually lower in cost than new rubber, but is easier to process and is used in large quantities even when the price is higher. Reclaimed rubber is sold in sheets, slabs, pellets, and powder, but much of the rubber powder, or granulated rubber, used for adhesives and molding is not reclaimed rubber but is made by spray-drying latex. Vultex is a natural rubber powder in paste form for coatings and adhesives. Mealorub is a rubber powder developed by the Indonesian Rubber Research Institute for mixing with asphalt for road surfacing.

Several types of modified natural rubber are used in the production of coatings, protective films, and adhesives. These are chlorinated rubber, rubber hydrochloride, and cyclized or isomerized rubber. Chlorinated rubber, for example, modified with any one of a number of plastic resins, provides maximum protection against a wide range of chemical. These coatings are widely used in chemical plants, in gas works, and as tank-car linings.

Red rubber is rubber colored red, but was originally rubber vulcanized with antimony pentasulfide that broke down with the heat of vulcanization, yielding sulfur to the rubber and coloring it red with the residual antimony trisulfide. Many trade names accelerators, fillers, and stiffeners are marketed for rubber compounding.

Crumb rubber is any form of porous particles than can be dissolved easily without milling, cutting, or pelletizing. It is used in adhesives and plastics.

Magnetic rubbers, produced in sheets and strips of various magnetic strengths, are made of synthetic rubbers compounded with magnetic metal powders.

Chlorinated Rubber. An ivory-colored or white powder produced by the reaction of chlorine and rubber. It contains about 67% by weight of rubber, and is represented by the empirical formula $(C_{10}H_{13}Cl_7)_x$, although it is a mixture of two products, one having a CH_2 linkage instead of a CHCl. Chlorinated rubber is used in acid- and corrosion-resistant paints, in adhesives, and in plastics.

The uncompounded film is brittle, and for paints chlorinated rubber is plasticized to produce a hard, tough, adhesive coating, resistant to oils, acids, and alkalies. The specific gravity of chlorinated rubber is 1.64, and bulking value of 0.0735 gal/lb. The tensile strength of the film is 4,500 lb/in.^{2} (31.5 MPa). It is soluble in hydrocarbons, carbon tetrachloride, and esters, but insoluble in water. The unplasticized material has a high dielectric strength, up to 2,300 bolts per mil (90.6 x 10^6 volts per meter).

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Product	Manufacturer	Remarks
Tornesit and Parlon	Hercules Inc.	Chlorinated rubbers.
Paratex	Truscon Laboratories	Chlorinated-rubber coating materials.
Roxaprene	Roxalin Flexible Lacquer Co., Inc.	Chlorinated-rubber coating materials.
Pliofilm	Goodyear Tire & Rubber Co.	Rubber hydrochloride made by saturating the rubber molecule with hydrochloric acid. Made into transparent sheet wrapping material, which heat-seals at 105 105 to 130°C, or is used as a coating material for fabrics and paper. Gives a tough, flexible, water-resistant film.
Pliolite	Goodyear Tire & Rubber Co.	A cyclized rubber made by highly chlorinating the rubber. Used in insulating compounds, adhesives, and protective paints. Is soluble in hydrocarbons, but is resistant to acids and alkalies. Pliowax is this material compounded with paraffin or ceresin wax. Pliolite S-1 is this material made from synthetic rubber.

Dartex and Alloprene are German chlorinated rubbers, and Rulahyde is Dutch.

Resistant fibers have also been made from chlorinated rubbers.

Product	Manufacturer	Remarks
Tensolite	Tensolite Corp.	Filter cloth made from chlorinated rubber.
Betacote 95	Essex Chemical Corp.	A maintenance paint for chemical-processing plants that is based on chlorinated rubber. Adheres to metals, cements, and wood and dries rapidly. The coating is resistant to acids, alkalies, and solvents.

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Cyclized Rubber. Cyclized rubber is made by heating rubber with sulfonyl chloride or with chlorostannic acid, $H_2SnCl_6 \cdot 6H_2O$. It contains about 92% rubber hydrocarbons, and has the long straight chains of natural rubber joined together with a larger ring-shaped structure. The molecule is less saturated than ordinary natural rubber, and the material is tougher. It is thermoplastic, somewhat similar to gutta percha or balata, and makes a good adhesive. The specific gravity is 1.06, softening point 80 to 100°C, and tensile strength up to 4,500 lb/in.^{2} (31.5 MPa). It has been used in adhesives for bonding rubbers to metals, and for waterproofing paper.

9.4.2 Synthetic Rubbers (General).

Elastomers. Synthetic rubbers are hydrocarbon, polymeric materials similar in structure to plastic resins. The difference between plastics and elastomers is largely one of definition based on the property of extensibility or stretching. ASTM defines an elastomer as "a polymeric material which at room temperature can be stretched to at least twice its original length and upon immediate release of the stress will return quickly to approximately its original length." Some grades of plastics approach this rubber-like state, for example, certain polyethylenes. Also, a number of plastics have elastomer grades, such as the olefins, styrenes, fluoroplastics, and silicones. As indicated above, the major distinguishing characteristic of elastomers is their great extensibility and high energy storing capacity. Unlike many metals that cannot be strained more than a fraction of 1% without exceeding their elastic limit, elastomers have usable elongations up to several hundred percent. Also, because of their capacity for storing energy, even after they are strained several hundred percent, virtually complete recovery is achieved once the stress is removed.

Until World War II, almost all rubber was natural. During the war, synthetic rubbers began to replace the scarce natural rubber, and, since that time, production of synthetic rubber has increased until now their use far surpasses that of natural rubber. There are thousands of different elastomer compounds. Not only are there many different classes of elastomers, but individual types can be modified with a variety of additives, fillers, and reinforcements. Also, curing temperatures, pressures, and processing methods can be varied to produce elastomers tailored to the needs of specific applications.

In the raw material or crude stage, elastomers are thermoplastic. Thus crude rubber has little resiliency and practically no strength. By a vulcanization process in which sulfur and/or other additives are added to the heated crude rubber, the polymers are cross-linked by means of covalent bonds to one another, producing a thermoset-like material. The amount of cross-linking that occurs between the sulfur (or other additive) and the carbon atoms determines many of the elastomer's properties. As cross-linking increases, resistance to slippage of the polymers over one another increases, resilience and extensibility decreases, and the elastomer approaches the nature of a thermosetting

plastic. For example, hard rubbers, which have the highest cross-linking of the elastomers, in many respects are similar to phenolics. In the unstretched state, elastomers are essentially amorphous because the polymers are randomly entangled and there is no special preferred geometrical pattern present. However, when stretched, the polymer chains tend to straighten and become aligned, thus increasing in crystallinity. This tendency to crystallize when stretched is related to an elastomer's strength. Thus, as crystallinity increases, strength also tends to increase.

There are roughly 15 major classes of elastomers that have been identified. The major characteristics of each group are highlighted. Two basic specifications that provide a standard nomenclature and classification system for these classes are: ASTM Standard D1418, which categorizes elastomers into compositional classes, and joint ASTM D2000/SAE J200 provides a classification system based on material properties. The first letter indicates specific resistance to heat aging, and the second letter denotes resistance to swelling in oil.

Chlorinated polyethylene elastomers are produced by substituting chlorine for hydrogen on a high density polyethylene chain resulting in a fully saturated structure with no double or triple bonds. The elastomer requires the catalytic reaction of a peroxide for curing. Thus, most molded parts are black Five grades of CPE polymers are produced, differing principally in chlorine content. The higher chlorine content grades have best oil and fuel resistance, tear resistance, gas impermeability, and hardness. The lower chlorine content grades have lower viscosities, better low temperature properties, and improved resistance to heat and compression set.

Chlorosulfonated polyethylene elastomer, commonly known as Hypalon, contains about one-third chlorine and 1 to 2% sulfur. It can be used by itself or blended with other elastomers. Hypalon is noted for its excellent resistance to oxidation, sunlight, weathering, ozone, and many chemicals. Some grades are satisfactory for continuous service at temperatures up to 350°F (177°C). It has moderate oil resistance. It also has unlimited colorability. Its mechanical properties are good but not outstanding, although abrasion resistance is excellent. Hypalon is often used in blends to improve oxidation and ozone resistance. Hypalon is used as tank linings, high temperature conveyor belts, shoe soles and heels, seals, gaskets, and spark plug boots.

Epichlorohydrin elastomers are noted for their resistance to oils, and excellent resistance to ozone, weathering, and intermediate heat. The homopolymer has extremely low permeability to gases. The copolymer has excellent resilience at low temperatures. Both have low heat buildup, making them attractive for parts subjected to repeated shocks and vibrations.

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Ethylene-propylene elastomers, or EPR rubber, are available as copolymers and ter-polymers. They offer good resilience, flexing characteristics, compression set resistance, and hysteresis resistance, along with excellent resistance to weathering, oxidation, and sunlight. Although fair to poor in oil resistance, their resistance to chemicals is good. Their maximum continuous service temperature is around 350°F (177°C). They are used in electrical insulation, footwear, and auto hoses and belts.

Fluorocarbon elastomers, fluorine-containing elastomers, like their plastic counterparts, are highest of all the elastomers in resisting oxidation, chemicals, oils, solvents, and heat. They are also the most expensive. They can be used continuously at temperatures over 500°F (127°C) and do not support combustion. Their brittle temperature is only -10°F (-23°C). Their mechanical and electrical properties are only moderate. Unreinforced types have tensile strengths of less than 2,000 lb/in.^{2} (13 MPa), and only fair resilience. They are used to make brake seals, O-rings, diaphragms, and hoses.

The phosphonitrile plastics and elastomers have high elasticity and high temperature resistance. They are derived from chlorophosphonitrile, or phosphonitrilic chloride, $P_3N_3Cl_3$, which has a hexagonal ring of alternating atoms of phosphorus and nitrogen with the chlorine atoms attached. In the plastic monomers the chlorine atoms are replaced by other groups. The PN polymers, of Horizons, Inc., contain OCH and C_3F_7 groups and are synthetic rubbers of high oxidation and chemical resistance. The tensile strength is up to 700 lb/in.^{2} (4.9 MPa) with elongation up to 600%. The material is used for as gaskets and cratings for severe service.

A phosphonitrilic fluorocarbon elastomer, of the Firestone Tire and Rubber Co., is a semi-organic phosphazene polymer. It remains flexible and serviceable at temperatures from -70 to 350°F (-57 to 177°C), and is highly resistant to oils and solvents over that temperature range.

Viton is a vinylidene fluoride hexafluoropropylene tetrafluorethylene copolymer, made by Du Pont, with extra high resistance to solvents, hydrocargons, steam, and water. Elastomers of the same type produced by 3M have the trade name Fluorel.

Perfluoroelastomer is a specialty, costly, fully chlorinated elastomer, by Du Pont, that resists commercial solvents, bases, and jet fuels. Kalrez can be used at continuous service temperatures of up 550°F (228°C) and at temperatures up to 650°F (343°C) for short time periods. Firestone's phosphonitrilic fluoroelastomer (PNF200) has improved low temperature flexibility and resistance to heat aging and fuels. Its maximum continuous service temperature is 350°F (176°C).

Butyl rubbers, also referred to as isobutylene-isoprene elastomers, are copolymers of isobutylene and about 1 to 3% isoprene. They are similar in many ways to natural rubber, and are one of the lowest priced synthetics. They have excellent resistance to abrasion, tearing, and flexing. They are noted for low gas and air permeability (about 10 times better than natural rubber). For this reason, butyl rubbers make a good material for tire inner tubes, hose, tubing, and diaphragms. Although butyls are non-oil resistant, they have excellent resistance to sunlight and weathering; and generally have good chemical resistance. They also have good low temperature flexibility and heat resistance up to 300°F (149°C); however, they are not flame resistance. They have lower mechanical properties such as tensile strength, resilience, abrasion resistance, and compression set, than the other elastomers. Because of their excellent dielectric strength, they are widely used for cable insulation, encapsulating compounds, and a variety of electrical applications. Other uses include weather stripping, coated fabrics, curtain wall gaskets, high pressure steam hoses, machinery mounts, and seals for food jars and medicine bottles.

Isoprene is synthetic natural rubber. It is processed like natural rubber, and its properties are quite similar although isoprene has somewhat higher extensibility. Like natural rubber, its notable characteristics are very low hysteresis, low heat build up, and high tear resistance. It also has excellent flow characteristics, and is easily injection molded. Its uses complement those of natural rubber. Its good electrical properties plus low moisture absorption make it suitable for electrical insulation.

Neoprene, also known as chloroprene, was developed in the 1930s. Neoprene was the first commercial synthetic rubber. It is chemically and structurally similar to natural rubber, and its mechanical properties are also similar. Its resistance to oils, chemicals, sunlight, weathering, aging, and ozone is outstanding. Also, it retains its properties at temperatures up to 250°F (121°C), and is one of the few elastomers that does not support combustion, although it is consumed by fire. In addition, neoprene has excellent resistance to permeability by gases, having about one-fourth to one-tenth the permeability of natural rubber, depending on the gas. Although it is slightly inferior to natural rubber in most mechanical properties, neoprene has superior resistance to compression set, particularly at elevated temperatures. It can be used for low voltage insulation, but is relatively low in dielectric strength. Products made of chloroprene elastomers are heavy duty conveyor belts, V-belts, hose covers, footwear, brake diaphragms, motor mounts, rolls, and gaskets.

Nitrile elastomers, or NBR rubbers, originally known as Buna N, are copolymers of acrylonitrile and butadiene. They are known for their outstanding resistance to oil and fuels at both normal and elevated temperatures. Their properties can be altered by varying the ratio of the two monomers. In general, as the acrylonitrile content increases, oil resistance, tensile strength, and processability improve while resistance, compression set, low temperature flexibility, and hysteresis characteristics deteriorate. Most

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commercial grades range from 20 to 50% acrylonitrile. Those at the high end of the range are used where maximum resistance to fuels and oils is required, such as in oil-well parts and fuel hoses. Low acrylonitrile grades are used when good flexibility at low temperatures is important. Medium-range types, which are the most widely used, are used in flexible couplings, printing blankets, rubber rollers, and washing machine parts. Nitriles as a group are low in most mechanical properties. Because they do not crystal-lize appreciably when stretched, their tensile strength is low, and resilience is roughly one-third to one-half that of natural rubber. Depending on acrylonitrile content, low temperature brittleness occurs at from -15 to -75°F (-26 to -60°C). Their electrical in-sulation quality varies from fair to poor.

Polyacrylate elastomers are based on polymers of butyl or ethyl acrylate. They are low volume use, specifically elastomers, used in parts involving oils (especially sul-fur-bearing) at elevated temperatures up to 300°F (149°C) and even as high as 400°F (204°C). A major use is for automobile transmission seals. Other oil resistance uses are gaskets and O-rings. Mechanical properties such as tensile strength and resilience are low. And, except for new formulations, they lose much of their flexibility below -10°F (-23°C). The new grades extend low temperature service to -40°F (-40°C). Polyacrylates have only fair dielectric strength, which improves, however, at elevated temperatures.

Polybutadiene elastomers are notable for their low temperature performance. With the exception of silicone, they have the lowest brittle or glass transition tempera-ture, -100°F (-73°C), of all of the elastomers. They are also one of the most resilient, and have excellent abrasion resistance. However, resistance to chemicals, sunlight, weathering, and permeability by gases is poor. Some uses are: shoe heels, soles, gas-kets, and belting. They are also often used in blends with other rubbers to provide im-proved resilience, abrasion resistance, and low temperature flexibility.

Polysulfide elastomer, also known as Thiokol, is rated highest in resistance to oil and gasoline. It also has excellent solvent resistance, extremely low gas permeability, and good aging characteristics. Thus, it is used for such products as oil and gasoline hoses, gaskets, washers, and diaphragms. Its major use is for equipment and parts in the coating production and application field. It is also widely applied in liquid form in sealants for the aircraft and marine industries. Thiokol's mechanical properties, includ-ing strength, compression set, and resilience, are poor. Although Thiokol is poor in flame resistance, it can be used in temperatures up to 250°F (121°C).

Silicone elastomers are polymers composed basically of silicon and oxygen atoms. There are four major elastomer composition groups. In terms of application, silicone elastomers can be divided into the following types: general purpose, low temperature, high temperature, low compression set, high tensile high tear, fluid resistant, and room temperature vulcanizing. All silicone elastomers are high performance, high price materials.

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The general purpose grades, however, are competitive with some of the other specialty rubbers, and are less costly than the fluorocarbon elastomers. They have outstanding resistance to high and low temperatures, oils, and chemicals. High temperature grades have maximum continuous service temperatures up to 600°F (316°C); low temperature grades have glass transition temperatures of -180°F (-118°C).

Electrical properties, which are comparable to the best of the other elastomers, are maintained over a temperature range from -100°F (-73°C) to over 500°F (260°C). However, most grades have relatively poor mechanical properties. Tensile strength runs only around 1,200 lb/in^2(8 MPa). However, grades have been developed with improved strength, tear resistance, and compression set.

Fluorosilicone elastomers have been developed that combine the outstanding characteristics of the fluorocarbons and silicones. However, they are expensive and require special precautions during processing. A unique characteristic of one of these elastomers is its relatively uniform modulus of elasticity over a wide temperature range and under a variety of conditions. Silicone elastomers are used extensively in products and components where high performance is required, such as, seals, gaskets, O-rings, insulation for wire and cable, and encapsulation of electronic components.

Styrene-butadiene elastomers, also called Buna S, SBR, and GR-S, are copolymers of butadiene and styrene. They are similar in many ways to the natural rubbers, and were the first widely used synthetics. They top all elastomers in volume of use, because of their low cost and use in automobile tires. A wide range of property grades are produced by varying the amounts of sytrene and butadiene. For example, styrene content varies from as low as 9% in low temperature resistant rubbers to 44% in rubbers with excellent flow characteristics. Those grades with 50% styrene are, by definition, considered plastics. Carbon black is sometimes added also as it substantially improves processing and abrasion resistance. SBR elastomers are similar in properties to natural rubber. They are non-oil resistant and are generally poor in chemical resistance. Although they have excellent impact and abrasion resistance, they are somewhat below natural rubber tensile strength, resilience, hysteresis, and some other mechanical properties. The largest single use is in tires. Other applications are similar to those of natural rubber.

Urethane elastomers are copolymers of diisocyanate with their polyester or polyether. Both are produced in solid gum form and viscous liquid. With tensile strengths above 5,000 lb/in^2(34 MPa) and some grades approaching 7,000 lb/in^2(49 MPa), urethanes are the strongest elastomers available. They are also the hardest, and have extremely good abrasion resistance.

Other notable properties are low compression set, good aging characteristics, and good resistance to oil and fuel. The maximum temperature for continuous use is under 200°F

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(93°C), and their brittle point ranges from -60 to -90°F (-51 to -68°C). Their largest field of application is for parts requiring high wear resistance and/or strength, for example, forklift truck wheels, airplane tail wheels, shoe heels, bumpers on earthmoving machinery, and typewriter damping pads.

9.4.3 <u>Thermoplastic Elastomeric Applications.</u>

Thermoplastic Elastomers. A group of polymeric materials having characteristics of both plastics and elastomers (also called elastoplastics). They can be processed on standard plastics processing equipment without vulcanizing or curing. They are lightweight, resilient materials that perform well over-a wide temperature range; There are a half-dozen different types of elastomplastics. The olefinics, as thermoplastic olefinics (TPOs), are produced in durometer hardnesses from 54A to 96A Specialty flame-retardant and semi-conductive grades are also available. The TPOs are used in automobiles for paintable body filler panels and air deflectors, and as sound-deadening materials in diesel-powered vehicles. Producers of olefinics include:

Company	Product
Uniroyal	TPF
Du Pont	Somel
Exxon Chemical	TPV
	Vistaflex
Hercules	Pro-fax
B. F. Goodrich	Telcar

The styrenics are block copolymers, composed of polystyrene segments in a matrix of polybutadiene or polyisoprene. Lowest in cost of the elastoplastics, they are available in crumb grades and molding grades, and are produced in durometer hardnesses from 35A to 95A Manufactured by Shell Chemical (Kraton) and Philips Petroleum (Solprene), they are used for shoe soles, sealants, tubing, and sheeting.

Copolyether-ester thermoplastic elastomers of Du Pont are high performance, high cost materials, and known in the market as Hytrel. The five basic grades by durometer hardness are 40D, 47D, 55D, 63D, and 72D. Their applications include tubing and hose, V belts, couplings, oil-field parts, and jacketing for wire and cable. Their chief characteristic is toughness and impact resistance over a broad temperature range. A thermoplastic elastomer of polyvinyl chloride and nitrile, produced by Uniroyal and known as TPR 3700, provides excellent oil resistance. Trans-Pip is a trans-1, 4 polyisoprene thermoplastic elastomer of Polystar Co., developed as a replacement for refined balata rubber in golf-ball covers.

Polyester Resins. Thermoplastic polyester is a crystalline plastic molding compound. One type is made by polycondensation of 1, 4-butaneodiol and dimethyl-terephthalate (DMT) to produce polyteremethylene terephthalate (PTMT); commonly referred to as polybutylene terephthalate (PBT). The many different grades that are produced by a number of different grades that are produced can be divided into four major types:

Unmodified. Unmodified types have the greatest elongation and usually the shortest molding cycles.

Flame retardant. Flame retardant grades can maintain their flame retardance in very thin sections -- at 1/32 inch (0.8 mm), for example.

Glass-fiber reinforced. Thermoplastic polyesters reinforced with glass fibers are among the toughest plastics materials. Along with good heat resistance, they provide excellent impact strength and mechanical properties. Glass loadings range from 10 to 50%.

Mineral filled. To counter warpage associated with glass-fiber reinforced grades, mineral fillers can be added. Although some strength is sacrificed, these grades have shrinkage of 0.5% or less.

A notable disadvantage of thermoplastic polyesters is notch sensitivity and unsuitably for long time hot-water immersion. However, water resistance at room temperature is excellent. Some producers of PBT materials are:

Company	**Product**
Celanese Plastics	Celanex
Eastman Chemical	Tenitre polyterephthalate
General Electric	Valox

A recently developed thermoplastic polyester is a modified polyethylene terephthalate (PET) with the trade name Rynite. Produced by Du Pont, the material (reinforced with glass fibers) provides unusually high temperature resistance, high tensile strength, good stiffness, and high impact strength. Rynite is used in automobile parts, hardware, and consumer goods.

An extensive group of polyesters and alkyd resins with good heat stability can be made from pyromellitic dianhydride, $C_{10}H_2O_6$, a benzene tetracarboxylic dianhydride. It is marketed by Princeton Chemical Research, Inc., as PMDA, a white powder with a melting point of 287°C. It reacts with alcohols, benzene, and other hydrocarbons. It is produced from mellitic acid, $C_{16}(COOH)_6$, which has a melting point of 288°C. It is

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found brown coal, peat, and the mineral mellite, or honeystone, which is hydrous aluminum mellate. Tetrahydrophthalic anhydride is easier to combine with styrene than phthalic or maleic anhydride, and gives coating resins that are flexible and have quicker cure with high gloss.

Urethanes. There are three types of thermoplastic urethanes, a high priced specialty material: polyester-urethane, polyether-urethane, and caproester-urethane. All three are linear polymeric materials, and, therefore, do not have the heat resistance and compression set of the cross-linked urethanes. They are produced in three durometer hardness grades -- 55A, 80A, and 90A. The soft 80A grade is used where high flexibility is required, and the hard grade, 70D, is used for low deflection load bearing applications. Producers of these elastoplatics are:

Company	Product
B. F. Goodrich	Estane
American Cyanamid	Cyanaprene
Mobay Chemical	Texin
Uniroyal	Pellethane
K. J. Quinn	Q-thene
Upjohn	
Hooker Chemical	

9.4.4 Superpolymers. Several plastics developed in recent years that maintain mechanical and chemical integrity above 500°F (260°C) for extended periods are: polyimide, polysulfone, polyphenylene sulfide, polyarylsulfone, novaloc epoxy, and aromatic polyester. In addition to high temperature resistance, they have in common high strength and modulus of elasticity, and excellent resistance to solvents, oils, and corrosive environments. They are also high in cost. A major disadvantage with superpolymers is that they are difficult to process. Molding temperatures and pressures are extremely high compared to conventional plastics. Some of them, including polyimide and aromatic polyester, are not molded conventionally. Because they do not melt, the molding process is more of a sintering operation. These plastics are used mostly in aerospace and nuclear energy fields because of their high cost. One indication of the high temperature resistance of the superpolymers is their glass transition temperature of well over 500°F (260°C), as compared to less than 350°F (177°C) for most conventional plastics.

In the case of polyimides, the glass transition temperature is greater than 800°F (427°C), and the material decomposes rather than softens when heated excessively.

Polysulfone has the highest service temperature of any melt-processable thermoplastic. Its flexural modulus stays above 300,000 lb/in^2 (2,068 MPa) at up to 320°F (160°C). Even at such temperatures it does not discolor or degrade.

Armomatic polyester, a homopolymer also know as polyoxybenzoate, does not melt, but at 800°F (427°C) can be made to flow in a nonviscous manner similar to metals. Thus, filled and unfilled forms and parts can be made by hot sintering, high velocity forging, and plasma spraying. Notable properties are high thermal stability, good strength at 600°F (316°C), high thermal conductivity, good wear resistance, and extra high compressive strength. Aromatic polyesters have also been developed for injection and compression molding. They have long term thermal stability and a strength of 3,000 lb/in.^{2} (20 MPa) at 550°F (288°C).

At room temperature, polyimide is the stiffest of the group with a top modulus of elasticity of 7.5 million lb/in.^{2} (51,675 MPa), followed by polyphenylene sulfide with a modulus of 4.8 million lb/in.^{2} (33,072 MPa). Polyarysulfone has the best impact resistance of the superpolymers with an impact strength of 5 ft"lb/in. (0.27 kg"m/cm) (notch).

Polyetherimide, trade name Ultem, is an amorphous thermoplastic that can be processed with conventional thermoplastic processing equipment. Its continuous use temperature is 340°F (170°C) and its deflection temperature is 400°F (200°C) at 264 lb/in.^{2} (MPa). The polymer also has inherent flame resistance without using additives. This feature, along with its resistance to food stains and cleaning agents, make it suitable for aircraft panels and seat component parts. Tensile strength ranges from 15,000 to 24,000 lb/in.^{2} (103 to 165 MPa). Flexural modulus at room temperature is 48,000 lb/in.^{2} (3,300 MPa).

Polyimide foam is a spongy, lightweight, flame resistant material that resists ignition up to 800°F (427°C) and then only chars and decomposes. Some formulations result in harder materials that can be used as lightweight wallboard or floor panels while retaining fire resistance.

9.4.5 **Industrial Uses of Plastic Materials.** In industry, plastics are used as a construction material above and below ground, at the waterfront both under and above the water under constant and cyclic immersion conditions, and in the air in all types of aircraft. Their use is so endemic that they cover all but the most stringent or extreme Navy requirements. They are used for: utility lines (hot and cold water, sewage) and their hangers, conduit lines, ducting for venting and air handling, valves (gate and ball), insulation (electrical and thermal), coatings, glazing, piling jackets, tanks, tank linings, doors (interior and exterior), electrical housings, bridges, walkways, steps, and hoses (air, fuel, water) just to name a few.

9.4.6 Plastics Summary. The Modem Plastics Encyclopedia provides specifications/materials data that covers the physical and chemical properties of plastics with ASTM test designation. Other references and sources covering specific physical and chemical properties and the recommended uses, applications, and designs of various plastics are given.

These tables are updated yearly and are available from the Modern Plastics Reprint Department in New York. Other tables that address other aspects such as fire retardants and machinery are also available. Subscription cost to Modern Plastics (in 1990) for a Government organization is $38.00 for 1 year and $76.00 for 3 years. The subscription includes monthly issues of Modern Plastics and the yearly Modern Plastics Encyclopedia wherein the tables are printed. The Encyclopedia is an excellent reference source for materials, machinery, and manufacturers.

CHAPTER 10. CATHODIC PROTECTION

10.1 INTRODUCTION. Cathodic protection is second only to the use of protective coatings as a means of corrosion control. It is widely used at Naval Shore Activities for protecting buried and waterfront structures and for protecting the interiors of water storage tanks. In some cases, such as underground pipelines, field experience has shown that cathodic is such an effective means of providing the required levels of safety in the operation of the systems that cathodic protection is required by regulation.

10.2 WHEN CATHODIC PROTECTION SHOULD BE CONSIDERED. Cathodic protection should be considered, possibly in conjunction with other forms of corrosion control, such as protective coatings, wherever the system requiring protection is exposed to an aggressive environment in such a manner that cathodic protection is technically feasible. Cathodic protection is technically feasible when the surfaces to be protected are buried or submerged.

      10.2.1 <u>Structures That Are Commonly Protected.</u> External surfaces of buried metallic structures, surfaces of metal waterfront structures, such as sheet pilings or bearing piles, and the internal surfaces of tanks containing electrolytes, such as water, are applications where cathodic protection is usually technically feasible and cathodic protection is used in protecting such structures. Internal surfaces of small diameter pipelines and other areas where ion flow in the electrolyte is restricted by electrolyte resistance, cathodic protection has limited applicability.

      10.2.2 <u>Determining the Need for Protection.</u> When construction of a new buried or submerged system is being planned, the corrosivity of the environment should be considered as one of the factors in the design of the system. If experience with similar systems in the vicinity of the construction site has shown that the site conditions are aggressive based on leak and failure records, cathodic protection should be considered as a means of controlling corrosion on the new system. Cathodic protection is one of the few methods of corrosion control that can be effectively used to control corrosion of existing buried of submerged metal surfaces. Thus, if leak records on an existing system show that corrosion is occurring, cathodic protection can be applied to stop the corrosion damage from increasing. Cathodic protection can, however, only stop further corrosion from occurring and cannot restore the material already lost due to corrosion.

      10.2.3 <u>When Protection Is Required.</u> In some cases, cathodic protection is required by policy or regulation as discussed in Chapter 2.1 of this manual. Regulations by the Department of Transportation have established standards for transporting certain liquids and compressed gas by pipelines in order to establish minimum levels of safety. These regulations require that these pipelines be protected by cathodic protec-

tion combined with other means of corrosion control, such as protective coatings and electrical insulation. These regulations provide excellent guidelines for the application of cathodic protection to buried and submerged pipelines.

In addition to these regulations, primarily due to the safety and environmental consequences of system failure, there are an increasing number of federal, state and local governmental regulations regarding the storage and transportation of certain materials that require corrosion control. Many of these regulations either specify cathodic protection as a primary means of corrosion control or allow its use as an alternative method of controlling corrosion.

10.3 WHERE CATHODIC PROTECTION IS FEASIBLE. In order to be technically feasible, cathodic protection requires that the structure to be protected be electrically continuous and be immersed in an electrolyte of sufficient volume to allow the distribution of current onto the structure.

10.3.1 Electrical Continuity of Structure. Electrical continuity of the structure to be protected may either be through metallic continuity provided by bolting or welding of the structure. Continuity is often achieved or insured by means of electrical connections installed specifically to insure the effectiveness of cathodic protection. These connections are called "bonds."

10.3.2 Electrolyte. The electrolyte is water or the water contained in moist earth. The conductivity of the electrolyte is an important factor in the design of cathodic protection systems.

10.3.3 Source of Current. Cathodic protection also requires the presence of a source of electrical current at the proper voltage or potential to prevent attack on the structure. These sources of current are called "anodes." As described below, the anodes can either be fabricated from an active metal, such as magnesium or zinc, which provides a high potential source of electrons through corrosion on its surface or from a relatively inert material. This inert material has the ability to pass current from its surface without being consumed at a high rate, but requires using an external energy source to increase the potential of the electrons supplied to the structure being protected. The systems that use active anodes are called "sacrificial" systems as the anode material is sacrificed to protect the structure under protection. The inert anode systems are called "impressed current" systems as the external energy source is used to impress a current onto the structure under protection.

10.4 GUIDANCE FOR DESIGN, INSTALLATION, OPERATION, AND MAINTENANCE. Guidance for the design and installation of cathodic protection systems is available in Military Handbook 1004/10 (Ref 5). Guidance for the operation

and maintenance of cathodic protection systems is available in NAVFAC Maintenance and Operation Manual MO-306 (Ref 6).

10.5 PRINCIPLES OF OPERATION. Understanding the principles of operation of cathodic protection systems is based on understanding the nature of the corrosion process. Corrosion is basically an electrochemical process. That is, it is a process where chemical reactions take place through the exchange of electrons. By preventing the exchange of electrons, cathodic protection systems prevent the corrosion reactions that would otherwise naturally occur.

10.5.1 The Cathodic Protection Cell. Cathodic protection prevents corrosion by making a metal, which would ordinarily behave like an anode and corrode, behave like a cathode and be free from corrosive attack. In cathodic protection this is achieved by providing electrons of a higher energy level (electric potential) than those which would be produced in the corrosion reaction at the anode. This is illustrated in Figure 10-1.

On the right side of Figure 10-1, corrosion is proceeding. Metal atoms are reacting to form metal ions and electrons. The electrons formed have a certain amount of energy as a result of the reaction. The presence of these electrons in the metal give the metal a characteristic electrochemical potential. On the left side of Figure 10-1, the application of a potential that is higher (more negative) than the potential that was produced by the corrosion reaction prevents the flow of electrons in the ordinary - to + direction and the corrosion reaction is prevented. The metal that was formerly a location from which electrons flowed (an anode) has been changed to a location to which electrons flow (a cathode) by the application of a negative charge. Corrosion has been stopped. The potential required for cathodic protection depends on the metal being protected and the environment.
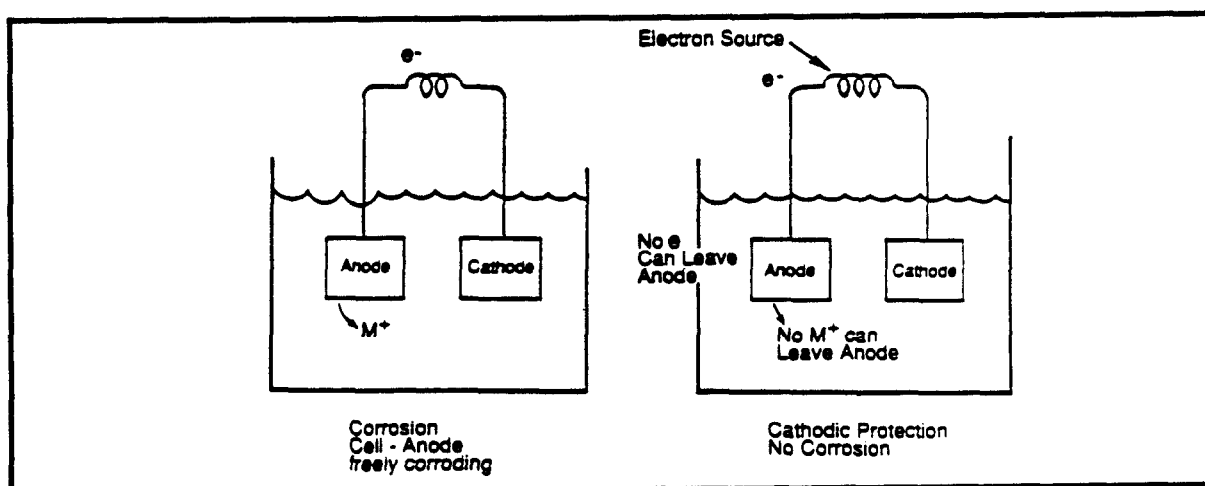
Figure 10-1
Cathodic Protection Cell

10-3

10.5.2 Current and Potential Requirements. In order to achieve these protective potentials, current must flow from the anode to the structure being protected. The amount of current required to protect a given structure is proportional to the area of the structure that is exposed to the electrolyte. Therefore, current requirements are usually given as current densities in units of amperes or milliamperes (0.001 amperes) per square foot of exposed surface. For coated structures the amount of current required is much lower than for bare structures as only those areas on the coated structure where the coating has been damaged or has deteriorated require or will receive current. Many coatings can reduce current requirements by over 90%. The current densities required for cathodic protection depend on the metal being protected and the environment. Values for the current densities required for cathodic protection of bare steel structures is shown in Table 10-1. Values of the current densities required for cathodic protection of coated steel structures is shown in Table 10-2.

Table 10-1
Current Requirements for Cathodic Protection of Bare Steel

Environment	Milliamperes per Square Foot
Soil with resistivity > 10,000 Ohm-cm	2.0 - 3.0
Soil with resistivity 1,000 - 10,000 Ohm-cm	4.0 - 6.0
Soil with resistivity < 1,000 Ohm-cm	7.0 - 25.0
Highly aggressive soil with anaerobic bacteria	15.0 - 40.0
Still Freshwater	2.0 - 4.0
Moving Freshwater	4.0 - 6.0
Turbulent Freshwater	5.0 - 15.0
Hot Freshwater	5.0 - 15.0
Still Seawater	1.0 - 3.0
Moving Seawater	3.0 - 25.0
Concrete	0.5 - 1.5

Table 10-2
Current Requirements for Cathodic Protection of Coated Steel

Structure	Milliamperes Per Square Foot
Pipeline, epoxy or other high performance coating	0.001 - 0.005
Pipeline, reinforced coal tar or asphalt enamel	0.005 - 0.025
Pipeline, grease coating with wrapper	0.05 - 0.150
Pipeline, asphalt mastic 1/2-inch thick	0.001 - 0.005
Pipeline, old asphalt or other deteriorated coating	0.05 - 0.35
Pipeline, old paint coating	0.10 - 0.30
Tank bottoms	0.05 - 2.0
Cold potable water tanks	0.05 - 2.0
Tanks for cold seawater	0.05 - 4.0
Hot potable water tanks	0.30 - 3.0
Steel sheet piling fresh water side	0.10 - 1.5
Steel sheet piling seawater side	0.10 - 2.0
Steel sheet piling soil side	0.05 - 1.0

10.5.3 Sacrificial Versus Impressed Current Systems. The method that is used to supply the required current to the structure being protected depends on the type of cathodic protection system being used: sacrificial anode or impressed current.

10.6 SACRIFICIAL ANODE CATHODIC PROTECTION SYSTEMS. In sacrificial anode systems the high energy electrons required for cathodic protection are supplied by the corrosion of an active metal. This is illustrated in Figure 10-2.
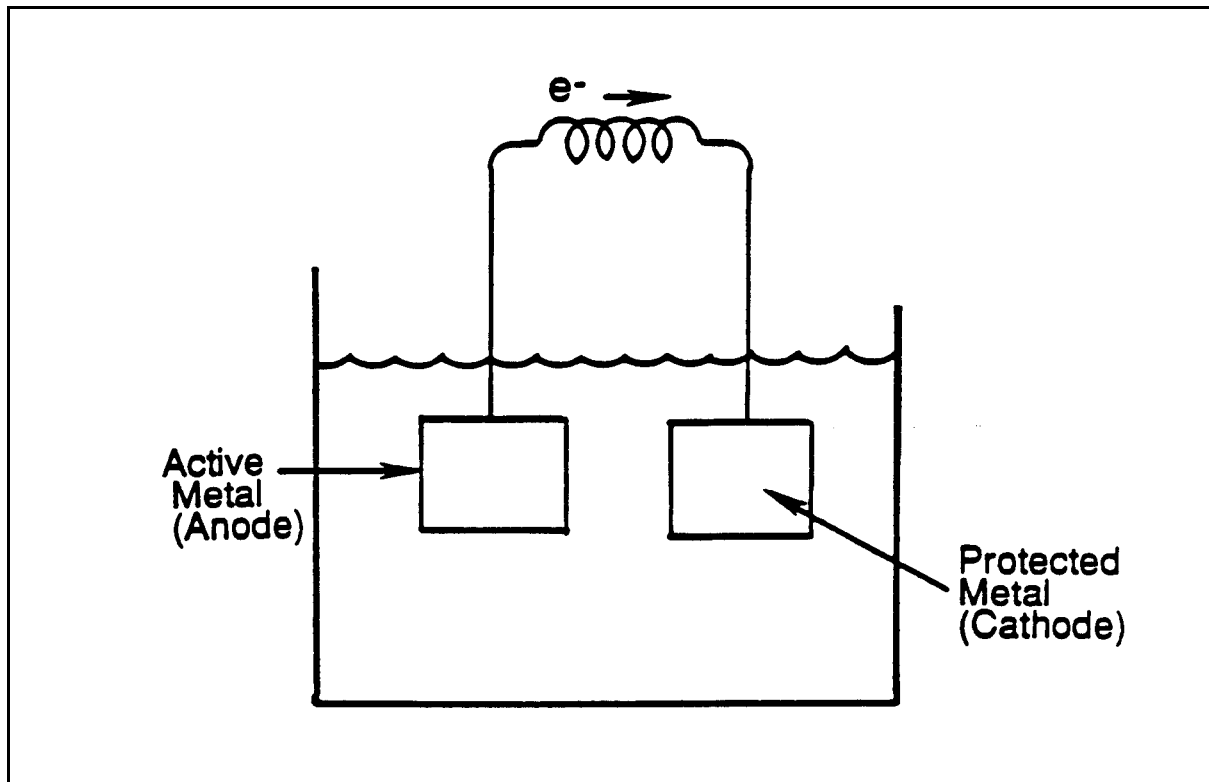
Figure 10-2
Sacrificial Anode Cathodic Protection System

Sacrificial anode systems depend on the differences in corrosion potential that are established by the corrosion reactions that occur on different metals or alloys. For example, the natural corrosion potential of iron is about -0.550 volts in seawater. The natural corrosion potential of zinc in seawater is about -1.2 volts. Thus if the two metals are electrically connected, the corrosion of the zinc becomes a source of negative charge which prevents corrosion of the iron. Sacrificial anode cathodic protection systems are illustrated in Figure 10-3.

The materials used for sacrificial anodes are either relatively pure active metals, such as zinc or magnesium, or are magnesium or aluminum alloys that have been specifically developed for use as sacrificial anodes. In applications where the anodes are buried, a special backfill material surrounds the anode in order to insure that the anode will produce the desired output.

Sacrificial anodes are normally supplied with either lead wires or cast-m straps to facilitate their connection to the structure being protected. The lead wires may be attached to the structure by welding or mechanical connections. These should have a low resistance and should be insulated to prevent increased resistance or damage due to corrosion. When anodes with cast-in straps are used, the straps can either be welded directly to the structure or the straps can be used as locations for attachment using mechanical

10-6
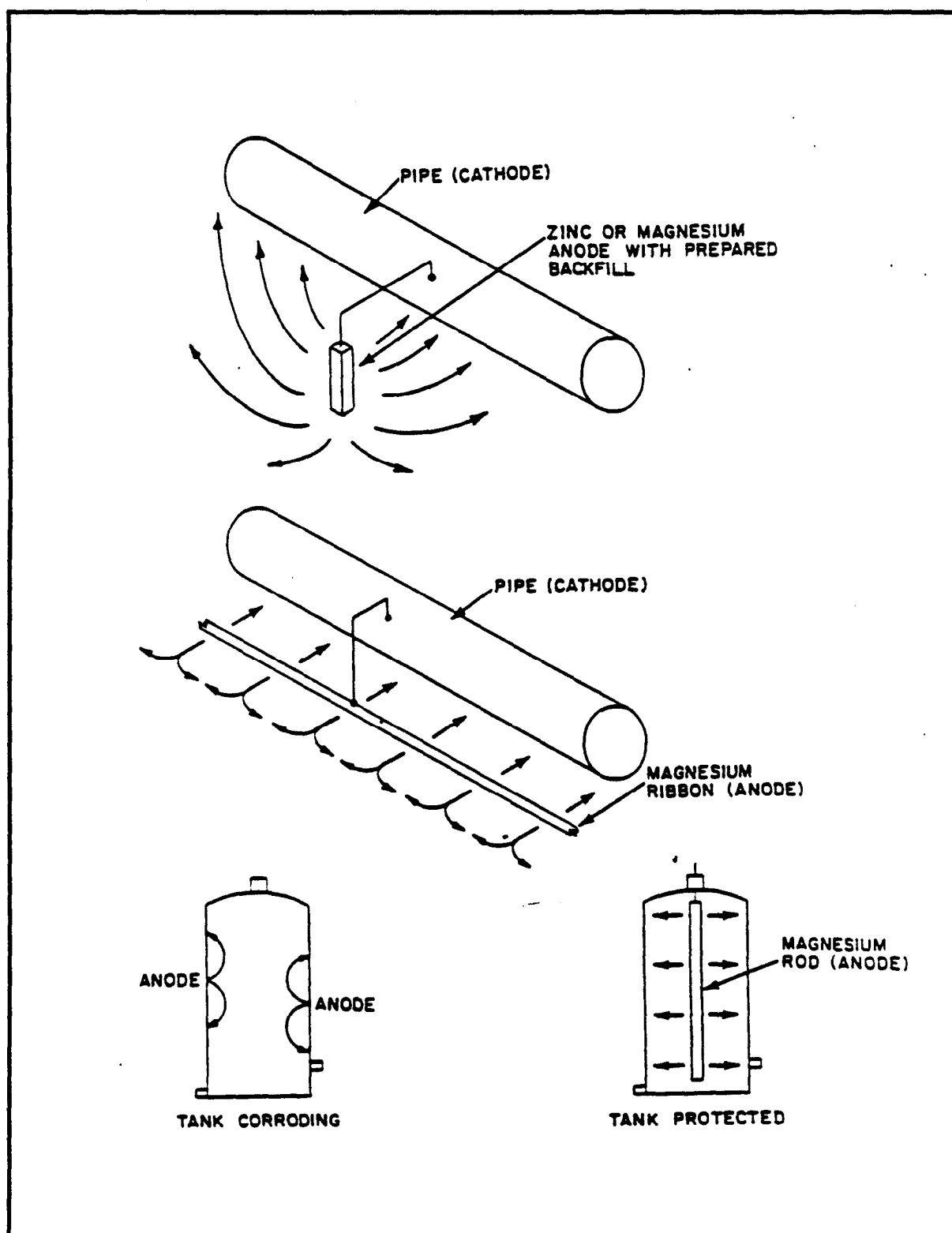
Figure 10-3
Cathodic Protection by the Galvanic Anode Method

fasteners. A low resistance mechanically adequate attachment is required for good protection and resistance to mechanical damage.

In the process of providing electrons for the cathodic protection of a less active metal the more active metal corrodes. The more active metal (anode) is sacrificed to protect the less active metal (cathode). The amount of corrosion depends on the metal being used as an anode but is directly proportional to the amount of current supplied. The anodes in sacrificial anode cathodic protection systems must be periodically inspected and replaced when consumed.

10.7 IMPRESSED CURRENT SYSTEMS. As in sacrificial anode systems, impressed current systems depend on a supply of high energy electrons to stifle anodic reactions on a metal surface. In the case of an impressed current system these high energy electrons are supplied by a rectifier. As shown in Figure 10-4 low energy electrons that are picked up at a non-reactive anode bed are given additional energy by the action of a rectifier to be more energetic than the electrons that would be produced in the corrosion reaction.
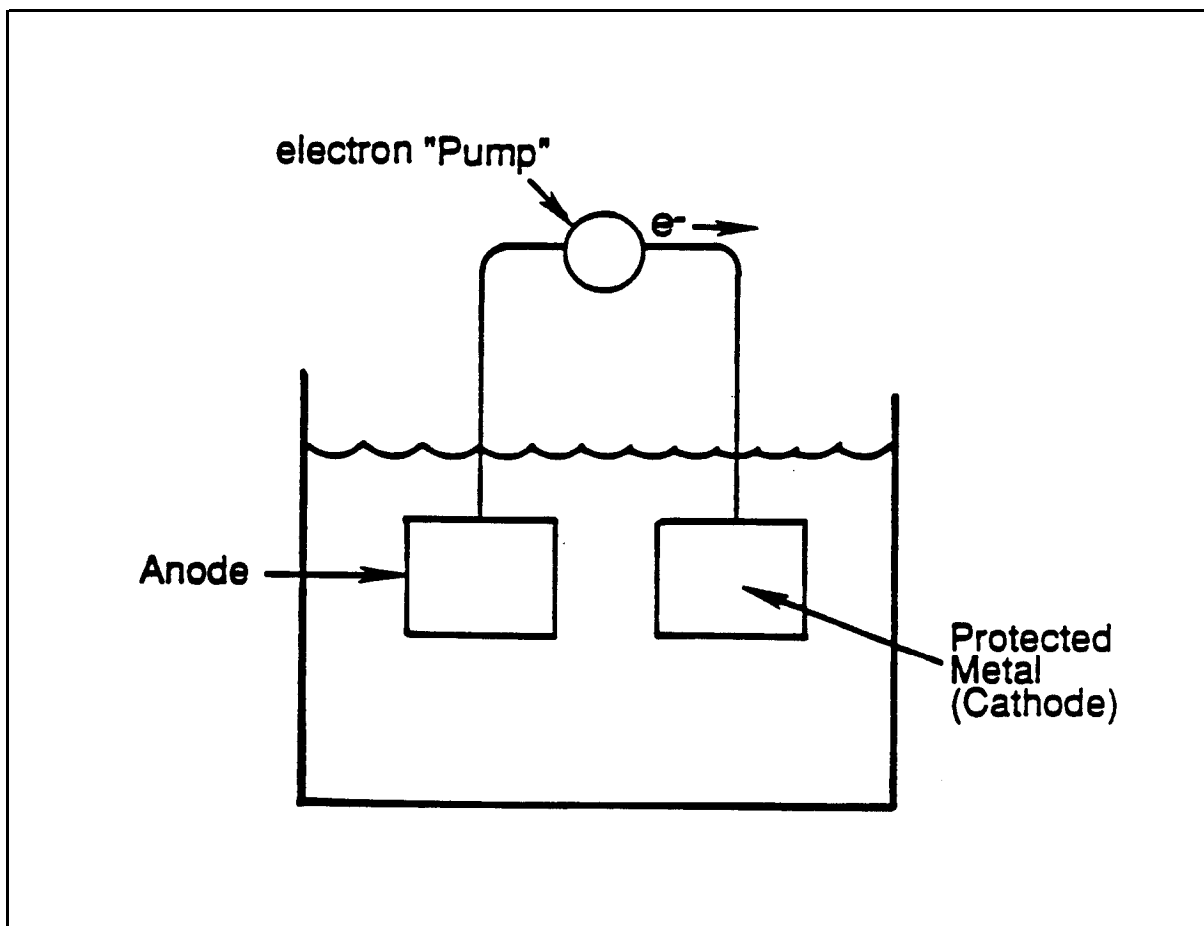
Figure 10-4
Impressed Current System

10-8

The energy for the "electron energy pump" action of the rectifier is provided by ordinary alternating current. The effect of these electrons at the structure being protected is the same as that derived from the sacrificial anode type of cathodic protection system. However, the anode material serves only as a source of electrons and need not be consumed in providing protective current. The materials used for impressed current cathodic protection can the pass a current into the environment without being consumed at a high rate. Graphite and high silicon cast iron are the most commonly used impressed current cathodic protection anode materials, however, other materials (such as magnetite, platinum, and newly developed ceramic materials) have been successfully used. For buried anodes, a backfill of carbonaceous material is used to surround the anode to decrease the electrical resistance of the anode, to provide a uniform, low resistivity environment surrounding the anode and to allow gasses produced at the anode surface to vent.

In practice, materials such as graphite are used for impressed current cathodic protection system anodes that are slowly consumed. Anodes in impressed current systems must be inspected and replaced if consumed or otherwise damaged. As is the case for any electrical equipment, rectifiers used for impressed current cathodic protection systems require preventative maintenance to insure proper operation. An impressed current cathodic protection system is shown in Figure 10-5.
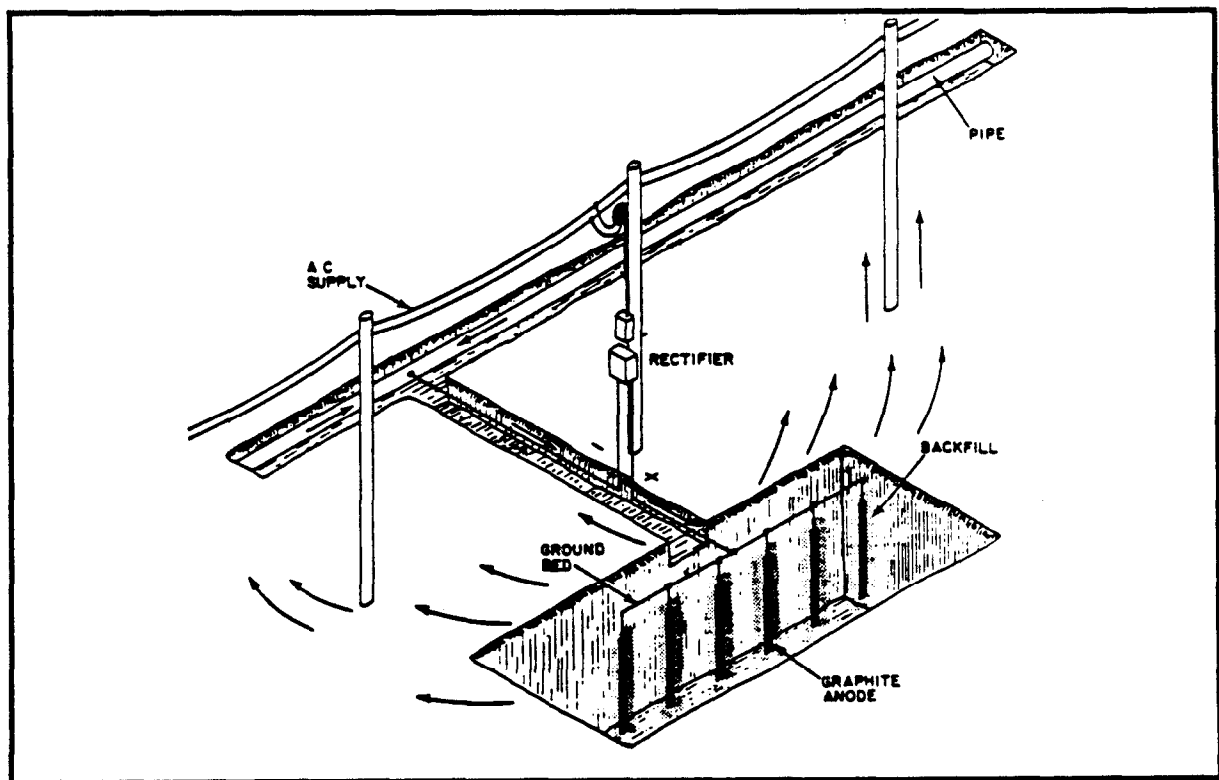
Figure 10-5
Cathodic Protection by the Impressed Current Method

10.8 DESIGN AND INSTALLATION. Methods for designing a cathodic protection system are well developed and are described in MIL-HDBK-1004/10 (Ref 5).

10.9 OPERATION AND MAINTENANCE. In order to effectively provide the increased structural lifetime and reliability intended, cathodic protection systems must be monitored and maintained. Economic considerations made at the time that the cathodic protection was selected as a means of corrosion control should have included the cost of periodic monitoring and maintenance in the analysis.

   10.9.1 Why Periodic Monitoring and Maintenance Are Required. The effectiveness of cathodic protection systems usually change with time. The consumption of both sacrificial and impressed current anodes can result in decreased anode output that results in inadequate protection. Deterioration of cable insulation or connections can result in increased circuit resistance with similar effect. Rectifier output can be reduced by aging of the stacks, or can be completely interrupted by electrical failure. The corrosion environment can change if there is a change in drainage patterns or the area around an anode is paved reducing local soil moisture content. Construction of additional structures or modification to existing structure in the area can interfere with the cathodic protection system.

   In order for a cathodic protection system to be effectively monitored and maintained, the parameters used in the design of the system and the "as built" configuration of the system must be known. "As built" drawings of the cathodic protection system and the structure being protected should be available as well as drawings of other structures in the area that might cause interference problems. The cathodic protection system drawings should include, as a minimum, the location and configuration of all test stations, the location and type of all anodes and rectifiers, and the location of all connections and insulating joints. These drawings should be periodically updated to show any changes made to the cathodic protection system, the structure being protected or nearby structures.

   The desired potentials used in the design of the cathodic protection system should be indicated. In some cases, different criteria can be used to establish minimum protective potentials at different locations of the same structure.

   The design current outputs of the rectifiers or sacrificial anodes in the system should be recorded. These data are most important in the initial system checkout but can also be used to evaluate discrepancies in structure to electrolyte potential readings.

   The initial system settings and potential readings should be recorded. Changes to the system such as rectifier adjustment should be periodically recorded. Potential readings taken both at the time of initial system adjustment and during periodic monitoring should be recorded in order to detect trends in the readings. Changes in potential read-

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ings are often more important than the actual values themselves in determining the cause of improper system operation.

In order that any rectifiers in the system can be properly maintained, adjusted, and repaired, instructions for the rectifiers should be retained. An original copy should be kept in the maintenance files and a copy should be kept within the rectifier enclosure for field reference.

10.9.2 Basic Maintenance Requirements. Basic maintenance requirements are:

Monthly: Take rectifier panel meter and tap setting readings. Record readings on NAVFAC Form 11014-74B.

Quarterly: Take structure to electrolyte potential readings at selected locations (not less than four points per system). Record readings on NAVFAC Form 11014-74A.

Annually: Inspect submerged sacrificial and impressed current anodes for consumption. Inspect test stations for broken wires, loose connections, or other damage.

In addition to the basic requirements listed above, opportunities to inspect buried or otherwise inaccessible structure surfaces should be used to inspect the surfaces for evidence of corrosion or coating deterioration. Such opportunities may be presented by construction or maintenance in the vicinity of the protected structure.

CHAPTER 11. IDENTIFICATION AND CHARACTERIZATION OF CORROSION PROBLEMS

11.1 INTRODUCTION. In order to establish the need for and proper methods for the application of corrosion control to existing structures and equipment, it is necessary to locate the sites where corrosion is occurring or likely to occur and to establish the causes of corrosion. Only after the corrosion problem is located and diagnosed can it be effectively solved.

11.2 CONTROL INSPECTIONS. Maintenance control inspections are the primary means for identifying actual or potential corrosion problems. Visual observations are the primary means of performing maintenance control inspections. Inspectors must be familiar not only with the structures and equipment that they are inspecting but with the corrosion problems experienced in those structures and equipment and with the forms of corrosion that occur. It is important that the maintenance control inspector be able to properly identify and describe the type of corrosion that is detected. Through an understanding of the basics of corrosion control, the maintenance control inspector can also identify factors, such as trapped water or deteriorated protective coatings, that will eventually lead to corrosion damage.

11.3 SPECIALIZED INSPECTIONS. Specialized inspections require skills or equipment over and above that required for maintenance control inspections. Inspection of the underwater portions of waterfront structures, and some of the inspections performed on cathodic protection systems are considered specialized inspections.

  11.3.1 Underwater Inspections. As divers or other means of making visual observations and other tests are required for. the effective inspection of underwater portions of waterfront structures, these inspections require specialized expertise. The Chesapeake Division, Naval Facilities Engineering Command, Fleet Project Office One has been tasked with performing these inspection both in-house and by contract.

  11.3.2 Specialized Inspection of Cathodic Protection Systems. Monthly readings of rectifier settings do not require specialized expertise or equipment and are considered part of the maintenance control inspection. Other measurements such as pipe to soil potentials do require specialized equipment and expertise. The Geographical Engineering Field Division/Engineering Field Activity (EFD/EFA) provides the required training for performing these tests at the activity level or provide a standard scope of work for performing these tests by contract.

11.4 FAILURE ANALYSIS. In order to determine the cause of service failures two basic questions must be addressed: (1) What mechanisms were responsible for the corrosion? (2) What conditions lead to the attack?

11.4.1 <u>Determination of Failure Mechanisms.</u> In order to understand the causes of failures so that they can be avoided, the mechanisms of failures must be established. While the tests needed to identify and verify specific failure mechanisms must be selected depending on the mechanisms suspected, most metal failure analyses rely heavily on visual observation and metallurgical and chemical analyses. All of these require substantial skill and training in order to establish the causes for failure. However, field personnel often play an important part in establishing the conditions that lead to the failure, documenting the conditions of the failed components immediately after failure, selecting proper treatment and preservation of the failed components, and identifying other potential evidence, such as corrosion products.

11.4.1.1 Visual Examination. The visual appearance of failures is often one of the most important factors in evaluating the failure and in determining the need for further tests. In marine exposures, seeing the surfaces is made more difficult by possible damage to the features of interest by corrosion, mechanical damage during retrieval from remote sites, contamination of surfaces, and, as often occurs, loss of the damaged components or portions of them Assuming that the components of interest are retrieved, it is important that the information that they contain be preserved. If the components can not be inspected immediately, the surfaces should be photographed to show all details of potential interest. Close-ups color photographs with shallow angle lighting best records the features of interest.

Methods for preserving the surfaces depends on the specific materials involved, but rinsing in freshwater and drying in warm air are usually sufficient to preserve the surfaces. The components should then be stored in dry air until a more detailed examination is performed. Ultrasonic cleaning using a mild detergent solution followed by a freshwater rinse and drying in warm air is also effective. For some alloys (such as steel) that corrode freely in air, the surfaces can be rinsed in freshwater, dried, and then coated with a light oil if dry storage is not available.

The composition of corrosion products is often a clue as to the mechanisms responsible for corrosion. Corrosion product samples should be carefully removed, treated, and analyzed in accordance with the methods specified in the National Association of Corrosion Engineers Recommended Practice RP-01-73 "Collection and Identification of Corrosion Products" (Ref 7).

11.4.1.2 Service Environment. Determining the service environment is often difficult. In some cases, such as atmospheric corrosion, time of wetness, surface contamination, and temperature are important but can vary considerably with time. Exposure to a uniform non-changing environment is often rather benign in that corrosion product films that form under these conditions after an initial period of rapid attack of the clean surface can provide substantial protection from corrosion. However, when the conditions of exposure change, these films may not be stable and can quickly break

down exposing the metal to a new environment in an unprotected condition. In the new condition, initial rapid corrosion of the clean surface can result on the formation of a new protective layer. If the sequence is repeated, the attack experienced can be more severe in the alternating exposure than an equivalent exposure in either of the environments.

In other cases, extreme conditions can be responsible for the breakdown of passive films or other initiation of corrosion attack which can then proceed under the more average conditions experienced. This often occurs when elevated temperatures are occasionally experienced or when salts concentrate by evaporation.

Immersion Service. Service under immersion conditions assumes that an uncorroded material is fully exposed to a liquid environment during its entire service life and that, when removed from immersion is quickly treated to arrest any corrosion that can occur.

a. Temperature. In general, corrosion rates increase with increasing temperature. In seawater, this increase is much less than the doubling of reaction rates with each 18°F rise in temperature that would be expected if the reactions were under diffusion control as are many other chemical reactions. For many materials, such as steels, where the oxygen content of the water directly affects the corrosion rate, the effect of temperature is minimal as in situations where the corrosion rate would be increased by increased temperature, the solubility of oxygen is decreased with increasing temperatures and the two effects counteract each other. Steels and copper alloys are particularly insensitive to temperature effects in normal marine immersion.

For other alloys that depend on a passive film for their corrosion resistance, the effects of temperature can be more pronounced. At elevated temperatures the solubility oxygen required for repairing protective oxide films found on many passive materials is reduced and the reactions that cause the films to break down are enhanced by the increased temperatures. Many stainless steels have what is essentially a "critical pitting temperature" in seawater that is in the range of temperatures experienced in natural seawater. In cold waters they do not pit but in warmer waters they are susceptible.

b. Chemical Composition. In some cases, the chemical composition of a given environment for immersion service is fairly stable and a complete laboratory analysis of a single sample can establish the environment responsible for corrosion. In other cases, the environment varies considerably with time or location in the system and multiple samples must be taken and analyzed.

c. Dissolved Gasses. The content of dissolved gasses, particularly oxygen is often an important factor in corrosion in immersion service. Samples for determining

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dissolved gasses must be taken on site using special techniques. Analysis of a liquid sample for dissolved gasses will often give very misleading results unless the sample is properly taken and handled.

      d. pH. pH is a measurement of the acidic or alkaline nature of a solution. Strictly speaking it is the negative logarithm of the hydrogen ion concentration. In acidic solutions the pH is low and can be less than one in highly acidic solutions. Neutral solutions have a pH of 7.0. Alkaline solutions have a pH greater than 7 and the pH of a strongly alkaline solution can approach 14. pH solutions can be effectively measured using either a special pH meter or special papers that change color.

      e. Pollutants. Pollutants can have both direct and indirect affects on the corrosion of metals. Acid or alkaline pollutants from industrial plants can have an adverse effect on the performance of many materials. Heavy metal ions can dramatically affect the performance of many metals. Aluminum alloys are particularly susceptible to increased corrosion from small amounts of dissolved metal ions such as copper. Pollution can also have an indirect affect on corrosion by affecting the biological activity that controls the oxygen content in many seawater environments. In some cases, the oxygen content can fall to zero and aggressive hydrogen sulfide can form. Polluted environments are often unique both to the environment at a specific site but over time at a particular site. Pollution effects are sometimes seasonal.

      Atmospheric Service. Atmospheric exposure is considered to be a continuous exposure to air without liquid immersion. Sea spray contamination and rain are considered part of atmospheric exposure.

      a. Relative Humidity. Corrosion can normally occur at perceptible rates on surfaces where there is actually free moisture. Moist air where no moisture is present on the surface is usually insufficient for corrosion to occur. Materials on the surface of metals such as corrosion products and salt deposits can be hydroscopic and can absorb sufficient amounts of water from moist air to allow corrosion to proceed. The relative humidity of the environment affects the ability of such layers to provide sufficient moisture on the surface for corrosion to proceed and also affects the time required for the surfaces to dry after being wet by rain, dew, or spray. In general, corrosion is more severe in humid environments than in dry environments. In order to arrest corrosion on equipment by storing in a dry atmosphere, the relative humidity must be reduced to below 50% with 35% being necessary to completely arrest corrosion on some materials. When hydroscopic materials are on the metal surface, these must be removed before dehumidified storage will be effective unless very low humidities can be achieved. Sea salts are particularly hydroscopic and must be removed in order to prevent rapid atmospheric attack. Unless removed, the sea salts will effectively concentrate when dried and, unless very low humidities are achieved, will cause accelerated attack on many metals.

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b. Temperature. The temperature of the environment can have an effect on corrosion, but the effect of temperature is usually combined with the effect of relative humidity. Warm, moist environments are most corrosive. In environments with lower relative humidity, the effect of elevated temperatures can reduce the time of wetness and the severity of corrosive attack. There is little attack on metals below the freezing point.

c. Salt. The amount of salt that accumulates on surfaces exposed to marine environments varies considerably. In general, in environments where more salt accumulates and where the salt that accumulates remains on the surface for longer periods without being washed off, corrosion will be more severe. In some cases, little salt accumulates at sites within a few feet of the sea. However, at other sites, prevalent onshore winds can carry salts several miles inland. At a site near the ocean, unless it has been shown otherwise, sufficient salt accumulation to make the site more corrosive than in uncontaminated environments must be assumed. The amount of time that salt remains on the surface is determined by the rainfall to wash the surfaces free of salt. Atmospheric corrosion is usually characterized as rural, marine, industrial and industrial marine in order of increasing corrosion.

d. Pollutants. Atmospheric pollution, particularly from heavy industry which produces acid fumes, can make an atmosphere particularly corrosive. This effect is particularly severe when the effects of pollution and salt accumulation are both present.

e. Precipitation. Not only is the amount of rain an important factor, the frequency of rain and prevailing wind are also important factors. Frequent rains followed by prolonged periods of high humidity lead to long periods where surfaces are wet with high attendant corrosion rates. In some cases when rain occurs during periods of onshore winds, and onshore winds are infrequent when rains do not follow, salt that is carried to the site is rapidly washed off and little salt accumulates. This can make a site near the sea more like a rural than a marine exposure.

Alternate Immersion. The effect of alternate immersion can often be more severe than exposure under either immersion or atmospheric conditions alone. As in the case of other variations in environment, this can cause protective films that form in one environment to break down and be exposed to conditions that can cause rapid attack of the unprotected surface. In addition, salts that accumulate during immersion can concentrate during subsequent atmospheric exposure unless completely removed. In the atmosphere, accumulations of fouling organisms usually die and this can form hydrogen sulfide and other corrosive gasses on the metal and result in accelerated attack. Tidal type immersion where portions of the surface are completely immersed and other portions alternately immersed can be particularly aggressive. The high availability of oxygen in the zone of alternate immersion can make these areas

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cathodic to the continuously submerged area with oxygen concentration cell attack occurring in the submerged area.

In other cases, alternate immersion can be less severe than continuous immersion. This is true for metals that depend on the availability of oxygen for the maintenance of protective films on their surface. When exposed to alternate immersion, particularly when well rinsed after immersion, many of the stainless steels that show poor performance in long-term immersion can give good service. In some cases, the time to initiation of corrosion can be very long, up to 2 or 3 years for some alloys, and cleaning and atmospheric exposure can effectively restart the time to initiation. Thus, under conditions of alternate immersion with rinsing, a given material could withstand 20 years of alternate 6-month immersion when it would show severe attack after 1 year of continuous immersion.

First Exposure. In many cases the environment to which a metal is exposed is important in its subsequent performance. This is particularly true where materials that are dependent on a protective film for their corrosion resistance are concerned. If a stainless steel is exposed to a very aggressive environment, its protective film can be damaged and reduce corrosion resistance. In some configurations where water will penetrate into crevices, it is best to first expose the equipment to freshwater. Subsequent marine immersion may eventually allow salt to penetrate the crevice area but freshwater can increase the stability of passive films in the crevice and will certainly reduce the time the surfaces in the crevice are exposed to full strength seawater.

Mechanical Factors. In addition to the chemical nature of the environment, there are many other factors that can affect both the severity of corrosion and the impact of the corrosion damage on the function of the equipment.

a. Structural Versus Dynamic Applications. Structures are often designed based on resistance to deformation rather than resistance to collapse. Localized corrosion often has a minimal effect on the stiffness of many structures and surprisingly large amounts of corrosion can be tolerated before structural failure. In other cases, the stiffness of a structure more depends on its shape to resist buckling forces. Considerable localized and general attack can be tolerated without reducing structural strength. Such structures are also often overdesigned and, if failure does occur in one member, stresses are transferred to other members and collapse is avoided. Under dynamic loadings and in many mechanical applications, small amounts of corrosion can have a large affect on function. Small amounts of corrosion in bearings or seals can have a disastrous effect. Small pits on cyclically loaded parts can serve as fatigue enhancing stress raisers. In assessing the potential effect of corrosion on function, the consequences of corrosion in specific locations must be carefully evaluated. Mechanical functions often have little redundancy and a single point of failure can result in the failure of an entire system or mission.

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b. Stress. Areas of high stress are not only more likely to fail if corroded, but corrosion in more likely to occur in such an area. Situations where the effect of stress has established a type of concentration cell where the high energy of the highly stressed areas has established a corrosion cell have been suspected but not well documented. High stress, however, often cracks the protective coatings and can also rupture naturally occurring passive films. High strength materials also are commonly used in areas of high stress and are subject to both gross corrosion and environmental cracking.

c. Wear. As described in the section on fretting corrosion, the combined effect of corrosion and wear can be catastrophic. In such cases, materials that are effectively immune to attack are often used.

d. Fluid Flow. As described in the sections on erosion corrosion and cavitation, high velocity fluid flow can adversely affect many materials. Aluminum alloys are particularly susceptible to velocity attack. Steels are somewhat susceptible even at low velocities. At high velocities, copper alloys are used but most of these have a limiting flow velocity that must not be exceeded. If flow is continuous, stainless steels have a good resistance to velocity effects but if the flow is interrupted, they have poor resistance to stagnant conditions. The corrosion that began under stagnant conditions can propagate rapidly even under subsequent flow conditions. Corrosion resistant nickel base alloys and titanium alloys have excellent resistance at high velocities, but can also be affected when the velocities are extreme (in excess of 25 fps).

Velocity. High velocities should be avoided whenever possible. In hydraulic systems where high velocities cannot be avoided, the effect of velocity on corrosion must be carefully assessed. At velocities up to 10 fps 90-10 copper nickel has been widely used with success. At velocities above 10 fps, stainless steels can be used if the flow is never less than 5 fps. If both high velocity (10 fps) and low velocity (fps) flow is anticipated, recommend titanium or Inconel 625 be used. Several recently developed duplex and "super austenitic" stainless steels have been widely used in heat exchanger applications, primarily in power plants and in offshore oil production. Their performance has been good but some failures have occurred. Their performance under extended low flow conditions remains questionable.

Turbulence. Turbulence causing features in hydraulic systems should be avoided for not only corrosion considerations but from the standpoint of power or pumping requirements. Such features as those described in the sections on erosion and cavitation corrosion should be avoided in the design of seawater containing hydraulic systems.

11.4.1.3 Material Composition. Like all man made materials, the composition of metals and alloys are subject to variability. In most cases, variability within the limits established by the manufacturer will not have an effect on the proper-

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ties of the materials that are critical in the application for which they are commonly used. Variations of composition within normal manufacturers limits can affect a critical performance characteristic of the material. It is vital that the material specifications used are indeed specific. Using industrial standards, such as American Society for Testing and Materials (ASTM) standards or Copper Development Association (CDA) alloy composition standards, is highly recommended. Proprietary materials procured by trade name from the original manufacturer or from authorized distributors are usually satisfactory. The specification and procurement of materials by common name such as "red brass," "mild steel," or "CRES," should be avoided. Proper quality control, certification, marking, and testing are necessary in order to insure that proper materials are used. All personnel involved must be sensitized to the fact that using improper materials can cause failures even though their intentions are to use a material that is "just as good as" or "better than" the material specified. When a material has a characteristic property, such as the non-magnetic character of stainless steel or the color of some of the copper alloys, this can often be used to identify material substitutions. In critical applications, non-destructive tests, such as chemical spot tests or X-ray spectrometry, can be used in a 100% inspection of final components to insure that the proper materials have been used.

Composition Limits. Although it is common to report alloy composition as "nominal" or "typical" or to report the actual analysis of a specific sample or heat of material, manufacturers or standardization organizations have established composition limits for most alloys. In most cases, all materials with compositions within these limits will give similar performances. In some cases, however, special composition limits have been identified for marine service and, when necessary, materials meeting these special limits must be obtained. For example, nickel aluminum bronze is used for marine castings, but in order to give a satisfactory performance, it is important that the nickel content exceeds the iron content in the material, otherwise, pitting corrosion is likely to occur. The composition limits for nickel in this alloy are 4 to 5% and the composition limits for iron are 3.5 to 4.5%, thus a casting within the normal composition limits can have the undesirable situation where the iron content exceeds the nickel content by up to 0.5%, which can be significant.

Variability. There can also be considerable variability in alloy composition from different domestic or foreign manufacturers. In very critical applications, mill certifications are required. Receipt analysis is sometimes used to verify that proper raw materials have been supplied before expensive fabrication or catastrophic failure occurs.

Material Quality. In some cases, several grades of material are available based on the level of defects that they contain. Often, rather than manufacturing the materials to more stringent specifications, a single batch of material is simply inspected and sorted according to its quality. In critical applications, special grades of material

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may be required and, when specified, it must be insured that materials conforming to the requirements are actually used.

Material Condition. Material properties, especially corrosion resistance, strength, and toughness are sensitive not only to material composition but other metallurgical factors. When designing equipment it is vital that these factors be considered when selecting materials and in their fabrication and use.

a. <u>Heat Treatment.</u> Heat treatment can dramatically affect many material properties. It is vital that the proper heat treatment be specified and used. This is true for all alloy systems. Aluminum alloys and stainless steels are particularly susceptible to variations in corrosion properties with heat treatment. Carbon and alloy steels are primarily susceptible to variations in mechanical properties in different heat treated conditions. In some cases, the material must be in a specific initial condition before subsequent heat treatment can be successfully performed. When this is required, the initial condition must be verified either by certification or by metallurgical examination. Hardness testing can confirm the heat treatment. However, in some cases, particularly in aluminum alloys and stainless steels, more than one heat treatment sequence can result in a given material hardness but with significant differences in other properties, such as toughness or corrosion resistance. It is often necessary to obtain specific heat treatment validations from the manufacturer or heat treater and to verify the heat treatment by mechanical tests, metallurgical examination, or both.

b. <u>Cold Work</u>. Cold work is often used to increase the strength of materials. Aluminum alloys are particularly susceptible to variations in corrosion properties with cold work. Almost any alloy will be more susceptible to damage by corrosion when it is hard worked, not because corrosion is necessarily greater, but in high stress applications, the impact of attack on the function of the highly stressed component is increased.

c. <u>Welding</u>. Joining by welding is highly desirable as it can produce mechanically sound and leak tight joints that exclude seawater from the interior of the joints. However, welding is a complex metallurgical process. In the weld pool, alloys are produced in few seconds from a mixture of the filler metal and base metal and are contaminated by the weld slag or shielding gas. Unlike the manufacture of the base alloy, there is not enough time for adjusting the composition of this molten metal before it solidifies and there is usually no post solidification chemical analysis. In addition, the base material adjacent to the weld is heat treated to varying degrees. Developing welding procedures that produce welded structures with appropriate strength, toughness, and corrosion properties is often one of the most difficult steps in the development of an alloy. As in the case of heat treatment, aluminum alloys and stainless steels are susceptible to variations in corrosion properties when welded and the mechanical properties of steels are sensitive to welding effects. If a welded component has been used with success or tests of welded materials are the basis for design, it is important that identical

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welding materials and processes be used. In addition, when manual welding is used, the welder's is critical. The welder must be qualified to perform the specific welding procedure being used and on the specific material being welded. In addition, the welder should be periodically re-certified. In many applications, non-destructive testing, such as magnetic particle inspection; radiography; and ultrasonic testing, are used in the quality control of welded components. In some critical applications, random samples of welded components are destructively tested to assure weld quality.

   d. Form. Some materials are difficult to manufacture in some forms. This affects their availability. While carbon and alloy steels are manufactured in bars, plates, sheets, forgings, and rolled products; many materials are not as widely available in some forms and some may be incompatible with manufacture in certain forms. For example, many aluminum alloys are normally only produced as sheets or plates. While some of these alloys can easily be made into extrusions, limited demand for specific shapes may require that large amounts of material be ordered at one time in order to make a special manufacturing run economical.

In some cases, again particularly in the case of aluminum alloys, variations in product form can affect corrosion resistance as well as other material properties. As an example, a plate of aluminum alloy 5086 suffered pitting of up to 0.020 inch in 1 year of immersion in seawater. An extruded angle of the same material, within composition limits, was pitted only to a depth of 0.001 inch.

  11.4.2 Causes of Service Failures. It is important to realize that there is a difference between the mechanism by which a failure occurs and the cause of failure.

   11.4.2.1 Causes Versus Mechanisms. The cause of a failure is a description of the conditions that lead to the failure. The mechanism of failure describes the mode of failure rather than the conditions that lead to the failure. For example, a stainless steel part may fail due to crevice corrosion when the cause of failure was substituting an improper grade of stainless steel, improper assembly, or failure of a protective coating.

   11.4.2.2 Design Related Failures. Causes of failures often relate more closely to features of design rather than the properties of the materials used. As described in the sections on specific forms of corrosion, design features that create such features as crevices, high stresses, and high velocity turbulent flow can be important factors leading to corrosion failures. The sensitivity of equipment to failure by corrosion attack is also primarily a function of design.

   11.4.2.3 Material Related Failures. Some failures are caused by the actual material deficiencies. A material sometimes does not perform as it was expected to based on its anticipated properties.

Material Selection. In some cases, material related failure is simply an indication of selecting the wrong materials. This is often due to the lack of consideration of the effect of some important service factor in the design and selecting a material that is unsuitable under the actual service conditions. Corrosion is often one of the factors that is not properly included in the overall design process.

Faulty Material. In some cases, material defects can result in service failures. All materials contain discontinuities or defects. Only when these defects are more significant than is common in the material or are more significant than a specified defect level are they referred to as flaws. In some cases, defects are also introduced during fabrication. Improper welding and heat treatment are common ways that defects are introduced during fabrication. Surface contamination from corrosion damage is also possible and should be avoided when necessary, particularly on aluminum alloys and stainless steels. Remember, however, that no engineering material is perfect and all will contain defects. The actual cause of a given failure should not be attributed to a failure that initiates at a defect if that defect is the size and type that should be anticipated in the specified material. Only when the defects are more significant than those that are commonly present can they be considered a flaw.

Wrong Material. In too many cases, failures are caused simply caused by using the wrong material.

11.4.2.4 Manufacturing Related Failures. Some failures are caused, not by deficiencies in the materials used, but improper fabrication practices. Many manufacturing processes can, if improperly performed, affect the properties of a material as much or more than its composition. Special analytical techniques are often required to determine if failures are due to manufacturing problems.

Heat Treatment. When heat treatment is required for the development of required material properties, improper heat treatment can result in failure. In some cases, hardness testing is sufficient to confirm the heat treatment but in other cases, microscopic examination or mechanical testing is required to verify the heat treatment that the material has received.

Welding. Welding is also a critical process and improper welding techniques can lead to failure. However, many welds are susceptible to failure than the base material. Failure may occur in the welds even though the welding was properly done. In these cases, the failure occurred in the weld but the actual cause of failure is not an improper weld but is due to some other factor.

Machining. Improper machining can lead to failure in several ways. For example, improper tolerances can lead to high assembly stresses; improper surface finishes can lead to accelerated wear of bearing surfaces; and improper clearances can

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cause seals to leak. It is often difficult to establish machining problems as a cause of failure due to service wear, corrosion, or deformations that have occurred as a result of the failure through an analysis of the actual failed part. Analyzing similar parts either from service or from spares can sometimes be used to identify machining problems.

11.4.2.5 Protective Coatings. Coating failure can be due either to using the wrong coatings, improper application of the coating, or improper surface preparation. Chemical analysis of the coating can be used to verify that the proper coating was used. Several tests can be used to measure coating thickness, but in failure analysis, using Tooke gauge can not only identify the overall thickness of the coating but can identify the thickness of each of the individual coats that were applied. Surface preparation is often difficult to establish as a cause of coating failure but, in some cases, adhesion tests or examining surfaces from which sound coating has been chemically removed can identify improper surface preparation.

11.4.2.6 Assembly Errors. In some cases, failure is due to assembly errors: improper tightening of bolts, improper tensioning of cables, or using incorrect parts, such as improperly sized O-rings. Careful part-by-part disassembly and inspection of failed assemblies is an important part of any failure analysis.

11.4.2.7 Service Related Failures. In some cases, failures are due primarily to the environment that was encountered rather than any material or manufacturing problem.

Mechanical Overload. Overload is a common cause of service failure. This type of failure is one of the most difficult causes of failure to properly analyze as the loads that caused the failure are not often measured during service and disappear on failure. Mechanical deformations of associated equipment can sometimes be used to evaluate the loads that were encountered at the time of failure. Analysis of the operation just before and at the time of failure can also identify loading conditions. It is often the direction in which loads are applied rather than their magnitude that causes overload failures to occur.

Improper Use. Improper use is often one of the most difficult causes of failure to establish. It is usually difficult to obtain impartial descriptions of the situations leading to this type of failure.

Improper Maintenance or Repair. Maintenance and repair are often inadequate or improper. The condition of equipment at the time of failure is usually easy to establish. Reviewing maintenance requirements and records can determine whether the maintenance required was performed or whether the maintenance requirements were inadequate.

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CHAPTER 12. REFERENCES AND BIBLIOGRAPHY

12.1 REFERENCES.

1. Office of Federal Register. CFR Title 49, Chapter 1, Part 192, Subpart 1, Washington, DC.

2. Office of Federal Register. CFR Title 49, Chapter 1, Part 195, Washington DC.

3. Naval Facilities Engineering Command. P-442: Economic Analysis Handbook. Alexandria, VA, Jun 1986.

4. Naval Facilities Engineering Command, Pacific Division. DM-11.1: Tropical Engineering, Mar 1980.

5. Department of Defense. Military Handbook 1004/10: Electrical Engineering Cathodic Protection, 31 Jan 1990.

6. Naval Facilities Engineering Command. MO-306: Corrosion Prevention and Control, June 1964.

7. National Association Corrosion Engineers. Recommended Practice RP-01-73: Collection and Identification of Corrosion Products.

12.2 BIBLIOGRAPHY.

American Society of Testing and Machines International. Composites, Engineered Materials Handbook, Vol I, 1987.

G. S. Brady and H. R. Clauser. Materials Handbook, 12th Edition. McGraw-Hill Book Co., 1986.

Federal Highway Administration, Department of Transportation. FHWA-TS-79-203: Structural Plastics Design Manual, Phase 1, Chapters 1-4.

Federal Highway Administration, Department of Transportation. FHWA-TS-82-216: Structural Plastics Design Manual, Phases 1 and 2, Chapters 5-10.

M. Grayson. Encyclopedia of Composite and Components, John Wiley & Sons, 1983.

G. Lubin. Handbook of Composites, Van Nostrand Reinhold Co., 1982.

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Modern Plastics. Modem Plastics Encyclopedia. Hightstown, NJ, 1989.

Appendix A

ECONOMIC LIFE GUIDELINES*

To provide a basis for comparison between competing projects, economic lives are established for the general investment classifications listed below. These guidelines can be used in the absence of better information. However, due to the constraints of mission life and technological life, the economic life chosen should not exceed the applicable figure below.

1.	ADP Equipment	8 years
2.	Buildings	
	a. Permanent	25 years
	b. Semi-permanent, non-wood	25 years
	c. Semi-permanent, wood	20 years
	d. Temporary or rehabilitated	15 years
3.	Operating Equipment	25 years
4.	Utilities, Plants, and Utility Distribution Systems	25 years

(This category includes investment projects for electricity, water, gas, telephone, and similar utilities.)

5.	Energy Conserving Assets	
	a. Insulation, solar screens, heat recovery systems, and solar energy installations	25 years
	b. Energy monitoring and control systems	15 years
	c. Controls (e.g., thermostats, limit switches, automatic ignition devices, clocks, photocells, flow controls, temperature sensors, etc.)	15 years
	d. Refrigeration compressors	15 years

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*Source: Economic Analysis Handbook, NAVFAC P-442, June 1986.

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Appendix B

PROJECT YEAR DISCOUNT FACTORS*

Table A

Table B

PRESENT VALUE OF $1 (Single Amount -- to be used when cash flows accrue in varying amounts each year)

PRESENT VALUE of $1 (Cumulative Uniform Series -- to be used when cash flows accrue in the same amount each year)

Project Year	10%	10%
1	0.909	0.909
2	0.826	1.736
3	0.751	2.487
4	0.683	3.170
5	0.621	3.791
6	0.564	4.355
7	0.513	4.868
8	0.467	5.335
9	0.424	5.759
10	0.386	6.145
11	0.350	6.495
12	0.319	6.814
13	0.290	7.103
14	0.263	7.367
15	0.239	7.606
16	0.218	7.824
17	0.198	8.022
18	0.180	8.201
19	0.164	8.365
20	0.149	8.514
21	0.135	8.649
22	0.123	8.772
23	0.112	8.883
24	0.102	8.985
25	0.092	9.077

NOTE: Table A factors are based on continuous compounding at a 10% effective annual discount rate, assuming uniform cash flows throughout state 1-year periods. Table A factors are approximated by an arithmetic average of beginning and end of year single amount factors found in standard present value tables. Table B factors represent the cumulative sum of Table A factors through any given project year. Formulae for these factors are provided in Appendix C.

*Source: Economic Analysis Handbook, NAVFAC P-442 of June 1986.

Appendix C

PRESENT VALUE FORMULAE*

Project Year 10% Discount Factors

Table A Single Amount Factor:

$$a_n = \frac{1}{(1 + R)^n}$$

Table B Cumulative Uniform Series Factor:

$$b_n = \frac{(1 + R)^n - 1}{R(1 + R)^n}$$

where: n = number of years
R = 0.10, effective annual discount rate.

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*Economic Analysis Handbook, NAVFAC, P-442, June 1986.

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