ERDC/CERL TR-02-5

US Army Corps
of Engineers®
Engineer Research and
Development Center

Materials Selection Guide for Army Installations Exposed to Severely Corrosive Environments

J.R. Myers, Ashok Kumar, and L.D. Stephenson

March 2002

Construction Engineering
Research Laboratory

20020507 113

Approved for public release; distribution is unlimited.

ERDC/CERL TR-02-5

US Army Corps
of Engineers®
Engineer Research and
Development Center

Materials Selection Guide for Army Installations Exposed to Severely Corrosive Environments

J.R. Myers, Ashok Kumar, and L.D. Stephenson

March 2002

Construction Engineering
Research Laboratory

Foreword

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit CF-C20, "Corrosion Control Selection System." The technical monitor was Joseph P. Hartman, CECW-EI.

The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Dr. Ashok Kumar. The technical editor was Gordon L. Cohen, Information Technology Laboratory – Champaign. Martin J. Savoie is Chief, CEERD-CF-M, and L. Michael Golish is Chief, CEERD-CF. The Technical Director of the Facility Acquisition and Revitalization business area is Dr. Paul A. Howdyshell, CEERD-CV-ZT, and the Director of CERL is Dr. Alan W. Moore.

CERL is an element of the Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of the ERDC is COL John W. Morris III, EN, and the Director is Dr. James R. Houston.

Contents

List of Tables

1 Introduction

1.1 Background

Facilities and equipment operated by the U.S. Army are exposed to a wide variety of environmental conditions, including soils, waters or atmospheres of varying corrosivity. The various types of resulting corrosion can create a costly maintenance and repair (M&R) burden while adversely affect Army operations. The major types of corrosion phenomena are (1) general corrosion, (2) pitting attack, (3) galvanic corrosion, (4) environmentally induced delayed failure (e.g., stress, corrosion, cracking), (5) concentration-cell corrosion, (6) dealloying, (7) intergranular corrosion, and (8) various forms of erosion corrosion. It is not at all unusual for more than one form of corrosion to act on the same structure at the same time. For example, the steel components in a steam-heating system can be simultaneously subjected to conditions that cause general corrosion, pitting attack, galvanic corrosion, and the cavitation form of erosion corrosion.

A number of viable and cost-effective techniques are available for mitigating corrosion. These include (1) proper materials selection, (2) improved design, (3) the use of properly selected, applied, and inspected protective coatings, (4) alteration of the corrosive environmental characteristics, (5) the use of corrosion inhibitors, and (6) cathodic protection. In many cases two of these mitigation techniques are used concurrently in order to take advantage of synergistic effects that result. For example, the most viable option for mitigating corrosion of underground steel fuel storage tanks exposed to aggressive soils is a combination of protective coatings and cathodic protection. It is also not at all unusual to apply organic coatings to metallic coated (e.g., galvanized) steel structures in order to achieve the desired corrosion mitigation.

It is important to understand that the characteristics of soils, waters, and atmospheres at Army installations can be expected to vary greatly, and that this variation has important implications for corrosion mitigation strategies. No two installations have identical environmental conditions, and corrosion-promoting conditions can even be expected to vary within the boundaries of a given installation. For example, soils at an inland installation may be even more naturally corrosive than the chloride-containing soils along an ocean. Another example: many island and peninsular locations have atmospheric conditions that are severely corrosive on the windward sides but relatively mild on the leeward sides. There are also many locations where the atmosphere can be unusually aggressive due to the proximity of facilities such as paper mills or power plants burning high-sulfur coal.

Knowledge of the soils, waters, and atmospheric conditions (e.g., the chemistries and physical properties of the environments) at the target geographical location should be known and evaluated before attempting to establish an optimal corrosion-control program. To acquire this information, many international corporations employ or retain corrosion engineers who have considerable specific knowledge of local corrosion conditions and the best ways to mitigate them. The Army generally does not have the resources to hire such specialists, however, so engineers and constructors in the field may not have access to all the corrosion-related data they need. Nevertheless, even without detailed data, field personnel need 'as-best-possible' corrosion control guidelines for the design, construction, and operation of an Army installation.

It is well understood that there is no universal solution to all corrosion concerns. For example, although protective coatings are an effective option for mitigating many varieties of atmospheric corrosion they are basically useless in steam-heating systems. Similarly, methods for altering the internal environments in a steam-heating system to mitigate corrosion of the boiler, pipes, and heat exchangers should *not* be considered for corrosion control on the soil-side surfaces of the steel conduits and casings that house the steam and condensate lines. In the latter case effective corrosion control can be achieved only by protective coatings used in conjunction with cathodic protection. But neither of these corrosion-control techniques will work properly if wet, chemically aggressive insulation contacts the inside surfaces of the casings/conduits or the outside surfaces of the steam and condensate pipes.

The current investigation was conducted for Headquarters, U.S. Army Corps of Engineers by the Construction Engineering Research Laboratory (CERL) in order to develop and publish viable, cost-effective corrosion-mitigation guidelines for Army real property and associated equipment exposed to severely corrosive environments.

1.2 Objectives

The objectives of this study were to consider the environmental characteristics of severely corrosive locations; consider the forms of corrosion that can damage real property and associated equipment; and specify corrosion-control measures that are cost-effective and ensure the operational readiness of Army installations.

1.3 Approach

The following tasks were executed to establish the corrosion-control guidelines presented in this technical report:

1. a critical review of recent technical literature on the corrosion of metallic materials as they are commonly used at Army facilities
2. a review of applicable documents from the military, commercial, and industrial sectors that have reported on facilities corrosion in a variety of geographical locations
3. technical discussions with individuals having special expertise in the corrosion of building system components and/or their associated equipment
4. summarization of the best available information into a coherent set of guidelines.

1.4 Scope

This report focuses on corrosion problems and mitigation guidance related to selected building components and systems that are most strongly affected by exposure to a severely corrosive environment. The included materials selection guidelines are proposed specifically for situations in which established Army guidance (e.g., Unified Facility Guide Specifications, formerly called Corps of Engineers Guide Specifications [CEGS]; or Technical Manuals [TMs]), do not address severely corrosive conditions. Pertinent guide specifications are listed in Appendix A, and relevant TMs are listed in Appendix B. These documents should be consulted before determining the applicability of the guidelines presented in the current report.

1.5 Mode of Technology Transfer

It is recommended that the information and guidelines presented in this report be incorporated into applicable Unified Facility Guide Specifications (UFGS) and/or TMs.

1.6 Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for the International System (SI) of units is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 sq in.	=	6.452 cm^2
1 gal	=	3.78 L
1 lb	=	0.453 kg
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32

2 Corrosion Severity Indices

2.1 Overview

Corrosion severity indices (CSIs) have been developed to give relative indications of the degree of corrosion encountered in various environments. The various indices provide information for quantifying site-specific corrosivity. The three environments where these indices may be the most useful are (1) above-ground, i.e., exposed to the atmosphere, (2) below ground, i.e., exposed to the soil, (3) exposed to water, e.g., water pipes.

2.2 Corrosivity Indices for Atmospheric Corrosion

Corrosion rates of metals vary as a function of the environment. The need to quantify the relative corrosivity of different atmospheric environments has motivated researchers to develop location-specific corrosivity indices. Two location corrosivity models that can be used to develop atmospheric CSIs are presented below.

2.2.1 PACER LIME Model

In 1971 the U.S. Air Force implemented a program called "PACER LIME" to quantify corrosion risk factors by developing a corrosion severity index (Summitt 1979). An algorithm was developed for computing a numerical corrosion severity index that combines weather information and other environmental and location-specific factors. Many studies have shown that atmospheric factors such as moisture, salt, and other airborne particulates are the major contributors to corrosion processes (Tomashov 1966; Ailor 1978; Rozenfeld 1972). Environmental locations that are particularly high in salt are especially corrosive. Also, there is a synergistic effect between salt deposits and atmospheric water content. Proximity to salt sources, therefore, is an important factor in development of corrosion-severity algorithms. Earlier studies have indicated that the critical distance for the salt source factor is 80 miles from an ocean, beyond which the effects of salt are negligible (Summitt 1979).

Dew point and relative humidity are related to location corrosivity in that they both indicate moisture content of the air. Sunshine and wind velocities are both factors in the drying of exposed surfaces. Finally, although heavy rains contribute moisture, they also tend to wash away particulates and contaminants that cause corrosion.

Thus, the most severely corrosive environments in many cases will be those located close to the ocean where humidity is high, temperatures are frequently close to the dew point, winds are frequently calm, skies are often cloudy, but heavy rains rarely fall. Alternatively, the least severe environments are those located more than 80 miles from the ocean where the atmosphere is arid, windy, skies are generally clear, but where short, heavy rainfalls are frequent. The primary difference between an *inland* and a *coastal* environment would be the much higher chloride content of the coastal atmosphere (i.e., depending upon the prevailing winds) and the nearby body of salt water along with its associated high humidity. It should be understood, however, that high humidity could exist at inland locations (e.g., Atlanta, GA, which is located a significant distance from the Gulf of Mexico); high chloride content atmospheres can also exist at inland locations (e.g., in the vicinity of the Great Salt Lake, UT).

By the early 1980s the PACER LIME program had produced a location-based corrosion severity index comprising six location-specific parameters: (1) average relative humidity; (2) proximity to the sea; (3) days per month when the temperature is within 4 °F of dew point for three or more consecutive hours; (4) days per month with six or more hours of no cloud ceiling (i.e., sunny skies); (5) days per month of heavy rains (0.11 to 0.3 in. of rain in the preceding hour or 0.01 to 0.03 in. in a 6 minute interval); and (6) average wind velocity (Summitt 1979).

The PACER LIME Corrosion Severity Index Equation is given below as Equation 1.

Equation 1: $CSI = [2(RH) + 2(PS) + DP + NC + HR + WV]/6$

where:

CSI= Corrosion Severity Index

RH= average relative humidity

PS= proximity to the sea

DP= days per month when the temperature is within 4 °F of dew point for three or more consecutive hours

NC= days per month with six or more hours of no ceiling (meaning that sunshine is present during that period of time)

HR= days per month of heavy rains (0.11 to 0.3 inches of rain in the preceding hour or 0.01 to 0.03 inches in a 6 minute interval)

WV= average wind velocity.

The parameters are not used directly in this CSI model but are entered as integer indices (1, 2, or 3) representing a range of values for the particular parameter, with 1 representing the most severe condition and 3 representing the most benign condition. Table 1 provides the parameter integer indices to be used in the equation corresponding to the environmental parameters representative of the location in question.

Table 1. Parameters and corresponding integer indices to be used in CSI equation.

Rating	Integer	RH (%)	PS (miles)	DP (days)	NC (days)	HR (days)	WV (mph)
Severe	1	100 – 70	<10	>10	<5	0 – 1.5	1 – 1.5
Moderate	2	70 – 50	10 – 80	5 – 10	5.1 – 12.0	1.51 – 6.00	1.51 – 6.00
Mild	3	49 – 0	>80	<5	>12	>6	>6

Inserting the appropriate parameter indices into Equation 1 produces a CSI which is interpreted in Table 2.

Table 2. CSI values and corresponding rating.

Rating	CSI
Severe	1.33 – 2.00
Moderate	2.01 – 2.85
Mild	2.85 – 4.00

The maximum CSI value from Equation 1, representing the least corrosive environment is 4.00, the minimum CSI value is 1.33, representing the most severely corrosive environment.

As an example of how to use the CSI algorithm, suppose that a given location of interest is 60 miles from the sea, and has an average relative humidity of 75 percent, with 9 days per month when the temperature is within 4 °F of dew point for three or more consecutive hours, 10 days per month with six or more hours of no ceiling, more than 6 days per month of heavy rain, and an average wind velocity of 1 mph.

Using Table 1, RH=1, PS=2, DP=2, NC=2, HR=3, WV=1. Using Equation 1 for that location, the CSI is 2.33. Using Table 2, the corrosivity rating is determined to be "moderate."

The CSI equation has been used to compute CSI for 158 military locations throughout the United States. Some typical CSI values for selected military installations are given below.

2.2.1.1. Severe Rating

McChord AFB, WA	2.00
Fort Lewis, WA	2.00
Elmendorf AFB, AK	1.83
Fort Richardson, AK	1.83
Dover AFB, DE	1.83

2.2.1.2. Moderate Rating

Pope AFB, NC	2.83
Fort Bragg, NC	2.83
Altus AFB, OK	2.83
Fort Sill, OK	2.83
Fort Sam Houston, TX	2.83

2.2.1.3. Mild Rating

Holloman AFB, NM	3.33
Peterson AFB, CO	3.17
Fort Carson, CO	3.17
Edwards AFB, CA	3.33
Fort Irwin, CA	3 .00

Using the appropriate data, the PACER LIME equation can be used for computing the CSIs for other locations.

2.2.2 Corrosivity Indices Based on Mass Loss Models

CSIs based on the 1980 PACER LIME model have the inherent disadvantage of only providing three levels of severity classification, and in many cases it has been found that they do not adequately differentiate among various locations. Another disadvantage is that the PACER LIME model (i.e., equation), although it was developed for nonferrous metals, cannot account for *differences between* nonferrous materials such as copper, aluminum, and zinc (Summitt 1979).

From the mid-1980s to the mid-1990s the Air Force pursued development of a more advanced location corrosivity algorithm that provided greater differentiation of the severity among various corrosion environments and among different metals. Further development of the PACER LIME equation was abandoned in lieu of a location-specific corrosivity model based on environmentally induced corrosion damage, i.e., mass loss due to local environmental factors causing corrosion (NCI Information Systems 1988).

Corrosion occurs after some period of initiation and proceeds as a stochastic process; not all identical samples corrode at the same rate. Furthermore, any variation in the local environmental conditions will change the corrosion rates. Therefore, many reliable field samples must be analyzed over a long period of time to provide adequate data for development of the mass-loss-based CSIs.

The new CSI algorithms were based on corrosion damage equations proposed in NAPAP, the National Acid Precipitation Assessment Program (Berarie 1983; Lipfert et al. 1985; Berarie and Lipfert 1986), and involved eight test programs at more than 70 test sites over 20 years. Separate equations were developed for alloys of aluminum, zinc, copper, and steel. The resulting equations predict corrosion loss only to within a factor of 2. Of course, difficulties have been encountered in assembling experimental data of adequate size for proper statistical analysis.

The factors that most greatly influence corrosion-severity algorithms are (1) duration of wetness, (2) chloride concentration, (3) temperature, (4) relative humidity, (5) sulfide content, (6) hydrogen ion concentration, and (7) dust loading. All of these factors were considered relevant parameters in the development of the new NAPAP CSI algorithms.

The corrosion process requires an electrolyte (usually water or water vapor) and it is enhanced in solutions of higher (H^+) concentrations. However, in these algorithms, rain provides a negative contribution to corrosivity because it tends to wash away the salts and contaminants that accelerate corrosion.

Fort Lewis, WA (near Seattle) has a high corrosion severity index due to its proximity to the ocean and the almost constant dampness caused by the drizzle and cloud cover. At Fort Lewis, surfaces are dampened by light rains and high humidity and rarely get a chance to dry out; however, the rains are usually not heavy enough to wash away the salts and other corrosion-promoting contaminants.

One of the major factors contributing to corrosion damage is the accumulation of chlorides. The chloride (Cl^-) concentration is greatest near salt sources such as an ocean, salt flat, or roads where de-icing salts are frequently applied. However, the Cl^- diminishes logarithmically in accordance with the formula $[Cl^-]= A \exp(-kx)$ where x is the distance in kilometers from the salt source, A= 94.6, and k= -0.689. However, in locations where road-deicing salts are used, corrosion damage occurs in much the same way as it does near an ocean.

Sulfide concentration is another factor that promotes corrosion of metals, but environmental sulfide concentrations in the United States have dropped dramatically in the past decade due to strict enforcement of antipollution regulations at the Federal, state, and local levels. Consequently, the importance of sulfide concentrations in computing a corrosivity index has likewise diminished.

The new mass loss algorithms developed in the 1990s are based on corrosion damage as a function of time and the seven location-specific parameters:

pH = pH of the condensate
Cl^- = chloride concentration ($mg/m^2/day$)
f = fraction of time when temperature > 32 °F and relative humidity > 80%.
SO_2 = sulfur dioxide concentration ($\mu g/m^3$)
H^+ = hydrogen ion deposition ($\mu eq/yr$)
DUST = dust loading ($mg/m^2/day$) (Use 150 in the absence of data)
RAIN = rainfall (m/yr)
t = time (years)

The mass loss equations are modified by assuming t = 1 year, so the mass loss is given in terms of milligrams per year:

Equation 2a (Zinc)

$$M=4.8+0.53(SO_2+Cl^-)(f\,t)^{(1.55-0.142pH)}$$

Equation 2b (Copper)

$$\ln M=0.802+0.805\ln t+0.641\ln(0.492f\,SO_2+0.327Cl^-+0.058H^+-0.0046\,DUST)$$

Equation 2c (Aluminum)

$$\ln M=-1.595+0.987\ln t+0.87\ln(0.139f\,SO_2+0.0925Cl^-+0.0164H^+-0.0013\,DUST)$$

Equation 2d (Steel)

$$\ln M = 5.74 + 0.541 \ln(f\,t) + 0.257 \ln(f\,SO_2) + 0.067 \ln H^{+} + 0.125 \ln Cl^{-} 0.022 \ln DUST - 0.150\,RAIN$$

where:

M= mass loss in g/m^2-yr

f=fraction time temperature above 32 °F and RH above 80%

Finally, the equations are scaled and adjusted to give a corrosivity index based on relative mass loss for each case as follows:

Equation 3a (Zinc)

$$CSI_{Zn} = 4.8 + 0.53(SO_2 + Cl^{-})(f)^{(1.55-0.142pH)}$$

Equation 3b (Copper)

$$CSI_{Cu} = \exp[0.802 + 0.641 * \ln(0.492 * f * SO_2 + 0.327 * f * Cl^{-} + 0.058 * H^{+} - 0.0046 * DUST)]$$

Equation 3c (Aluminum)

$$CSI_{Al} = 100 * \exp[-1.595 + 0.87 * \ln(0.139 * (f * SO2) + 0.1825 * (f * Cl^{-}) + 0.0164 * H^{+} - 0.0013 * DUST)]$$

Equation 3d (Steel)

$$CSI_{Steel} = (0.1) * \exp[5.74 + 0.541 * \ln(f) + 0.257 * \ln(f * SO_2) + 0.067 * \ln(H^{+}) + 0.125 * \ln(f * Cl^{-}) - 0.15 * RAIN - 0.022 * \ln(DUST)]$$

Equations 3a — 3d are the algorithms from which the local CSI is computed. Location-specific environmental parameters are entered into the equations. Table 3 gives the CSI values as computed for 167 locations (primarily Air Force bases and airports) around the world for which location parameter data exist. These values have been normalized to the give a value of 100 for the most corrosive location within the United States for which data exist. For steel, that location is Patrick Air Force Base, Florida; for aluminum, copper, and zinc, it is Shemya AFB, Alaska. Note that some locations outside of the United States have CSIs greater than 100. For steel, Brindisi/Casale AFB, Italy, and Kunsan AFB, Korea, have CSIs of 226 and 105, respectively. CSIs for other locations may be determined by using appropriate local environmental parameters in these equations.

The algorithm has been partially validated at test sites, including 50 Air Force bases and five civilian test sites. The sample packages included metallic coupons mounted on plastic sample holders and placed in a location suitable for exposure, but remote enough that the package would not be disturbed (e.g., an airport runway visual range control tower). The samples included were silver, copper, aluminum alloys, and mild steel (Abbott 1999). The corrosive effects of the ambient atmosphere on copper, steel, and aluminum alloys were determined based on mass loss, and the silver coupons were used for determining atmospheric chloride concentrations. (Chlorides react with silver in predictable ways.) To date, approximately 12 months of data have been collected.

Table 3. Corrosion severity indices for selected locations.

Location	Zinc	Aluminum	Steel	Copper
al Jouf, SA	6	0	6	0
Allen C. Thompson Field, MS (Jackson)	8	4	54	13
Altus AFB, OK	7	1	20	6
Anchorage IAP, AK	7	2	21	6
Anderson AFB, Guam	38	39	58	51
Andrews AFB, MD (Washington)	10	6	45	18
Atlantic City Airport, NJ	11	9	63	22
Aviano, IT	32	29	90	62
Bahrain	21	17	41	30
Bangor IAP, ME	8	4	39	14
Barksdale AFB, LA (Bossier City)	7	3	42	11
Barnes Municipal Airport, MA (Westfield)	10	6	46	18
Beale AFB, CA (Marysville)	7	1	18	4
Birmingham Airport, AL	9	5	53	17
Boise Air Terminal, ID	6	0	10	1
Bradley IAP, CT (Windsor Locks)	9	5	44	16
Brindisi/Casale AFB, IT	83	83	226	109
Buckley ANGB, CO (Denver)	7	1	15	6
Burlington IAP, VT	7	3	35	10
Byrd Field ANG, VA	10	7	61	20
Cannon AFB, NM (Clovis)	6	1	13	3
Capital Municipal Airport, IL (Springfield)	9	6	47	18
Carswell AFB, TX	7	2	23	6
Channel Islands AP, CA	44	46	75	57
Charleston AFB, SC	12	9	74	21
Charlotte/Douglas IAP, NC	9	6	52	18
Cheyenne AP, WY	6	1	13	3
Columbus AFB, MS (Biloxi)	8	4	43	11
Dahran, SA	10	5	32	14

Location	Zinc	Aluminum	Steel	Copper
Davis-Monthan AFB, AZ (Tucson)	6	0	6	1
Des Moines IAP, IA	7	2	26	8
Diego Garcia	53	54	56	64
Dover AFB, DE	10	7	53	21
Duluth IAP, MN	7	2	27	6
Dyess AFB, TX (Abilene)	7	1	22	6
Eastern WV Reg. AP/Shep. Field, WV (Martinsburg)	11	8	58	22
Edwards AFB, CA (Rosamond)	6	0	6	1
Eglin AFB, FL (Valparaiso)	17	14	69	28
Eglin AUX 3, FL	11	8	64	20
Eielson AFB, AK	6	1	15	3
Ellington Field, TX (Houston)	11	8	71	21
Ellsworth AFB, SD (Rapid City)	6	1	12	2
Elmendorf AFB, AK	7	1	21	5
F.E. Warren AFB, WY (Cheyenne)	6	1	13	2
Fairchild AFB, WA (Spokane)	7	1	22	5
Falcon AFB, CO	7	2	15	6
Forbes Field, KS	8	4	36	12
Fort Smith Municipal Airport (AR)	8	4	41	12
Fresno Air Terminal, CA	8	2	31	8
General Mitchell IAP/ARS, WI (Milwaukee)	8	4	38	12
Grand Forks AFB, ND	7	1	15	3
Great Falls IAP, MT	7	1	13	5
Greater Peoria Airport, IL	9	6	47	18
Griffiss AFB, NY	7	3	33	11
Grissom ARB, IN	8	4	42	13
Harrisburg IAP, PA	9	6	46	17
Hector IAP, ND (Fargo)	7	1	20	5
Hickam AFB, HI	21	19	37	30
Hill AFB, UT	7	2	10	5
Holloman AFB, NM (Alamogordo)	6	0	8	1
Homestead ARB, FL	12	10	40	19
Howard AFB, Panama	13	11	66	23
Hulman Regional Airport, IN	9	6	50	18
Hurlburt Field, FL (Fort Walton Beach)	19	18	79	32
Incirlik AB, Turkey	15	12	79	30
Jacksonville IAP, Florida	8	5	50	13
Jeddah, SA	9	4	23	12
Joe Foss Field, SD (Sioux Falls)	7	1	18	4
Kadena AB, Japan	47	54	78	64
Keesler AFB, MS (Biloxi)	29	30	84	44
Kelly AFB, TX (San Antonio)	7	2	28	7
Key Field, Meridian, MS	8	4	52	13
King Khalid, SA	7	1	17	4
Kirtland AFB, NM (Albuquerque)	6	0	9	2
Klamath Falls IAP (Kingsley Field), OR	7	2	27	6

Location	Zinc	Aluminum	Steel	Copper
Kunsan AB, Korea	21	21	105	40
Lajes Field, Azores	57	59	74	69
Langley AFB, VA (Hampton)	15	14	63	27
Laughlin AFB, TX	7	1	21	5
Lincoln Municipal Airport, NE	7	1	19	5
Little Rock AFB (AETC), AR	8	4	39	12
Louisville IAP AGS (Standiford Field), KY	9	6	46	18
Luke AFB, AZ (Phoenix)	6	0	6	1
MacDill AFB, FL (Tampa)	27	27	71	40
Malmstrom AFB, MT (Great Falls)	7	1	12	4
Mansfield Lahm Airport, OH	8	4	42	14
March ARB, CA (Riverside)	7	2	26	6
Martin State Airport, MD (Baltimore)	9	6	46	18
Maxwell AFB, AL (Montgomery)	8	4	39	13
McChord AFB, WA (Tacoma)	13	10	70	24
McClellan AFB, CA (Sacramento)	7	1	23	5
McConnell AFB, KS (Wichita)	9	4	40	13
McEntire ANGB, SC (Columbia)	7	2	23	8
McGhee Tyson Airport, TN (Knoxville)	9	6	54	17
McGuire AFB, NJ (Trenton)	9	5	42	16
Memphis IAP, TN	8	4	46	13
Minn-St. Paul IAP/ARS, MN	8	3	25	9
Minot AFB, ND	7	1	13	3
Misawa AB, Japan	14	12	65	25
Moffett Field, CA	14	10	36	19
Moody AFB, GA (Valdosta)	9	5	51	15
Mountain Home AFB, ID (Boise)	6	0	10	1
NAS Keflavik, Iceland	30	31	81	44
NAS New Orleans, LA	11	8	70	22
Nashville Metropolitan Airport, TN	10	6	56	19
Nellis AFB, NV (Las Vegas)	6	0	4	1
New Castle County Airport, DE (Wilmington)	11	8	56	23
Newburgh AP, NY	7	3	24	10
Niagra Falls IAP/ARS, NY	9	6	47	19
Offutt AFB, NE	8	3	27	10
O'Hare IAP ARS, IL	7	3	34	11
Osan AB, S. Korea	18	16	75	37
Otis ANGB, MA (Falmouth)	10	7	49	19
Patrick AFB, FL (Cocoa Beach)	60	67	100	76
Pease ANGB, NH (Portsmouth)	15	13	57	26
Peterson AFB, CO (Colorado Springs)	6	1	12	3
Pittsburgh, IAP/ARS, PA	12	10	57	26
Pope AFB, NC (Fayetteville)	8	4	41	13
Portland IAP, OR	11	6	58	18
Prince Sultan AB, SA	6	0	4	1
Puerto Rico IAP (Muniz ANGB), PR	23	23	66	35

Location	Zinc	Aluminum	Steel	Copper
Quonset State Airport, RI (Providence)	41	43	81	57
RAF Lakenheath, UK	15	12	85	32
RAF Mildenhall, UK	17	15	91	36
Ramstein AB, Germany	12	9	71	26
Randolph AFB, TX (San Antonio)	7	2	28	7
Reese AFB, TX (Lubbock)	7	1	19	5
Reno/Tahoe IAP, NV	6	0	8	1
Richards-Gebauer, AFRB	7	2	21	8
Rickenbacker IAP, OH (Columbus)	9	5	45	15
Riyadh, SA	6	0	4	1
Robins AFB, GA (Macon)	9	5	53	16
Rosecrans Memorial Airport, MO (St Joseph)	10	6	42	18
Schenectady County Airport, NY	9	6	48	17
Scott AFB, IL (Belleville)	8	4	35	13
Selfridge ANGB, MI (Mount Clemens)	8	5	41	15
Seymour Johnson AFB, NC (Goldsboro)	9	4	47	14
Shaw AFB, SC (Sumter)	7	3	32	10
Shemya AFB, AK	100	100	75	100
Sheppard AFB, TX (Wichita Falls)	7	2	33	8
Sioux Gateway Airport, IA	7	2	24	6
Spangdahlem AB, Germany	12	9	73	25
Springfield-Beckley Municipal Airport, OH	8	5	39	15
Suffolk County Airport, NY	20	19	76	35
Sulayel, SA	6	0	11	2
Syracuse Hancock IAP, NY	9	6	49	16
Tabuk, SA	6	0	2	1
Taegu, SK	11	8	54	24
Taif, SA	6	0	8	0
Tinker AFB, OK (Oklahoma City)	7	2	21	6
Toledo Express Airport, Swanton, OH	10	7	54	18
Travis AFB, CA (Fairfield)	7	2	26	7
Travis Fld, GA (Savannah)	14	12	71	25
Truax Field (Dane City Regional AP), WI (Madison)	8	3	37	11
Tulsa IAP, OK	9	4	41	14
Tyndall AFB, FL (Panama City)	27	28	84	42
Van Nuys AP, CA	9	5	45	12
Vance AFB, OK (Enid)	7	1	21	6
Vandenburg AFB, CA (Lompoc)	10	6	30	13
Volk Field, WI (Madison)	8	3	34	10
Westover AFB, MA (Springfield)	9	5	42	17
Whiteman AFB, MO (Knob Noster)	8	3	31	10
Willow Grove ARS, PA (Philadelphia)	8	5	38	15
Wright-Patterson AFB, OH (Dayton)	8	4	38	14
Yeager Airport, WV (Charleston)	12	9	61	25
Yokota AB, Japan	9	6	49	18
Youngstown-Warren Regional Airport ARS, OH	11	8	57	22

Empirical data indicate that the lower corrosivity indices *overpredict* corrosion damage while the higher indices tend to *underpredict* it (Abbott 1999). Thus, a corrosion-mitigation program based on these indices should provide more than adequate protection where the predicted corrosion damage is low to moderate. Where higher corrosivities are predicted, however, corrosion-protection procedures would probably need to be enhanced compared to what the indices may indicate.

The use of the CSI and related algorithms for assessing the relative corrosion severity of a given location can be very useful in materials selection and developing maintenance practices for any given location. For environments with severe corrosivity ratings, extra care must be exercised to select corrosion-resistant materials and to conduct preventive maintenance more rigorously. For locations with mild CSI ratings, more freedom can be allowed in materials selection and preventive maintenance practices. For mild environments, the judicious selection of materials can save money, both on the first cost of materials and savings that accrue due to decreased maintenance requests.

For more severe environments where corrosion is a major factor, proper use of the CSI may prevent costly premature failures that result from improper materials selection and lack of proper maintenance.

It is generally believed that coastal locations pose more severe atmospheric corrosivity conditions than inland sites, in part because seawaters are typically considered to be more aggressive than fresh waters, and salt-laden atmospheres are commonly understood to be more corrosive than atmospheres free of chlorides. Coastal environments are typically thought to have high relative humidities, whereas inland locations are thought to automatically have lower relative humidities. These rules of thumb are not always true, however; a variety of coastal atmospheres exist. For example, there are tropical coastal atmospheres and temperate coastal atmospheres. One might intuitively suspect that a tropical coastal atmosphere would be more corrosive than a temperate coastal atmosphere because of the commonly (but somewhat erroneously) cited rule of thumb that corrosion rates double for each 18 °F rise in temperature. This belief can be misleading, though. For example, one may suspect that the corrosion rate for steel exposed at Kure Beach, NC (i.e., a temperate coastal environment) should be lower than that for the same steel exposed at Singapore, Malaya (i.e., a tropical coastal environment). However, tests have established that the corrosion rate for steel in Singapore is only about one-quarter that for steel exposed at Kure Beach. This contradiction of the basic rule in Singapore probably results from the frequent, heavy rains which remove the aggressive chlorides from steel surfaces. To confuse the matter even further, the corrosion rate for steel in Pittsburgh, PA (i.e., an inland atmosphere) is nearly 75 percent higher than it is at Kure Beach.

Although SSPC (the Society for Protective Coatings, formerly Steel Structures Painting Council) has categorized atmospheric conditions into 12 zones, either coastal or inland, it is well established that these categories are, at best, inadequate. For example, the 12 SSPC atmospheric zones fail to account for tropical and subtropical locations that are unique unto themselves (Drisko 1999). Furthermore, the five primary metal exposure zones found in coastal environments (i.e., the atmospheric, splash, tidal, full-immersion, and mud zones) are well established to be site-specific (Ross and Tuthill 1990).

This report provides guidelines for corrosion control for facilities exposed to severely corrosive conditions, whether at coastal or inland locations. However, it should be noted that location and external environment do not necessarily affect the specification of certain corrosion control applications. For example, a cathodic protection system can be designed for use in a Florida freshwater swamp applying the same principles used in seawater-saturated coastal sand. Similarly, geographical location has no impact on boiler water treatment and related techniques for condensate line corrosion control.

2.3 Corrosivity Indices for Soil

Corrosivity of the buried structures such as underground pipelines and underground storage tanks (USTs) can be determined by assessing the relative corrosivity of the soil in which the structures are buried. One simple assessment is based on an interpretation of the resistivity of the soil, as shown in Table 4.

Table 4. Soil corrosivity rating versus soil resistivity.

Soil resistivity (ohm-cm)	Corrosivity Rating
0 – 5,000	Severe
5,000 – 10,000	Moderate to severe
10,000 – 30,000	Mild
>30,000	Very Mild

An alternative for determining the relative corrosivity of the soil is based on computing the age at which a UST will begin to leak (Stephenson 1998).

The equation for predicting the leak age was determined by nonlinear regression of leak data for 83 USTs known to be leaking and 127 non-leaking tanks. The equation uses tank geometric parameters (thickness and capacity) and soil properties in which the UST is buried. The algorithm was based on an earlier algorithm (Rogers, circa 1981) that provided a semi-empirical leak-prediction model rooted in well established corrosion chemistry principles and basic corrosion rate formulae.

The algorithm is given by:

$$PLA= (A)(R^B)(S^C)(E)(T^F)$$

where:

> $E \equiv \exp[(\alpha pH)+(\beta M)+(\gamma Su)]$ and $A=256.6$, $B=0.072624$, $C= -0.194713$, $F=0.862292$, $\alpha=0.000392$, $\beta=-0.195012$, and $\gamma=-0.067732$

and where:

> PLA=predicted leak age in years; R= soil resistivity in ohm-cm; S=tank capacity in gallons; T= the tank's original shell thickness in inches; and pH= soil's pH; M=relative moisture content (M); and Su=relative sulfide content, where M =1 if the soil is saturated, otherwise M=0; and Su=1 if sulfides are present, otherwise Su=0.

2.4 Corrosivity and Scaling Indices for Water

The Langelier Saturation Index (LSI) provides a relative indication of the tendency of water to either corrode the waterside of a steel, galvanized steel, or iron pipe wall or to deposit solids on the pipe wall (Smith 1989; Blake 1980). The LSI is based on an equation that establishes the level at which the water is saturated with calcium carbonate ($CaCO_3$); it provides a comparison of the actual pH of the water with the pH at saturation. The LSI is a function of water temperature, pH, total alkalinity, calcium ion concentration, and total dissolved solids. The LSI is derived from thermodynamic analysis of the equation:

$$Ca^{2+} + HCO^{3-} \longrightarrow CaCO_3\,(s) + H^+$$

It is calculated as: $LSI = pH_{sat} - pH$, with pH_{sat} given by:

$$pH_{sat} = A + B - \log\,[Ca^{++}] - \log\,(\text{Total Alkalinity})$$

Thus, the LSI is given by:

$$LSI = A + B - \log [Ca^{++} - \log (\text{Total Alkalinity}) - pH]$$

where:

> pH_{sat} = pH at saturation, pH = the measured pH, total alkalinity = HCO^{3-} concentration (measured in ppm), $[Ca^{++}]$ = calcium ion concentration stated as calcium hardness (measured in ppm).

"A" is a function of temperature and "B" is a function of total dissolved solids (TDS), as given by Table 5.

Table 5. Constants A and B for calculation of the Langelier Saturation Index.

Constant A as a function of water temperature				Constant B as a function of total filter residue	
Deg C	Deg F	A		TDS (ppm)	B
0	32	2.60		0	9.70
4	39.2	2.50		100	9.77
8	46.4	2.40		200	9.83
12	53.6	2.30		400	9.86
16	60.8	2.20		800	9.89
20	68	2.10		1000	9.90
25	77	2.00			
30	86	1.90			
40	104	1.70			
50	122	1.55			
60	140	1.40			
70	158	1.25			

The interpretation of the LSI is given in the Table 6.

Table 6. Interpretation of Langelier Saturation Index (LSI).

LSI	Definition
+2	Scale forming, non-corrosive
+0.5	Scale forming, slightly corrosive
0	Balanced, very little corrosion, or scale formation
-0.5	Slightly corrosive, nonscale forming
-2.0	Very corrosive, non-scaling

Negative LSI values indicate a tendency of the water to cause $CaCO_3$ dissolution while positive values indicate a tendency toward scaling. While the LSI indicates the tendency of water to corrode the waterside of a steel, galvanized steel, or cast iron pipe wall it can indicate the scaling tendencies of water in all metal pipes. Corrosion control programs often rely on the addition of chemicals to the water in order to adjust the LSI to a balanced state (i.e., LSI = 0). However, it also is known that water can have an LSI of around –0.1 to –0.2 without being corrosive. Furthermore, other important factors also influence whether corrosion or scale will develop, including temperature differences in a system, variations in operating conditions, and the presence of other minerals in the system (e.g., silica, sulfates, or chlorides). The following caveats also apply: (1) positive LSIs can cause pitting corrosion if carbon dioxide content is excessive (e.g., >20 ppm); (2) positive LSIs do not always lead to the formation of scale, especially if the water has high sodium alkalinity or other dissolved solids that tend to increase the solubility of calcium carbonate; (3) for the LSI to be properly used, the water should have total dissolved solids of less than 150 ppm.

Another tool for determining the relative tendency of water to cause either scaling or corrosion of the water side of a ferrous-based pipe is the Ryznar index (RI), which is given as:

$$RI = 2pH_{sat} - pH$$

where:

> pH_{sat}=pH of saturation of calcium carbonate; pH= measured pH of the water; and $pH_{sat} = A + B - \log [Ca^{++}] - \log (\text{Total alkalinity})$

and, as before:

> $[Ca^{++}]$ = calcium ion concentration stated as calcium hardness (measured in ppm); Total Alkalinity = HCO^{3-} concentration (measured in ppm); and the constants A and B are given in Table 5.

The advantage of the Ryznar Index is that it more accurately indicates the extent of scaling or corrosion (Blake 1980). Its interpretation is given by Table 7.

Table 7. Interpretation of Ryznar Index.

Ryznar Index	Tendency of Water
4.0 – 5.0	Heavy scale forming
5.0 – 6.0	Light scale forming
6.0 – 7.0	Little scale or corrosivity
7.0 – 7.5	Significantly corrosive
7.5 – 9.0	Heavily corrosive
≥ 9.0	Severely corrosive

Obrecht and Myers (1973) have suggested that Table 8 be used in lieu of the LSI or Ryznar Index. This table considers the effects of dissolved sulfates, silica, and oxygen. The Character column describes the resulting corrosion/scaling tendencies of the water under the conditions given in the preceding columns.

Table 8. Corrosive and scaling tendencies of water.

Category	Calcium (Ca) ppm	Sulfate (SO_4), ppm	Silica (SiO_2), ppm	Dissolved Oxygen, ppm	Character
1A	0-18	As found	0-15	1-10	Extreme corrosion, hot and cold
1B	0-18	0-25	0-15	0-1	Moderate corrosion, hot and cold; extreme corrosion with CO_2> 8 ppm
1C	0-18	0-60	>15	1-5	Slight corrosion cold; considerable hot; aggressiveness reduced and perhaps not troublesome due to high natural silica
2A	18-35	0-25	0-15*	1-10	Considerable corrosion hot, moderate, and cold; may be slightly scale forming hot
2B	18-35	>Ca but not <25	0-15	1-10	Moderate to slight corrosion, hot or cold; may be scale forming hot
2C	18-35	0-25	>15	1-8	Corrosion unlikely; may be scale forming hot
2D	18-35	<Ca	As found	0-1	Corrosion unlikely; may be scale forming hot
3A	35-75	<Ca	0-15	1-10	Moderate corrosion hot; slight cold; considerable scale formation
3B	35-75	>1.5Ca	0-15	1-10	Considerable corrosion hot, slight cold; considerable scale formation hot
3C	35-75	<1.5Ca	>15	1-10	Considerable scale formation; slight corrosion hot
3D	35-75	As found	As found	0-1	Considerable scale formation; corrosion unlikely
3E	35-75	1.5Ca –2 Ca	>30	1-10	Corrosion unlikely hot and cold; excessive scale formation
4A	>75	<2Ca	0-30	1-10	Excessive scale formation; corrosion unlikely to slight cold, slight to moderate hot
4B	>75	>2Ca	0-30	1-10	Excessive scale formation; galvanic corrosion considerable hot and cold
4C	>75	<3Ca	>30	1-10	Excessive scale formation

Notes: Presence of chlorides in concentrations >100 ppm with high sulfates makes the water more corrosive than corresponding category indicates. Presence of CO_2 in concentrations of 5 ppm accelerates corrosion; if greater than 20 ppm, it can make a nominally non-corrosive water corrosive. *With SiO_2 over 15 ppm, corrosion may be reduced in proportion to SiO_2 content.

3 Guidelines for Corrosion Mitigation

The following sections present guidelines for corrosion mitigation of various building components and associated mechanical and electrical systems in severely corrosive environments. The components discussed are those known to be the most susceptible to corrosion based on site visits, experience, and past reports of performance in these environments. Based on the corrosivity indices discussed in the previous section, the component in question is classified as to whether the severely corrosive environment is caused by exposure to atmosphere, soil, or water as shown in Table 9.

Table 9. Severely corrosive environments defined by index ratings.

Environment to which component is directly exposed	Index rating for "severely corrosive" environments
Atmosphere	Corrosion Severity Index > 70
Soil	Resistivity < 5000 ohm-cm, *or* Predicted leak age for USTs <10 years
Water	Langelier Saturation Index < -2.0 for ferrous-based metals, *or* Category 1A in Table 8.

Thus, an atmospheric environment considered severely corrosive to steel is one where the CSI > 70 based on mass loss models (see Section 2.2.2 and Table 3) and applies to structures, buildings, and all related components exposed to the atmosphere as described in this report. A severely corrosive soil has a resistivity of less than 5000 ohm-cm or contains a buried underground structure (e.g., pipe or UST) that could develop a leak in less than 10 years (PLA<10). Severely corrosive waters (for steel, galvanized, or iron pipes) are those that have a LSI < –2.0 or those that have the characteristics of Category 1A in Table 8.

3.1 Sitework

3.1.1 Steel H-Piles

(See also UFGS 02456A.)

Since ASTM A588 steel reportedly has twice the atmospheric corrosion resistance of ASTM A36 steel containing 0.2 percent copper, and ASTM A690 steel has two to three times the splash zone corrosion resistance, copper-bearing carbon steel (i.e., A36) should not be used to fabricate H-piles that will be exposed to seawater.

Corrosion (especially pitting) is generally most severe in the splash zone. Underwater and mud or soil corrosion can be effectively mitigated using coatings in conjunction with cathodic protection, regardless of the steel selected. Although A588 steel is generally acceptable for H-pile applications, A690 is believed to be the best option because of its reported inherent resistance to corrosion in the splash zone (Hock et al. 1988).

Regardless of the steel selected for fabrication, H-piles should be coated for atmospheric corrosion resistance, coated or jacketed in the tidal and splash zones, coated in the submerged zone, and coated (as best possible) in the mud/soil zone (Jones and Sansum 1996).

Coatings or barrier systems (e.g., surrounding a corroded H-pile section with 0.060 in. thick rigid PVC and filling the volume between the PVC and the H-pile with mastic) could be applied/installed during H-pile rehabilitation programs.

Since most coatings contain holidays (small defects), H-piles should be cathodically protected in the submerged and mud/soil zones. Cathodic protection can also provide partial protection in the tidal zone (i.e., when the tide is in). Unless the structure is small, or a large structure is extremely well coated, impressed current cathodic protection would be more cost effective than installing sacrificial zinc or aluminum alloy anodes.

3.1.2 Steel Sheet Piles

(See also UFGS 02464A.)

Sheet piling fabricated from steel containing 0.54% Ni, 0.53% Cu and 0.12% P (ASTM A690) should be considered instead of the materials described in ASTM Standards A328 and A572. This suggestion is supported, in part, by the results of tests conducted at 10 different coastal and offshore locations which revealed that uncoated Ni-Cu-P steel had at least twice the corrosion resistance of uncoated carbon steel when exposed to the tidal, splash, and atmospheric zones (Hock et al. 1988).

Sheet piling in contact with soils, mud, and saline waters should be cathodically protected. This should be done using impressed current cathodic protection systems having deep anode beds properly installed on the shoreside of the piling. The advantage of using deep anode beds is that both the water and soilsides of the piling can be protected using one cathodic protection installation.

Since cathodic protection cannot protect the sheet piling in the splash, tidal, and atmospheric zones, two options are available for corrosion control in these areas. These are (1) concrete jackets, and (2) protective coatings.

An epoxy polyamide mastic is available for jacketing. This can be applied to the atmospheric, splash, and underwater zones by troweling the two component coating in place. Underwater, this is done by divers wearing rubber gloves. Surface preparation can be performed underwater by sand blasting.

Where jacketing is not cost effective, protective coatings should be applied to the sheet piles (at least the splash, tidal, and atmospheric zones). Protective coatings that are available and have been successfully used for this application are (1) coal-tar epoxies; (2) epoxies; (3) metallized zinc with vinyl, epoxy, saran, or furan seal topcoats; (4) metallized aluminum with vinyl, epoxy, saran, or furan seal topcoats; and (5) phenolic mastics (Kumar and Wittmer 1979).

The coal-tar epoxies are probably the best coating system for this application. For best results the coating should be applied to steel that has been prepared to a near-white finish (i.e., SSPC SP-10). These coatings will exhibit considerable curing in 24 hours at 70 °F and are completely cured in 24 hours at 140 °F. The dry film thickness of the two- to three-coat system should be approximately 0.016 in. for immersion service.

Regardless of the coating system used, the surface preparation and coating application should be performed indoors prior to shipment of the sheet piling to the construction site.

Rehabilitation of corroded, in-service sheet piling should include the application of special polyamide-cured epoxies that will cure in the presence of water or even underwater. In general these special epoxies require a sandblasted surface finish. These epoxies can also be used to repair damaged coal-tar epoxy and other coatings.

Selection of a product formulation for a protective coating for sheet piling should be made on the basis of a proven performance record. Furthermore, the manufacturers' recommendations for surface preparation and application must be strictly followed.

3.1.3 Fences

(See also UFGS 02821A)

3.1.3.1. Chain Link Fence

Only PVC-clad galvanized steel chain link fencing should be used for permanent installations where aggressive, severely corrosive atmospheres exist and the strength of the steel fabric is required. Galvanized steel and vinyl-clad steel without the zinc coating cannot be expected to provide the needed extended life expectancy in these environments (Hock at al. 1988). It is equally important that the posts, gates, and accessories for chain-link fences have a sufficiently thick galvanized coating under the PVC cladding. The posts, gates, and accessories should have a coating system consisting of (1) 0.9 oz of zinc per sq ft; (2) a minimum of 0.015 mg of zinc chromate per sq in; (3) a minimum of 0.0003 in. of crosslinked polyurethane acrylic; and (4) a minimum of 0.007 in. of vinyl topcoat. The vinyl topcoat should approach 0.015 in. for severe atmospheric conditions. The 2 oz per sq ft of galvanize on the fence fabric should have a 0.020 in. thick vinyl topcoat for severe atmospheres; a 0.007 in. thick topcoat is considered acceptable for locations more than 1500 feet away from a salt water body. A vinyl topcoat of light brown or tan would be appropriate for beach and desert locations; dark green should be used where it will blend with the local vegetation.

The components of gate reinforcement systems being installed to prevent forced entry (e.g., ramming with vehicles) into secure areas also require corrosion control. The wire rope, chain, clamps, and accessories associated with these systems should be galvanized and vinyl coated. Vinyl-coating the wire rope and chain is especially important since they contact vinyl-coated components of the security fence or gates. Uncoated wire rope and chain rubbing against these coated components would abrade the vinyl coating from the basic security system. If vinyl-clad wire rope and chain are unavailable at the installation, the galvanized steel wire rope and chain should be positioned inside flexible PVC or polyethylene sleeves.

Grounding of security fences should be done using solid copper rods and straps. The ground rods should be cathodically protected using sacrificial anodes (usually zinc) where soils aggressive to copper exist.

Alternatively, the fencing system could be fabricated using aluminized steel. In this case, all steel components must be aluminized. Chain link fence systems for severely corrosive locations can also be fabricated using anodized aluminum alloys, providing they have the desired strength and will not be in metallic contact with any more-noble materials such as copper, copper-based alloys and/or steel.

3.1.3.2. Barbed Wire Fences

The posts (i.e., the line, end, corner, and intermediate posts), bracing members, and stay wires of permanent barbed wire fences at severely corrosive locations should be galvanized and vinyl-coated in accordance with the guidelines presented in Section 3.1.3.1. Manufacturers' instructions should be followed to ensure that the vinyl coatings are not damaged during installation. Concrete placed around the posts should be non-aggressive to steel. Driven posts should not be used for permanently installed barbed wire fences unless their underground surfaces are suitably protected from corrosive soils by cathodic protection. Driven posts should also be galvanized and vinyl-coated to mitigate atmospheric corrosion.

The barbed wire for severely corrosive (coastal or heavy industrial) environments should consist of vinyl-coated galvanized wire with aluminum alloy barbs. The barbs may be fabricated from 5000 or 6000 series aluminum, but they must *not* be fabricated from 7000 or 2000 series aluminum alloys. Alternatively, stainless steel sawtooth tape can be used. The surfaces of stainless steels used for this application typically develop a tannish-yellow tarnish film in coastal atmospheres; the color of the tarnish film is considered to be compatible with the vegetation and soil color at many geographical locations (especially beaches).

Where permanently installed barbed wire fences must be electrically grounded, solid copper rods and straps should be used. The ground rods should be cathodically protected using sacrificial zinc anodes where soils aggressive to copper exist.

When Type 201 stainless steel sawtooth tape is used for concertina type fencing, the design pattern for the tape should not induce premature corrosion fatigue fracture in chloride-containing coastal atmospheres. Sharp notches must not exist at the locations where the tape will be flexed (i.e., subjected to fatigue stresses) during high winds or sand storms.

3.2 Metals

3.2.1 Structural Steel

(See also UFGS 05120N and TM 5-610.)

Under no circumstances should naturally weathering steels (e.g., high-strength, low-alloy steels such as ASTM-588) be considered for applications where it will be exposed to chloride-containing, high-humidity or wet environments (Seganetal 1991). Existing structures that have deteriorated from corrosion can only be protected from further deterioration by properly selected and applied coatings. Coating projects for corroded weathering steels can be abnormally expensive because they often require up to three times the amount of blasting sand and coating compared to coating projects for regular grades of structural steel. Furthermore, special coating systems (e.g., epoxy polyamide primers and polyurethane topcoats) can be required to ensure long-term protection for weathering steels exposed to aggressive environments.

Regardless of the steel used, designs where the structure will be directly exposed to the weather (e.g., desalination plants) should not include sections that will collect water. Alternatively, drain holes should be included in the design. Flange-to-flange and angle-to-angle crevices should be sealed by welding or using nonhardening sealants. It is important that designers allow for easy access to the structural steel so that it can be properly cleaned and coated once the structure is constructed.

If structural steel is directly exposed to coastal environments, consideration should be given to metal spraying of the steel components with aluminum either before or after assembly. If the spraying is performed prior to construction, aluminized steel bolts, nuts, and washers should be used to assemble the steel framework. For severe coastal or industrial environments, it may be necessary to apply an organic coating system to the metallic aluminum coatings.

All galvanized steel which will be directly exposed to salt-laden, severely corrosive atmospheres should be appropriately coated as part of the construction project (Table 10). Sharp edges on all structural steel should be rounded prior to coating. Otherwise, a thinner coating will exist on the edges and could lead to premature coating failure at these locations.

3.2.2 Steel Joists

(See also UFGS 05210A.)

For open building construction and high-humidity locations, open web steel joists should be designed such that they will not collect water and dust/salt/sand. Equally important, the joist design should not contain crevices. Even properly designed and fabricated steel joists should be coated using the guidelines presented in Table 10 if they are expected to be exposed to high-humidity, salt-laden atmospheres. The joists should be fabricated from aluminized steel if possible (Hock et al. 1988). Galvanized steel joists can be considered for enclosed buildings where highly aggressive atmospheric conditions exist outside.

Table 10. General coating selection guidelines for metals exposed at coastal locations.*

Exterior Steel	
Surface Preparation:	SSPC-SP-6
Primer:	MIL-DTL-24441/19B ≥ 2.5 mils
Midcoat:	MIL-DTL-24441/21A ≥ 3.0 mils
Topcoat:	SSPC Paint 36 Level 3 (2 coats)
Exterior Aluminum/Aluminum Alloys	
Surface Preparations:	SSPC-SP-1
Primer/Topcoat:	SSPC-PS 26.00 Type II
(Follow Manufacturer's requirements for coats and thickness)	
Exterior Galvanized Steel	
Surface Preparation:	SSPC-SPT
Primer:	MIL-DTL-24441/19B ≥ 2.5 mils
Topcoat:	SSPC Pain 36 Level 3 (2 coats)
Exterior Aluminum/Aluminum Alloys	
Surface Preparation:	SSPC-SP-1
Primer:	MIL-DTL-24441/20A ≥ 3.0 mils
Topcoat:	SSPC Paint 36 Level 3 (2 coats)
Steel Contacting Saline Sewage	
Surface Preparation:	SSPC-SP-6
Primer:	MIL-DTL-24441/19B ≥ 2.5 mils
Topcoat:	SSPC Paint 16 (2 coats) ≥ 8 mils/coat
Steel Water Tanks/Exterior Steel	
Surface Preparation:	SSPC-SP-6
Primer:	MIL-DTL-24441/19B ≥ 2.5 mils
Midcoat:	MIL-DTL-24441/21A ≥ 3.0 mils
Topcoat:	SSPC Paint 36 Level 3 (2 coats)
Steel Water Tanks/Interior Steel – Non-Potable Water	
Surface Preparation:	SSPC-SP-10
Primer:	MIL-DTL-24441/19B ≥ 2.5 mils
Midcoat:	MIL-DTL-24441/20A ≥ 3.0 mils
Topcoat:	MIL-DTL-24441/22A ≥ 3.0 mils
Steel Water Tanks/Interior Steel – Potable Water	
Surface Preparation:	SSPC-SP-10
Primer/Topcoat:	SEE NSF for epoxy polyamide system
Steel Smoke/Exhaust Stacks	
Surface Preparation:	SSPC-SP-6
Primer:	SSPC-SP5 with profile ≥ 3 mils
Topcoat:	Metallize with Aluminum ≥ 8 mills

* See also UFGS 09965A and UFGS 09971A.

3.2.3 Painting: General

(See also UFGS 09900A and TM 5-618.)

To be effective, coatings for corrosion mitigation must be properly (1) selected, (2) specified, (3) applied to adequately prepared surfaces/substrates, and (4) allowed to cure. In general, multiple coats (with the product for each coat furnished by the same coating formulator) are required to achieve the desired dry film thickness (DFT). A waiting period between coats is usually required and there must be neither inadequate nor excessive wet film application during each coat. Onsite inspection by properly trained personnel is mandatory during all phases of a coating project to ensure effective corrosion control (Hock et al. 1988).

Products and techniques used during a coating project should be identified by standards and specifications that are well known to those who will perform the work. For example, specifications for steel surface preparation should be defined by either the Steel Structures Painting Council (SSPC) or the National Association of Corrosion Engineers (NACE). Visual standards available from both organizations provide an effective onsite way to ensure that the specified surface preparations have been done. The importance of properly prepared surfaces in achieving adequate corrosion control cannot be overemphasized (Byrnes 1994 and Vernon 1997).

Equally important is that abrasive-blasted ferrous metal surfaces in aggressive environments are primed before any rust-bloom forms. To meet this requirement personnel must prepare only as many abrasion-blast cleaned surfaces as can be primed in a given work period. It should be noted that special products (e.g., silica sand or slag-based abrasives) are required for effective abrasive cleaning in order to develop the desired anchor pattern.

It must be appreciated that the life expectancy of even a properly applied and inspected coating system (i.e., the time before the first maintenance painting) depends upon a number of factors including (1) the coating system, (2) the surface preparation, (3) the number of coats, (4) the dry film thickness, and (5) the characteristics of the environment (Breevoort et al. 1997). For example, consider a steel surface commercially blast to a SSPC-SP-6 finish to which is applied by conventional spraying one coat of high-build epoxy primer and a single topcoat of high-build epoxy with a total dry film thickness of 8 mils (0.008 inch). This two-coat system could have a life expectancy of about 13 years in a rural environment and 7 years in a heavy industrial environment. The addition of a second topcoat to the coating system with a total dry film thickness of 10 mils would increase the life expectancies to 15 and 9 years, respectively (Breevoort et al. 1997). These life expectancies would be further increased to 20 and 14 years with the application of a three-coat system conventionally sprayed to the same SSPC-SP6 surface and a total dry film thickness of 9 mils using one coat each of inorganic zinc, high-build epoxy, and polyester urethane.

Guidelines for the selection of coatings or finishes and the associated surface preparations to be used for U.S. Army construction projects are presented in Table 10. If a coating system for a specific application is not included in these guidelines, the associated section of this report should be reviewed. For example, the guideline for coating underground fuel storage tanks are presented in the section of this report entitled "Fueling Systems for Motor Vehicles, Service Station Type" (Section 3.17)

Unless otherwise specified, all coatings should be applied at the spreading rates and dry film thicknesses recommended by the manufacturer.

Extensive information regarding the use of protective coatings for mitigating materials degradation including systems that are equally applicable for severely corrosive locations is presented in Table 10. It must be emphasized that coating projects at tropical coast locations are especially challenging because of concerns about mildew, unacceptably fast curing rates due to solar radiation, and salt particles in the atmosphere (Drisko 1999). The best coating systems available for steel in coastal locations along the Arabian Gulf have a service life of less than about 10 years, even if they are applied to properly prepared surfaces under near optimum application conditions (Carew et al. 1994).

Some of the coating systems that have been successfully recommended by U.S. Army personnel for use at coastal locations are presented in Table 10. Additional information regarding specific coating system applications used at other severely corrosive locations is included in the applicable sections of this report.

3.2.4 Roof Decking: Steel

(See also UFGS 05300A and TM 5-617.)

The roof decking should be galvanized steel. If the decking will be nested for shipment or storage, the galvanized steel surfaces should be chromate-treated and lightly oiled by the fabricator in order to prevent white-rust formation (i.e., localized/spotty corrosion of the zinc coating resulting in white corrosion products).

The nested decking should be enclosed in a heavy duty, waterproof wrapping that is protected on the ends by expendable steel shrouds for long distance shipments.

3.2.5 Miscellaneous Metal

(See also UFGS 05500A.)

If either a high-humidity, salt-laden, or industrially polluted atmosphere exists, the use of bare galvanized steel should be discouraged for outdoor exposures. Depending on the structure or component, either organically coated aluminized steel or an aluminum alloy should be the material used. Most plastic materials (e.g., PVC, CPVC, PP, PE, and ABS) are not viable options for outdoor applications because these nonmetallic materials are susceptible to ultraviolet degradation. Plastics, however, are satisfactory for the fabrication of many indoor components if the fire code permits their use.

Wire rope antenna guys and the associated hardware should be fabricated from aluminized steel for severely corrosive environments. Consideration should be given to supplementing the protection afforded by the aluminum on the wire rope with a factory-applied organic coating (e.g., a properly formulated vinyl). Type 304 stainless steel is a viable material for wire rope and accessory applications at most severely corrosive locations. However, Type 304 (or even Type 316) stainless steel rope and accessories must not be used where they might be exposed to either quiescent seawater or chloride-containing soils because they will lose passivity in these environments.

Ladders and accessories should be fabricated from an anodized aluminum alloy if the anticipated loads and fire codes permit. Fire escapes and their accessories should be fabricated from aluminized steel which is organically coated after erection. A properly formulated vinyl system usually suffices for the latter application at most severely corrosive locations.

Guardrails and handrails should be fabricated from a suitable anodized aluminum alloy such as 6061-T6.

For indoor locations, if fire codes permit, consideration should be given to the use of FRP floor gratings. Elsewhere, coated aluminized steel or aluminum alloy gratings should be used.

Aluminum and its alloys should not be used where the aqueous environment has a pH of less than about 6.5 or greater than about 8.5. Similar restrictions exist for lead, lead alloys, zinc, and zinc alloys.

It is also important that copper not be used where soft water (e.g., rain) flowing over its surface (as at roof flashings) will subsequently come into contact with either an aluminum alloy or aluminized steel. The transport of copper ions to the aluminum surface will result in an unacceptable pitting attack of the aluminum.

3.3 Metal Roofing

3.3.1 Metal Roofing and Siding, Plain

(See also UFGS 07412A, UFGS 07413A, and TM 5-617.)

Uncoated Type 2 aluminized steel is acceptable for roofing and siding at coastal and industrial locations. These buildings, however, will eventually require coating. The surface preparation and inability to coat critical areas of the building components at this later date may prevent the coating from achieving its intended objectives. Preferably, only factory coated, aluminized steel roofing and siding that have been properly designed should be used where aggressive environments exist (see Section 3.5.1).

Aluminum alloys can also be used for metal roofing and siding (Leong 1991). Aluminum alloy 3004 clad with aluminum alloy 7072 satisfying the requirements of ASTM Standard Specification B209 for Aluminum and Aluminum-Alloy Sheet and Plate, are commonly used for these applications. Minimum thicknesses for roofing and siding should be 0.040 in. and 0.032 in., respectively. The roofing should be secured using concealed, non-penetrating Type 316 stainless steel fasteners and clips. The siding can be secured using either concealed, non-penetrating Type 316 stainless steel fasteners or exposed Type 316 stainless steel fasteners through overlapping panels. If roofing and panels must be coated (generally they are not), a polyvinylidene fluoride (PVF) coating system should be used.

3.3.2 Metal Roofing and Siding, Factory Color Finished

(See UFGS 07412A and UFGS 07413A.)

The most viable material concept for roofing and siding at severely corrosive locations is factory coated Type 2 aluminized steel (Hock et al. 1988). The factory-applied coating should be an oven-baked fluoropolymer enamel. Coated galvanized steel is not acceptable for many coastal locations and other similarly corrosive environments. Coated galvanized steel, however, is acceptable for interior surfaces of a building regardless of its location.

3.4 Doors and Windows

3.4.1 Steel Doors and Frames

(See also UFGS 08110 and TM 5-610.)

As a general requirement, buildings doors in coastal locations should not face the coast if the prevailing winds are from that direction. Alternatively, a protective entrance structure can be installed to shield the doors from salt-laden winds (Leong 1991). Louvered doors are not acceptable for coastal locations.

If steel doors and frames must be installed (e.g., for security reasons), they should be aluminized steel with a factory applied, oven-baked fluoropolymer enamel coating. Hardware for the doors should be fabricated using Type 304 stainless steel. Coated, galvanized steel doors and frames are acceptable only for interior building locations.

When possible even factory coated, aluminized steel doors and frames should be avoided for installations where salt-laden, high-humidity atmospheres exist. It is nearly impossible to ship, store, and install factory coated steel doors without damage to the coatings. The rust which forms at the damage sites (holidays) cannot be effectively removed in the field; touch-up coating is generally ineffective in preventing the recurrence of rust. Also, the coatings on steel doors are susceptible to in-service damage and its associated rusting. Steel doors require unacceptable amounts of maintenance.

If sizes are available, FRP doors and frames should be installed (Hock et al. 1988). All of the hardware for the FRP doors and frames should be fabricated from Type 304 austenitic stainless steel.

3.4.2 Miscellaneous Doors

(See also UFGS 08120.)

Aluminum alloy doors, frames, and associated hardware (even when anodized) must not be in metallic contact with steel, copper, brass, or any other more-noble materials if they will be installed in salt-laden, high-humidity atmospheres. Insulating dissimilar metals and alloys at these locations is not a viable option because of the inherent problems associated with ensuring that the work will be properly performed. It should be appreciated that aluminum doors are especially susceptible to mechanical damage and localized galvanic corrosion where the aluminum alloys are in metallic contact with more-noble metals or alloys (esp., steel).

For high-humidity, severely corrosive locations, preference should be given to using FRP doors and frames with the associated hardware (hinges, screws, bolts, handles, kick plates, push plates, closers, thresholds, panic doors, and locksets) manufactured from Type 304 stainless steel. The doors should be factory mounted in the frames. The inner cavity of the FRP doors (filled with polyurethane foam) should have a minimum energy efficient R-factor of 9. FRP doors are available with a flame spread rating of less than 25 according to ASTM-E84 and satisfy the self-extinguishing requirements of ASTM-D635. These doors are especially advantageous for sanitary facilities (hospitals) because the sealed, non-porous outer resin does not provide conditions conducive to bacteria proliferation.

Large steel doors and frames should be factory coated in accordance with the guidelines presented in Table 10. Shipping, storage, and installation damage to the coatings on large doors should be repaired by qualified personnel who are specially trained for this work. This repair work involves proper surface preparation and the application of the same number of coats applied at the factory with proper sanding and "feathering" of the intermediate coats. The repair coating work can only be done after the doors and frames are installed. Following the repair coating work, the entire door assembly should be given one coat of the factory applied coating or a suitable and compatible coating.

3.4.3 Aluminum-Framed Sliding Glass Doors

(See also UFGS 08165A.)

The aluminum alloy frames for sliding glass doors should be electrically insulated from zinc and galvanized steel in addition to other dissimilar metals/alloys where high-humidity, salt-laden atmospheres exist. Aluminum is normally cathodic to zinc, so metallic contact between the two dissimilar metals or alloys can result in accelerated corrosion of the zinc. Destruction of the zinc on galvanized steel through this action would eventually allow the aluminum to contact steel that would, in turn, cause galvanic corrosion of the aluminum. Coating the aluminum (or the dissimilar metal) with TT-V-51 (i.e., an asphaltic varnish) or MIL-C-18480 (i.e., a bitumastic) would isolate the dissimilar metals/alloys.

3.4.4 Steel-Framed Glass Windows

(See also UFGS 08510)

Steel and galvanized-steel windows and their associated hardware should be avoided if they will be directly exposed to salt-laden, high-humidity atmospheres. Only aluminized steel windows and hardware should be used in severely corrosive environmental conditions if the windows are required to be fabricated from steel.

The aluminized steel components should be factory coated with an oven-baked, fluoropolymer enamel prior to installation of the glass.

When nonaluminized steel frames are used, the mesh cloth insect screens must not be manufactured from aluminum or an aluminum alloy or screen failure by galvanic corrosion will occur. Copper/brass/bronze mesh cloth is reasonably acceptable for uncoated steel (or galvanized-steel) frames providing the frames are suitably coated with an organic finish before installing the mesh cloth. Nonmetallic insect screens (polypropylene) are unacceptable because they are susceptible to ultraviolet degradation and mechanical damage.

3.4.5 Aluminum-Framed Glass Windows

(See also UFGS 08520A.)

When aluminum alloy windows will be in direct contact with mortar or concrete (or dissimilar metals or alloys) that could become wet, the contacting surfaces of the aluminum alloys should be coated to prevent corrosion by the alkaline environment and/or galvanic corrosion. Reportedly, a coating system as simple as a factory applied, clear methacrylate lacquer can achieve this objective. Alternatively, the contacting surfaces of the aluminum-alloy components can be coated with either an asphaltic varnish (e.g., TT-V-51) or a bitumastic such as MIL-C-18480 (Hock et al. 1988).

All aluminum alloy window frames and accessories should be anodized with the resultant hard-anodize coating having a thickness of 0.0007 in. (Leong 1991).

Only aluminum alloy mesh cloth insect screen should be used with aluminum framed windows.

3.4.6 Hardware, Builder's (General Purpose)

(See also UFGS 08710 and TM 5-805-8.)

Type 304 or Type 316 stainless steel nails, screws, bolts, nuts, and washers should be used for wood and plywood exposed at severely corrosive locations, especially when these woods are chemically treated with copper arsenate, ammoniacal copper arsenate, and other preservatives that are corrosive when wet to conventionally used steel and galvanized steel hardware (Bryant 1995). Even these materials may not be adequate if they contact wet insulation, especially wet insulation containing leachable chlorides (Rossiter et al. 1992). It is also important not to use free machining grades of austenitic stainless steel (e.g., Types 303 and 303 Se) for fasteners in marine environments (Ross and Tuthill 1990). Briefly, fasteners for severely corrosive environments should be manufactured using either the same material being joined or a more-noble metal/alloy. Large cathode-to-anode area ratios must be avoided.

For atmospheric exposure, the preferred fastener materials are usually copper-based alloys, austenitic stainless steel, and Monel 400. Although aluminum alloy fasteners may be satisfactory for joining wood exposed to severely corrosive atmospheres, it should be avoided if it will be in contact with graphite composites, concrete, fiberglass, and/or rubber.

Other externally exposed builders' hardware such as locks, latches, door trim, butts, and accessories should be manufactured using copper-based alloys, Type 304 or 316 stainless steel, and/or Monel 400.

Since there is a wide variety of types, styles, materials, and finishes found in the numerous items comprising finishing hardware, it is generally advisable to retain a knowledgeable hardware consultant before detailed specifications for the hardware is made for major construction projects (Hock et al. 1988). This is important because items that are standard today may not be available at a later date. The consultant should know the environmental conditions that exist at the severely corrosive location.

Galvanized steel and steel nails are reasonably acceptable for joining wood surfaces if they are fluorocarbon or epoxy coated. Uncoated steel and galvanized-steel nails should be restricted to indoor applications.

Conventional plastics should be avoided for door trim items such as push/mop/kick/armor plates because they are susceptible to ultraviolet degradation and brittle type fractures when impacted during even normal usage.

3.4.7 Hardware, Builder's (for Permanent Hospital)

All hardware (e.g., screws, bolts, nuts, washers, butts, hinges, and door plates) in high-use areas should be fabricated using an austenitic grade of stainless steel such as Type 304 or 316. Stainless steel is essentially maintenance free and it does not provide a surface conducive to bacteria proliferation. The sanitized surfaces are easily maintained.

3.5 Special Construction

3.5.1 Metal Buildings (Enclosed)

(See also UFGS 13120A and TM 5-620.)

Materials selection, protective coatings, and design are primary factors that must be considered to achieve optimum corrosion control for metal buildings. Since various components are involved in the total building system, the corrosion mitigation recommendations for each component are presented.

3.5.2 Structural Steel (Beams and Columns)

(See also UFGS 05120N and TM 5-620.)

The structural steel should be shop primed with TT-P-664 and, if necessary, subsequently coated after erection with a compatible coating system (see Table 10.)

For optimum corrosion control, consider using galvanized steel structural members.

3.5.3 Purlins

The purlins should be fabricated from galvanized steel if the building will be exposed to a salt-laden, high-humidity atmosphere.

3.5.4 Roof Panels

The exposed roof coverings should be fabricated from aluminized steel (Type 2) factory coated with an oven-baked fluoropolymer enamel such as Duranar 200.

The roof panels should be standing-seam interlocking design and secured to the purlins with a concealed structural fastening system in order to prevent the entrapment of moisture, sand, and dirt that will accelerate corrosion. The standing seams should have a factory applied nonhardening sealant and the seams should be continuously locked or crimped together by mechanical means during erection. Roof panels with lap type side (longitudinal) joints and exposed structural fasteners are not acceptable. The concealed clips or backing devices used to fasten the roof panels to the purlins or secondary support members should be fabricated from aluminized steel.

Through penetration of the roofing surface by exposed fasteners should only be at terminal locations of the roof panels; these fasteners should be stainless steel or aluminum alloy screws/bolts/rivets with weather seal washers.

Roof panel cross sections should be flat and free of cross ribbing in order to eliminate the need for closure plugs at the eave, ridge, and roof penetrations. This will permit free drainage of the roof surface and avoid the collection of moisture and dirt or sand.

3.5.5 Wall Panels

(See also UFGS 10260A and TM 5-620.)

The wall panels should be fabricated from aluminized steel (Type 2) factory-coated with an oven-baked polyester acrylic enamel. The wall panel side seams should be interlocking, concealed, or tongue-and-groove. Lap seams are not acceptable.

Wall panels should be fastened to their supports with clips/screws/bolts located on the inside of the panel or concealed in the joint, thereby eliminating undesirable exposed primary fasteners. Equally important, the panel edges should be located on the inside of the building.

3.5.6 Ventilators

Since roof-installed ventilators can be exposed to a wide-variety of atmospheric conditions, they should be fabricated using hot-dip applied galvanized steel for mild and slightly aggressive environments.

Where industrial atmospheres, especially in conjunction with high humidity and/or dusty conditions might be encountered, the ventilators should be fabricated using aluminized steel or a suitable aluminum alloy (e.g., 3000 or 6000-series). Alternatively, the galvanized steel components can be coated (see Section 3.2.3).

3.5.7 Gutters and Downspouts

The gutters and downspouts should be fabricated from a vinyl-coated aluminum alloy.

3.5.8 Building Insulation

The vapor barrier for the interior building insulation should be placed on the interior building side. All joints should be properly sealed. The vapor barrier should have a perm rating of 0.02 or less.

Preferably, the insulation should be fiberglass. The insulation must not contain any leachable aggressive ions such as chloride.

3.5.9 Sewage Lift Stations

All steel sewage lift stations and their associated steel components should be coated and cathodically protected where they contact the sewage and corrosive soil (see Table 11). Guidelines for coating the soil side surfaces of these structures are presented in Section 3.17. The required cathodic protection can be achieved using the guidelines presented in Section 3.16.1.

Internal ladders at sewage lift stations should be steel reinforced FRP rungs that are cast-in-place for concrete stations.

The pumps and pump components at sewage lift stations should be manufactured and assembled using the guidelines presented in Section 3.7.2.

Table 11. Guidelines for coating steel where it contacts either raw sewage or raw sewage fumes.

Surface/ Exposure	Surface Preparation/ Pretreatment	Finish Type	1st Coat	2nd Coat	3rd Coat
All Steel	Near white blast-cleaning, SSPC-SP-10	Epoxy	MIL-P-24441 (primer)	MIL-P-24441 (Three coats to an average DFT of 7 mils.)	MIL-P-24441
		Epoxy, coal-tar	SSPC Paint 16 (Two or more coats as required for an average DFT of 16 mils.)		

3.5.10 Incinerator: Rubbish and Garbage (Natural)

(See also UFGS 11181A.)

The effective mitigation of corrosion at incinerators used for rubbish and garbage burning are presented in Sections 3.2.3, 3.12, and 3.17. This does not include the aluminized steel or aluminized Type 409 stainless steel that should be used for sprayer equipment (including sprayers, expansion bolts/nuts, sliding doors, hoods, vents, and associated components).

3.6 Electrical

3.6.1 Underfloor Duct System; Underfloor Raceway System (Cellular Floor)

(See also UFGS 16113A and TM 5-683.)

All sheet metal components for underfloor electrical distribution systems should be fabricated using hot-dip galvanized carbon steel.

If galvanized steel sheets or sheet components will be nested for shipment and storage, the corrosion control recommendations presented in Section 3.2.4 should be followed.

3.6.2 Generating Units: Diesel-Electric; 10 kW to 6.0 MW, with Auxiliaries

Guidelines regarding the selection and installation of the USTs and associated pipes/fittings at diesel electric generating stations are presented in Section 3.17.

Corrosion of the exterior surfaces of the diesel engine exhaust stacks can usually be effectively mitigated using protective coatings (see Table 10). A system based on MIL-P-14105 (i.e., a frit-silicone) can be used for service up to 1400 °F; MIL-P-26915 and MIL-P-38336 can be used up to 750 °F where industrial or aggressive atmospheric conditions exist. Some high-temperature coatings must be cured at their use temperature before they become wet (e.g., rained on); or they will not achieve their intended objective. Alternatively, the exhaust stacks could be manufactured using aluminized steel or aluminized Type 409 stainless steel.

The closed system cooling waters for diesel engines must be chemically treated in order to prevent cavitation corrosion of engine cylinder liners. This can be done using the engine manufacturer's recommendations or the general guidelines presented in Section 3.9. When using the cooling water treatment program, serious cavitation corrosion concerns sometimes require the use of as much as 3000 mg/l sodium nitrite along with the required pH adjustment of the water.

If cooling towers may be used instead of radiators for heat rejection, the recirculating water (i.e., the open cycle water exposed to the atmosphere) must be chemically treated for scale, corrosion, and bacteria control. A water treatment specialist or firm should be retained to develop and implement the open cycle water treatment program.

3.6.3 Electrical Work, Interior

(See also UFGS 16415A and TM 5-811-2.)

All underground wires should be located inside galvanized steel conduits. The soil side surfaces of those conduits should be suitably coated and cathodically protected (see Sections 3.16.1 and 3.16.3) if the soils have electrical resistivities less than 10,000 ohm-cm or support deleterious microbiological activity such as sulfate reducing bacteria. Alternatively, where approved by code, the conduits can be Schedule 80 PVC or 6000 series aluminum alloy pipe. Regardless of the conduit material, the conduits must be installed so they prevent the ingress of water (the conduit ends must be adequately sealed). Aluminum alloy conduits must not be installed at locations where they will be exposed to wet concrete (e.g., conduits in floors and walls where the concrete will be poured with the conduits in place). Aluminum and its alloys are amphoteric; they will rapidly corrode in high pH wet concrete so the conduits will not be open for subsequent insertion of the wires/cables.

The electrical system for a building should be grounded using suitably sized, cold drawn copper rods and copper conductors and straps. In rare situations where the soil might be corrosive to copper, the grounding rods should be cathodically protected using a properly sized high-purity zinc or standard potential magnesium alloy anode (see Sections 3.6.6 and 3.16.1).

Alternating current (AC)-induced corrosion can be a special concern for metallic service lines if the water mains are nonmetallic. Although some versions of the National Electric Code require the grounding of electrical service to an underground water pipe, this practice can have very negative implications in terms of promoting soil-side corrosion of the water pipe.

3.6.4 Protective Lighting Systems

(See also UFGS 16528A and TM 5-684.)

The poles, standards, and accessories (shafts, anchor belts, bracket arms, and other hardware) for protective lighting systems should be galvanized steel only if they are exposed to relatively non-aggressive atmospheres. These same components should be aluminized steel or aluminum alloys if the environmental conditions are known to be corrosive. When long life expectancy lighting systems are required, it is most economical to use Type 304 stainless steel (Pettibone 1993). If a higher strength stainless steel might be required, Type 201 should be considered.

The 2000 and 7000 series aluminum alloys should not be used if they might be exposed to aqueous chlorides (such as deicing salts used for snow and ice control) because the materials are susceptible to both intergranular corrosion and stress corrosion cracking (SCC) when heat treated to their higher strengths (Hock et al. 1988). Preferably, a 6000 series aluminum alloy such as 6061-T6 or 6063-T6 would be used. The anchor bolts and other hardware for aluminum alloy and aluminized steel lighting systems should be aluminized steel to avoid galvanic corrosion. Alternatively, these components can be cadmium plated steel.

3.6.5 Electrical Distribution and Street-Lighting System

(See also UFGS 16710A and TM 5- 811-1.)

Where aggressive atmospheric conditions exist, poles and associated hardware for electrical distribution and street lighting systems should be aluminized steel. Wood poles are acceptable if there is no concern for termite (or woodpecker) activity or the poles have been properly pressure treated and are installed to ensure that the soil side surfaces of the poles are completely isolated from the soil using Type 304 or Type 316 stainless steel mesh (Chorley 1992).

All guy anchor rods should be electrically insulated from the wire rope by placing a porcelain insulator at the rope rod interface. Alternatively, the direct bond between the neutral and the guy wire at the top of the poles can be disconnected. Rods having wooden slug anchors should be avoided. Consideration should be given to the installation of filament reinforced plastic guy rods for aggressive atmospheric conditions if corrosive soils exist (see Sections 3.17 and 3.8.3). Steel and galvanized steel guy rods should be cathodically protected using sacrificial anodes when soil conditions are corrosive (≤ 500 ohm-cm resistivity) (see Section 3.16.1).

All grounding should be done using copper rods and straps or cables. Where soils corrosive to copper might exist the copper ground rods should be cathodically protected using sacrificial anodes (see Section 3.6.6). Similarly, galvanized steel tower footing corrosion and copper concentric neutral corrosion can be effectively mitigated using sacrificial anodes. Preferably, tower footings should be supported above grade on steel reinforced concrete pads. Copper concentric neutral corrosion can also be mitigated by jacketing the wires with semi-conducting nonmetallic materials.

Submersible (or direct burial) transformer corrosion can occur if the steel reinforced vaults become flooded with water. Provisions should be made for adequate drainage of vaults. Another option for mitigating this corrosion problem is by coating the steel (see Section 3.2.3) and attaching sacrificial anodes to the transformers, with the anodes located at the bottoms of the vaults. Stainless steel transformer cases are not considered to be satisfactory if the water/soil entering the vault can be expected to contain appreciable amounts of chlorides (along roadways where salt is used for snow and ice control).

Paper insulated lead sheath cable should be avoided for direct burial if the anticipated environmental conditions will be either acidic or basic. In general, only polyethylene jacketed cable should be used. Existing lead sheath cable can be protected using sacrificial anodes or impressed current type cathodic protection systems (see Sections 3.16.1 and 3.16.3).

3.6.6 Lightning Protection System

(See also UFGS 13100A and TM 5-811-3.)

The design of lightning protection systems should satisfy the requirements of the American National Standards Institute, the National Fire Protection Association (Bulletin No. 78, "Lightning Code") and Underwriters Laboratories (Standard UL96A, "Master-Labeled Lightning Protection Systems"). The need to install a lightning protection system for a building should be based on the results of a risk assessment analysis (Merritt and Ricketts 1994). Lightning protection is mandatory for buildings containing flammable, toxic, or explosive materials. It is also required to prevent induced overvoltages on outdoor electrical power lines.

The components for a lightning protection system are basically (1) conductors/rods* that extend at least 12 in. above the highest points (e.g., roofs) on the structure, (2) an electrical conductor/wire which is metallically connected to the lightning collectors and extends to the ground, and (3) a suitably sized ground with a resistance of 10 ohms or less.

All components of a lightning protection system should be copper. There must be no dissimilar metal contacts (electrical bonding of a galvanized-steel, aluminized steel, or aluminum alloy roof to copper) unless there is absolute assurance that the dissimilar metal connections will be completely isolated (suitably encapsulated) from the environment. Otherwise, galvanic corrosion can occur that will either sever the connection or result in a point of high electrical resistance. All of the solid copper wires must have a diameter of at least 0.25 in.

Aluminum, aluminum alloys, and galvanized steel should be avoided for lightning protection system components because of the possibility of galvanic corrosion if they are electrically connected to a more-noble metal or alloy. Furthermore, it is well known that galvanized steel has poor corrosion resistance in many environments. It is also known that aluminum wires have a natural tendency to oxidize and, when stressed at ambient temperatures, will creep. The latter phenomena can result in high-resistance bonds or connections. Although the oxidation of aluminum alloys

---

* A metal roof can act as the conductor (i.e., air terminal) if it is electrically continuous.

can be prevented by routinely spraying the connections with a preservative and creep can be corrected by routinely tightening the connections, these maintenance requirements are almost always neglected. This neglect was the cause of the Beverly Hills supper club fire in northern Kentucky where a high-resistance aluminum wire electrical connection resulted in the demise of nearly 200 people.

If the copper ground rod/electrode will be exposed to an aggressive soil, the concern can be eliminated by electrically attaching a small high-purity zinc or standard potential magnesium alloy anode to the copper (see Section 3.16.1). Active corrosion of copper in soil can be expected but is a very rare occurrence if the copper-to-soil electrochemical potential is equal to or more positive than about -0.1 volt relative to a copper-copper sulfate electrode. Adequate cathodic protection normally exists when the potential is equal to or more negative than about -0.5 volts (Myers and Cohen 1984).

3.7 Mechanical

3.7.1 Welding Pressure Piping

(See also UFGS 05093A.)

Where heavy-wall 300 series austenitic stainless steels will be field-welded (especially welds requiring three passes), the pipes and fittings should either be extra-low-carbon (Type 304L, 316L, or 317L) or stabilized (Type 321 or 347) alloys. Conventional Type 304, 316, and 317 grades of stainless steel should be avoided because of sensitization concerns (carbide precipitation) and the possibility of intergranular corrosion in certain aqueous environments. Also, the proper filler metal/welding electrodes must be used to preclude the introduction of carbon (or unstabilized carbon) into the pipes/fittings. For example, Type 304L pipe and fittings should be arc welded using Type 308L electrodes; Type 316L should be arc welded using either Type 318 or Type 316L electrodes.

When pressure pipes/fittings are pressure tested after welding, the testing must be done using disinfected waters having a near zero turbidity. Cases are known where weld-related microporosity, in conjunction with poor quality or bacteria-containing waters, resulted in extremely deleterious microbiologically influenced corrosion (MIC). An example of this has been seen in the hyperbaric medicine chamber of Wright-Patterson Air Force Base, Ohio.

When austenitic stainless steels are field welded and they contain products having temperatures in excess of about 150 °F, it is important that any insulation applied to the outside surfaces remain absolutely dry and not contain any leachable chlorides. Otherwise, residual tensile stresses associated with the welding combined with the surface tensile stresses created by pressurization can result in chloride induced stress corrosion cracking (SCC).

Welding of stainless steels should be done only by certified/qualified welders using the equipment, materials, and procedures recommended by American Welding Society guidelines.

3.7.2 Pumps: Sewage and Sludge

(See also UFGS 11310A and TM 5-814-2.)

Both horizontal and vertical model pumps are used for handling sewage and sludge. These are further classified as being either a dry-pit or wet-pit type wherein the wet-pit type is submerged in the product being pumped while the dry-pit type is not exposed to the sewage and sludge. An obvious advantage of the dry-pit pump is that it can be fitted with a clean-in-place (CIP) capability, that avoids the need to remove the pump for often needed maintenance.

Materials guidelines for sewage and sludge pumps are presented in Table 12.

Table 12. Materials selection guidelines for sewage and sludge pumps.

Component	Material
Casing	Ductile Iron
Impeller	Ductile Iron or Copper Alloy No. C83600
Shaft Sleeve	Type 416 Stainless Steel
Suction Cover	Ductile Iron
Impeller Screw	Type 302 Stainless Steel
Discharge Elbow	Ductile Iron
Bottom Bearing Housing	Ductile Iron
Choker Ring	Ductile Iron
Grommets	Nitrile Rubber
Pump Shaft	Type 410 Stainless Steel
Cooling Jackets	Type 304 Stainless
Stationary Wear Rings	Nitrile Rubber (40 IRH)
O-Rings	Nitrile Rubber (70 IRH)

Where the external components of the pumps will be exposed to sewage (wet-pit installations) the metallic components should be cathodically protected (see Section 3.16.1).

3.8 Heating Systems

3.8.1 Heating System: Steam, Oil-Fired

(See also UFGS 15562 and UFGS 15565.)

Cost-effective corrosion and scale control for the waterside surfaces of steam heating systems can be achieved by treating the feedwater before it enters the boiler in conjunction with the addition of chemicals to the boiler.* To do this, it is mandatory that almost all of the condensate (95%-plus) be returned to the heating plant for recycling. There must be no unauthorized use of steam (e.g., engine cleaning at motor pools) or excessive loss of product at leaks in the steam or condensate lines. The steam and condensate lines must be adequately maintained (Hock et al. 1988).

For low-pressure steam heating systems (pressures up to 200 psi) the initial boiler fill water (as well as the makeup water when the system is operating) should be demineralized or sodium zeolite softened (i.e., have a hardness in the range of 0 to 1 milligram per liter, mg/l, as calcium carbonate). No water, however, should be introduced into the boiler until it has been established that the boiler, the steam lines, and the condensate return lines are free of installation debris, oil and grease, and other foreign matter. If any water containing an appreciable amount of bicarbonate alkalinity is used for the boiler makeup, the heating plant should be equipped with a dealkalizer located immediately upstream of the deaerator/condensate tank(s). The dealkalizer should be sufficiently sized and capable of removing at least 90 percent of the methyl orange (M) alkalinity from the makeup water. Equally important, the deaerator must be properly vented.

Boiler waters must be chemically treated for both scale and corrosion control. This can be easily done using a well established procedure that involves adding certain polyphosphates (sodium tri-polyphosphate for low-hardness waters), sodium sulfite, sodium hydroxide, and tannin to the boiler water/feedwater. The total dissolved solids (TDS) content of the boiler water for a low-pressure system should be maintained at less than about 3500 mg/l. The desired TDS content of the boiler water can be achieved through proper blow down control. For normal operation, the boiler water should contain 30 to 60 mg/l phosphates (PO_4^-), 20 to 40 mg/l sodium sulfite

---

* Although water treatment is not a material selection issue, strictly speaking, information on the topic is included here because water chemistry has a significant impact on steam heating system materials. Because the goal is to protect installation infrastructure from corrosion, water treatment is addressed for purposes of completeness.

(Na_2SO_3) and about 80 mg/l hydroxide (OH^-); it should contain sufficient tannin to give it a tea color.

In general, the sodium sulfite (an oxygen scavenger, Cotton 1987) and caustic soda (for alkalinity control) are fed continuously (as required) at the condensate tank or the storage section of the deaerator. Polyphosphates can be fed intermittently at the same location or slug fed to the boiler water.

If there is reason to believe that the feedwater (i.e., the makeup water plus the returned condensate) will release even small amounts of carbon dioxide inside the boiler, a neutralizing amine should be added to the feedwater in order to mitigate general corrosion (i.e., CO_2 grooving) of the steel condensate return lines. Amines that have been routinely used for neutralizing carbon dioxide in the condensate systems include morpholine and cyclohexylamine. For long line systems, the use of cyclohexylamine is often more desirable than morpholine which is generally preferred for short line systems. Sometimes it is most advantageous to use a combination of the two amines. Filming amines such as octadecylamine are not recommended for condensate return line corrosion control at most Army facilities because their use requires constant attention by the plant operators. Octadeclamine should be introduced to older systems only with extreme caution because it is likely to cause the steam traps to clog with rust.

For a properly treated low-pressure steam heating system, condensed steam leaving the boiler should have a pH of about 7.4 to 7.8, contain a trace to 2 mg/l carbon dioxide, 0 mg/l oxygen, and have a specific conductance of less than 100 micro-mhos. A specific conductance greater than 100 micro-mhos indicates a carryover problem or that an excessive amount of amine exists in the steam. A pH of less than about 7.4 or greater than about 7.8 indicates inadequate or excessive amounts of volatile neutralizing amine in the steam, respectively.

The specific conductance of the condensate should be the same as that measured for the steam. The condensate hardness should be near zero. Measured hardness in the condensate suggests that the system is leaking where hard water is being heated.

Effective waterside corrosion and scale control for a steam heating system requires periodic chemical analysis of the boiler water, the steam, the condensate (at selected locations throughout the system), the makeup water, and the feedwater. The tests should be conducted at least every eight hours. Testing must be done by trained personnel only. In addition, a representative of the organization furnishing the treatment chemicals should visit the heating plant at least every two months, conduct the tests identified above, and compare his/her data with those of the on-site water analyst. Any discrepancies between the two sets of data should be immediately resolved.

Corrosion control for the underground steel fuel oil storage tanks and pipes at the heating plant is done using the guidelines presented in Sections 3.17 and 3.10.4.

Aboveground fuel oil storage tanks and pipes should be coated in accordance with the guidelines presented in Section 3.2.3.

When a boiler is not in service, it must be properly laid-up; otherwise it will corrode at a rapid rate. Generally, a wet lay-up is used for short out-of-service intervals. Dry lay-up is always recommended for a boiler that will not be operational for an extended time period (e.g., more than 30 days). The boiler manufacturer's recommended procedures for lay-up should be strictly followed. Alternatively, lay-up procedures should be provided by the representative of the organization furnishing the water treatment chemicals.

3.8.2 Miscellaneous Heating Systems

(See also TM 5-810-2.)

Forced Hot Water, Oil-Fired; Forced Hot Water, High Temperature Water Converter and Steam Converter; Hot-Water Plant and Heating Distribution System; and Hot Water Heating System Wet Fill and Cap water heating systems are generally categorized according to the temperature and pressure of the water conveyed (Hock et al. 1988). High temperature hot water (HTHW) systems operate above 350 °F and 450 psig, medium temperature hot water (MTHW) systems operate at 250 to 350 °F with pressures above 30 psig, and low temperature hot water (LTHW) systems operate below 250 °F with a maximum pressure of 30 psig.

Regardless of the system, it should be initially filled with water that has been either demineralized or softened to a near zero hardness only after the system has been properly cleaned and flushed with water of similar quality. It is important that every effort be made to ensure that these systems will initially be and remain closed systems.

Corrosion control for LTHW, MTHW, and HTHW systems can be readily achieved using chemical treatment programs established by a qualified water treatment firm or specialist. There should be little concern about scale or deposit formation in the systems if the water quality for the initial fill is proper, the systems operate using near zero hardness makeup water, and the corrosion control program is properly maintained.

LTHW systems should be chemically treated so that 3000 to 4000 milligrams per liter (mg/l) sodium nitrite is maintained in the water at a water pH of 8 to 8.5 where the water temperature will exceed 180 °F. For water temperatures below 180 °F, the amount of sodium nitrite to be maintained in the pH 8 to 8.5 water should be 1500 to 2000 mg/l. Corrosion control for any copper/copper alloys in the system should be achieved using BT, MBT, or TT (see Section 3.9.1). Any concerns about scale/deposits in closed LTHW systems can be minimized by adding chemicals such as sodium polyacrylates, polymethacrylates, polymaleates, sulfonated polystyrene, carboxymethyl-cellules, lignins, and/or phosphonates to the water.

Corrosion control for closed MTHW systems can be achieved by maintaining 20 mg/l sodium sulfite (an oxygen scavenger) in the water while concurrently using sodium hydroxide to maintain the water's pH in the 9 to 10 range. Any concern about scale/deposits in MTHW systems can be minimized through additions of polyacrylates, polymethacrylates, and/or phosphonates to the water.

Corrosion control for closed HTHW systems can be achieved by treating and maintaining 20 mg/l sodium sulfite in the water in conjunction with the use of sodium hydroxide such that the water's pH is in the range 9.0 to 9.5. Only thermally stable scale inhibitors and dispersants should be added to HTHW systems.

The initial chemical dosage for a closed hot water heating system can be estimated using the expression:

$$I = (P/120)(V/1000)$$

where P is the desired dosage in mg/l, V is the total volume of the system in gallons, and I is the initial chemical dosage in pounds.

Adequate testing (initially and immediately following upset conditions, at least every 8 hours; weekly, for systems having low rates of makeup) is required to ensure that the proper concentrations of inhibitors are maintained in closed hot water heating systems. Chemicals must be added to closed hot water heating systems in accordance with the results of these analyses. Only analysts who are adequately trained should conduct these tests. When the quantity of makeup water added to a closed system is known (e.g., through metering), the amount of inhibitor which should be added can be reasonably estimated using the expression:

$$F = (P/120)(M/1000)$$

where P is the desired dosage in mg/l, M is the makeup in gallons, and F is the pounds of inhibitor that must be added.

All testing must be conducted using accepted analytical methods and pH must be measured using a properly calibrated meter. Test data obtained by the on-site analyst should be compared at least every month with those obtained by a representative of the organization furnishing the treatment chemicals. Any discrepancies between the two sets of data should be immediately resolved. Chemicals should not be purchased from an organization that cannot provide this service.

Regardless of the chemical(s) used, a high state of cleanliness must be maintained in closed hot water heating systems. Side stream filters are recommended for this objective.

All expansion tanks associated with hot water heating systems should be nitrogen blanketed in order to prevent oxygen ingress when the water contracts during periods of cooling. Furthermore, maintenance personnel must ensure that an excessive amount of water is not lost because of leaks or the unauthorized use of hot water. The makeup water should be metered.

Hot water heating system distribution lines should be insulated externally with inert, non-aggressive materials (see Section 3.8.3).

It is important that water absorbing gaskets not be used in hot water heating systems. Otherwise, unacceptable concentration cell corrosion can occur at flanges.

Copper and copper-based alloy tubes and fittings must be installed using industry standard practices (see Section 3.12). Steam converter type heat exchangers should have Copper Alloy No. C70600 tubes and the steam used in these generators must be properly treated (see 3.8.1).

Hot water heating systems must be properly laid away when they are not operational. Otherwise, unacceptable pitting corrosion can occur on the waterside. Lay-away procedures recommended by the manufacturer of the hot water generator should be strictly followed. Alternatively, lay-away procedures should be provided by the representative of the organization furnishing the water treatment chemicals.

Corrosion control for the underground steel storage tanks and pipes can be achieved using the same procedure described for the tanks and pipes at the service station type fueling systems for motor vehicles (see Section 3.17).

3.8.3 Heat-Distribution Systems Outside of Buildings

(See UFGS 02552N and TM 5-810-1.)

All underground steel heat distribution system casings that are exposed to soils having a resistivity of less than 10,000 ohm-cm at the casing depth (distilled water saturated soil box determined) should be externally coated using a fusion bonded epoxy powder or a reinforced coat tar enamel such as that identified in MIL-P-15147 and AWWA-C203 (Walker 1993) and cathodically protected (see Section 3.16.3). If the soil box determined resistivities exceed this value, the services of a qualified (National Association of Corrosion Engineers, NACE, certified) corrosion specialist or cathodic protection specialist having a minimum of ten years experience in underground corrosion and its control should be retained to determine the requirements for corrosion control (Hock et al. 1988).

Casing coatings should be factory applied in order to prevent dirt and other foreign matter from becoming embedded in the coatings. All slag and sharp protrusions associated with field welding should be removed before the girth weld areas are field coated/encapsulated. The soil side coatings should be properly inspected for holidays using detectors of suitable voltage; all coating defects should be field repaired before the casings are covered with rock-free sand or soil.

Insulation inside the casings should not contain leachable, aggressive species such as chloride. Heavy metal (e.g., copper and iron) containing insulation should be excluded if an aluminum jacketing is used to protect heat distribution pipes located aboveground. The aluminum jacketing must be electrically insulated from the heat distribution pipes. Also, the aluminum used for the relatively thin (0.016 in. thick) aboveground jackets should have proven corrosion resistance in the atmospheres in which they might be exposed, especially those contaminated with industrial pollutants.

Immediately after installation of the heat distribution system, but before the underground sections of the system are covered with soil, warm air should be forced through the insulation containing annulus from one end of the system with a ambient temperature mirror (shaded from the sun) located at the other end. Warm air should be forced through the insulation until there is no condensation on the mirror. This will ensure that the as-installed insulation is dry and noncorrosive. Concurrently, it is desirable to force a gas such as helium through the insulation zone in order to locate and repair any leaks that might allow the reintroduction of water.

Manhole ladders should consist of U-shaped, steel reinforced fiberglass rungs that are cast-in-place in the concrete. Fiberglass manholes should be used for new and replacement construction if aggressive soils exist and water can be expected to collect in the manholes.

Foamed polyurethane insulated glass reinforced plastic condensate (or hot water) pipes should not be used if there is any possibility they will be exposed to thermal environments exceeding 250 °F.

Zinc coated steel casings should not be considered a reasonable substitute for organically coated and cathodically protected steel casings if aggressive soil conditions exist. Any zinc coated steel casings that arrive at the job site should be suitably coated prior to installation; installation should include the application of cathodic protection if the soils are corrosive to steel.

3.9 Chilled Water Distribution

3.9.1 Chilled-Water Distribution System Wet Fill and Cap; Chilled-Water Plant and Distribution System

The metallic pipes and other waterside components for closed-water systems theoretically should not corrode after the dissolved oxygen introduced with the initial fill is consumed by corrosion. True closed-water systems, however, almost never exist; makeup water containing dissolved oxygen is added to most systems. For corrosion to be effectively mitigated in closed systems, the water must be chemically treated.

Chemical treatment of the properly disinfected demineralized or distilled water (to prevent the introduction of any deleterious bacteria that may cause corrosion) used to initially fill the chilled water system should be done using a sodium nitrite-borax formulation containing a corrosion inhibitor for copper components that exist in nearly all chilled water systems. Chromates are no longer used for the chemical treatment because they are considered environmentally unacceptable. Also, they are not compatible with waters containing ethylene glycol type antifreezes.

The nitite-borax-copper inhibitor treatment program for waterside corrosion control requires the addition of sufficient sodium nitrite to the water so that at least 1400 (but not more than 2000) milligrams per liter (mg/l) sodium nitrite ($NaNO_2$) is added and continuously maintained in the water. Borax is included in the treatment program in order to maintain the pH of the water in the 8 to 9 range. Otherwise, the nitrite (an anodic inhibitor) cannot function as a corrosion inhibitor for the ferrous-based materials in the system. Adding and maintaining about 10 to 15 mg/l azole (e.g., benzotriazole, BT) in the water mitigates corrosion for the copper and copper alloys in a chilled water system.

The success of the chemical treatment program requires constant monitoring of the water's characteristics such as its pH, specific conductance, and nitrite and azole contents. For example, a sodium nitrite content of about 1400 mg/l will often be achieved when the specific conductance of the fill water has been increased by about 2700 micro-mhos. The specific conductance test, however, cannot be used alone because there are known cases where the nitrite was converted to nitrate. Therefore, it must be appreciated the nitrite and nitrate ions contribute equally to specific conductance, but nitrate is totally ineffective as a corrosion inhibitor.

The water treatment program should be established and implemented by a qualified specialist with the routine testing being conducted by the system operators who have been properly trained to conduct the required tests. The frequency of the testing should be established by the water treatment specialist.

3.9.2 Open-Cycle Condenser Water System

It is difficult to select optimum materials for open-cycle condenser water systems without knowing the chemistry of the water that the tubes/fittings will convey and the chemical/physical characteristics of the atmosphere.

In general, the condenser tubes, return bends, and headers should be copper for most installations. When soft water containing dissolved oxygen must be conveyed at velocities greater than about 5 feet per second (fps), the tubes should be Copper Alloy No. C70600 (i.e., Cu-Ni) and if the water might contain ammonia and/or sulfide (constituents that are sometimes found in well waters and/or polluted waters) the tubes, return bends, and headers should be commercial purity titanium or titanium alloy Ti-Code-12 (Myers, Bomberger, and Froes 1984) especially for systems designed to operate at high water velocities, so as to allow self-cleaning of the waterside surfaces.

If unusually humid or wet conditions do not exist and there is low atmospheric contamination, the condenser tube fins can be either an 1100-aluminum alloy or copper that is mechanically attached to the tubes so there is no ingress of water to the tube-fin interfaces. Tubesheets should be copper or copper-clad steel. If continuously wet conditions do not exist, the tubesheets could be hot-dip-applied galvanized steel. If waterboxes exist, they should be carbon steel factory-coated with baked phenolic or a coating selected using the guidelines presented in Section 3.13. The protection afforded by the coating system should be supplemented with cathodic protection if there is room available in the waterboxes (see Section 3.16.1).

Large diameter underground and aboveground pipes and fittings for conveying the cooling water should be cement-mortar lined ductile iron coated externally and cathodically protected if it is exposed to soils having resistivities less than 5000 ohm-cm. The smaller diameter pipes or tubes should be copper (see Section 3.12).

Chemical treatment for a once-through cooling water system should not be required if the proper materials are selected for fabrication of the condensers unless fouling and/or scale formation become a concern. Any chemical treatment for the cooling water should be developed and maintained by a qualified water treatment specialist. Nonchemical water treatment based on unproven electrostatic and/or magnetic principles should not be used for mitigating scale, fouling, corrosion, and/or microbiological activity.

3.10 Pumping Systems

3.10.1 Water, Centrifugal Pump

(See also UFGS 11211.)

The components for centrifugal pumps that contact seawaters and/or brines (the wetted components) should be manufactured using Monel 400 or a properly heat-treated aluminum bronze. Preferably, the bronze would be a nickel aluminum bronze (e.g., Copper Alloy No. C95800). The preferred materials for the assembly of centrifugal pumps are included in Table 13.

3.10.2 Water, Vertical Turbine Pump

(See also UFGS 11212A.)

The materials selection guidelines for assembling vertical turbine pumps that handle seawater and brines are presented in Table 14.

Table 13. Materials selection guidelines for centrifugal pumps handling seawater and brines.

Component	Material
Casing	Copper Alloy No. C95800
Cover	Copper Alloy No. C95800
Impeller	Copper Alloy No. C95800
Wear Ring	Copper Alloy No. C95400
Motor Shaft	Type 416 Stainless Steel
Shaft Sleeve	Copper Alloy No. C95400
Adapter	Cast Iron/Ductile Iron
Frame	Cast Iron/Ductile Iron
Seals	Buna N with Type 316 Metallics
Suction Head	Copper Alloy No. C95800
Stuffing Box	Copper Alloy No. C95800
Lantern Ring	Copper Alloy No. C95400
Gland	Copper Alloy No. C95800

Table 14. Materials selection guidelines for vertical turbine pumps handling seawaters and brines.

Component	Material
Impeller	Copper Alloy No. C95800
Intermediate Bowl	Copper Alloy No C95800
Impeller Shaft	Type 316 Stainless Steel
Intermediate Shaft	Type 316 Stainless Steel
Discharge Bowl	Copper Alloy No. C95800
Stuffing Box Gland	Copper Alloy No. C95800
Impeller Nut	Monel 400
Lantern Ring	Glass-Filled Fluorocarbon
Shaft Coupling	Monel 400
Enclosing Tube	Type 316 Stainless Steel
Column Bearing Housing	Copper Alloy No. C95800
Column Bowl	Copper Alloy No. C95800
Discharge Head	Copper Alloy No. C95800
Suction Bowl	Copper Alloy No. C95800
Strainer	Type 316 Stainless Steel
Slinger	Type 316 Stainless Steel

3.10.3 Pressure Vessels for Storage of Compressed Gases

(See also UFGS 13211A and TM 5-848-1.)

Type 304 and 316 stainless steels should be avoided for pressure vessels that are exposed to salt-laden, high-humidity coastal atmospheres unless the structures/welds can be suitably annealed after assembly to prevent intergranular corrosion (Hock et al. 1988). Type 304L or 316L stainless steels should be used instead of the higher carbon versions of these alloys. Alternatively, stabilized grades of austenitic stainless steel (Type 347 or 321) can be used. It is important that compatible electrodes/filler metal be used during the welding of austenitic stainless steels; a system must exist so there is no electrode mixing during either shop or field welding. Halogenated products should be avoided when cleansing the interiors of stainless steel pressure vessels unless all of the aggressive ions will be removed immediately after cleaning. It is equally important that neither internal nor external welding crevices exist in stainless steel pressure vessels. There should be no weld spatter.

Surface preparations for carbon and low-alloy steels should be specified according to either SSPC (The Society for Protective Coatings) or National Association of Corrosion Engineers (NACE) criteria instead of verbal descriptions. The SSPC and NACE criteria/specifications for steel are identified in Table 15.

Table 15. SSPC and NACE specifications for the surface preparation of steel.

Surface Preparation	SSPC Specification	NACE Specification
White Metal	SP 5	1
Near-White Metal	SP 10	2
Commercial Blast	SP 6	3
Brush-Off Blast	SP 7	4

Carbon and alloy steels should be coated externally according to the guidelines presented in Section 3.2.3. Stainless-steel surfaces should not be coated unless it is mandatory for color coding. In time, austenitic stainless steels will develop a tannish-yellow tarnish film at most coastal locations. This film should not be removed.

3.10.4 Water Lines

(See also UFGS 02510A and TM 5-813-5.)

All ductile iron pipes and fittings should be cement-mortar lined for conveying both fresh and saline waters. Copper tube is the most viable option for lines having diameters less than three inches. Copper tube systems must be properly designed and installed (see Section 3.12). A major reason for not using plastic pipe (PVC, chlorinated polyvinyl chloride, and polybutylene) at many locations is its vulnerability to rodent damage (Hock et al. 1998).

Coatings (see Section 3.2.3) supplemented with cathodic protection should be used to mitigate external corrosion of underground ferrous-based metal (ductile iron) pipe if it will be exposed to aggressive soil. Even corrosion-resistant copper should be cathodically protected externally in the rare circumstances where aggressive soil conditions exist. Underground metallic pipe/tube (esp., ductile iron systems) systems must be electrically continuous if cathodic protection is to achieve its intended objective. Joints and connections on ductile iron pipe systems must be bonded using suitably sized and insulated copper wires. High-resistance joints must be avoided. Insulating unions/flanges should only be used where it is necessary to separate individual systems.

Under no circumstances should unbonded, nonadherent polyethylene coatings (bagged/sleeved/loose wrapped polyethylene sheeting) be considered a reasonable substitute for coated and cathodically protected structures. The loose wrap polyethylene approach is unacceptable because the oxygen deficient envelope between the pipe and the sheeting is almost always environmentally conducive to anaerobic (sulfate reducing) bacteria activity and its known destruction of metallic pipe. Furthermore, the existence of the loose wrapping precludes the application of effective cathodic protection if it is required at a later date. The polyethylene sheeting acts as a shield or disbonded coating to the flow of cathodic protection currents.

Although PVC valve boxes are advantageous for coastal water distribution systems, the covers of these components should be metal impregnated so that the valve boxes can be easily located in case they become covered with sand or dirt.

Pipes and fittings that distribute seawater and/or brines having diameters up to 6 in. can be PVC manufactured in accordance with ASTM Standard Specification D1785 for Polyvinyl Chloride (PVC) Plastic Pipe, Schedules 40, 80 and 120 (Leong 1991); the fittings should be manufactured according to the applicable ASTM Specification (ASTM Standard Specification D2466 for Polyvinyl Chloride Plastic Pipe Fittings, Schedule 40). For pipes and fittings having diameters of 6 in. or larger, cement-mortar lined ductile iron (see AWWA C151) is acceptable. When pipe diameters of 8 in. or larger are required, consideration should be given to filament wound fiberglass pipe manufactured according to ASTM Standard Specification D2996 for Filament Wound "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Pipe (Delong 1991).

3.11 Sewage Treatment Plant: Wet-Burning Process, Prefabricated

(See also UFGS 11310A.)

Corrosion mitigation at sewage treatment plants (where components contact sewage and hydrogen sulfide-containing, high-humidity atmospheric conditions) can be achieved using properly selected, applied, and inspected protective coatings. Guidelines for selecting and applying these coatings are presented in Table 16.

Table 16. Coating selection and application guidelines for sewage treatment plants.

Surface/ Exposure	Surface Preparation/ Pretreatment	Coating Type	1st Coat	2nd Coat	3rd Coat
Steel sewage side surfaces of aerators, sludge settling tanks, and sludge holding systems	Near white blast-cleaning SSPC-SP-10	Coal-tar epoxy	SSPC Paint 16	SSPC Paint 16	
			(Two coats with a minimum DFT of 16 mils.)		
		Epoxy	MIL-P-24441	MIL-P-24441	MIL-P-24441
			(Three coats to an average DFT of 7.0 mils.)		
Steel--atmospheric exposure but with possible intermediate contact with sewage or chemicals	Solvent clean, commercial blast in accordance with SSPC-SP-6	High performance	MIL-P-38336 or MIL-P-26915	MIL-P-24441 (two coats)	MIL-P-83286
Steel--all other exposures	(see section of this report entitled "Painting: General")				

*Unless otherwise indicated, coatings should be applied at the DFT recommended by the coating manufacturer.

3.12 Plumbing, General Purpose

(See also UFGS 15400A and TM 5-810-1.)

It is known that many domestic waters are unacceptably corrosive to steel and galvanized steel (Obrecht and Myers 1973; Obrecht and Myers 1972). In general, these aggressive waters have low alkalinities and are either naturally soft or have been softened to a near zero hardness. They typically contain appreciable amounts of dissolved oxygen and/or dissolved carbon dioxide. Even waters that would be expected to deposit protective calcium carbonate can be aggressive when, for example, they contain appreciable amounts of chloride and/or sulfate. When corrosion occurs in steel and galvanized steel water systems, the rate of attack increases with increasing temperatures, especially at temperatures in excess of about 140 °F. In general, restricted flow conditions associated with the formation of voluminous tubercles (mounds of corrosion products resulting from the pitting attack) require that the lines be replaced long before corrosion-induced perforations through the pipe walls become a serious concern (Obrecht and Myers 1973; Myers 1973).

Type L copper tube (copper alloy No. C12200) manufactured in accordance with ASTM Standard Specification B88 for Seamless Copper Water Tube should be used for potable water lines having diameters up to 3 in. The fittings (elbows, tees, and couplings) should be copper and manufactured according to American National

Standard ASME B16.22 for Copper and Copper Alloy Solder Joint Pressure Fittings. All valves, expansion joints, pumps, controllers, and other hardware used to install domestic water systems should be manufactured using a suitable copper-based alloy. If there is concern about the dezincification of brass valve stems (as can occur in low temporary hardness waters containing appreciable amounts of chloride and having a pH greater than about 8) these stems can be fabricated using a phosphorus or arsenic-inhibited silicon red brass. Similarly, Monel 400 valve seats should be specified for faucets if the conventionally used plated brass seats will be subjected to conditions causing wire drawing, a term that has been used to identify the erosion corrosion of valve seats (Obrecht and Myers, June 1973). If copper alloys containing even small amounts of lead (e.g., leaded red brass) are unacceptable, faucets and other hardware can be manufactured (cast and machined) using lead-free materials (copper alloys No. C89510 or No. C89520).

Copper tube systems for domestic waters must be assembled using lead free solders such as 95 tin-5 antimony (95 Sn- 5 Sn) alloy. Soldering must be done with fluxes that satisfy the requirements of ASTM Standard Specification B813 for Liquid and Paste Fluxes for Soldering Application of Copper and Copper Alloy Tube. The guidelines to be followed for tube installation, joint preparation, and soldering are presented in ASTM Standard Practice B828 for Making Capillary Joints by Soldering of Copper and Copper Alloy Tube and Fittings. The information presented in these ASTM publications is especially useful in preventing the use of unusually aggressive fluxes and excessive flux that can result in soldering flux induced pitting attack of copper tubes and fittings (Myers and Cohen 1994; Cohen and Myers 1996).

Adhering to the guidelines presented in ASTM Standard Practice B828 are equally useful in preventing erosion corrosion of copper tubes and fittings (Myers and Cohen 1998). Many erosion corrosion concerns are associated with unreamed cut tube ends and the use of excessive solder that results in the presence of protrusions and localized turbulent flow on the waterside surfaces.

When potable hot waters must be heated to temperatures in excess of 140 °F and circulated at velocities greater than 4 to 5 fps, copper alloy No. C70600 tubes and fittings should be specified (Myers and Cohen 1998).

Although erosion corrosion of copper tubes and fittings is normally associated with circulating domestic hot water systems, it can occur in cold waters if, for example, the water pressure exceeds about 80 pounds per square inch gauge (psig) and/or assembly of the system involves poor workmanship.

In the design of copper tube systems for circulating domestic hot waters it is important to avoid velocities greater than about 4 to 5 fps, especially if the waters are soft and contain appreciable amounts of dissolved oxygen and/or dissolved carbon dioxide (Obrecht and Myers, April 1973; Obrecht and Myers, August 1973). Failure to properly size the tubes and circulating pumps can result in erosion corrosion and premature leaks.

Erosion corrosion of copper tube systems is also facilitated by heating the water circulated to temperatures in excess of 140 °F. There have been cases where erosion corrosion was effectively mitigated by simply reducing the temperature of the water to a safe and energy efficient 120 to 130 °F. Cold hot water concerns can be eliminated by upgrading the thermal insulation on the outside surfaces of the tubes and fittings. The thermal insulations must not be hygroscopic or contain leachable constituents (chlorides) that are aggressive to copper (Myers and Cohen 1985).

Although there are known cases where copper tubes and fittings were susceptible to pitting attack by certain cold waters, this phenomena can be viably and cost effectively mitigated by simply raising the pH of the water so it approaches 8.3. The corresponding dissolved carbon dioxide content of the water is then reduced to less than about 20 milligrams per liter (mg/l) (Myers and Cohen 1995; Cohen and Myers 1987).

On rare occasions, copper tubes and fittings associated with domestic hot water systems are susceptible to pitting attack because the products conveyed contain small amounts of iron, manganese, and/or aluminum, especially if the water is heated to temperatures in excess of 160 °F. This pitting concern can be effectively mitigated by reducing the quantities of iron, manganese, and/or aluminum in the waters to less than 0.1, 0.03, and 0.1 mg/l, respectively. This pitting phenomenon can, in some cases, be controlled by reducing the temperature of the water to the 120 to 130 °F range without adjusting the chemistry of the water. Often the iron related pitting can be eliminated by mitigating the corrosion of ferrous-based materials upstream of the copper tube systems.

Copper water tube systems that are properly designed, installed, and operated have a life expectancy greater than that of the building in which they are installed (Obrecht and Myers, September 1973).

Cement-mortar lined ductile iron pipe and fittings should be used where aggressive waters must be conveyed and the diameters of the pipes and fittings are 4 in. and larger.

Thin-walled Type 409 and 439 stainless steel tubes have failed prematurely because of pitting corrosion in domestic water service, and therefore are not recommended. PVC, chlorinated polyvinyl chloride (CPVC), and polybutylene (PB) pipe can be used for domestic water service if long-term building service for these materials is available (Obrecht and Myers, August 1973). However, these plastic materials do have limitations. For example, some fire codes prohibit the use of combustible, toxic-gas-generating plumbing materials. Also, plastics are susceptible to damage by gnawing rodents and have temperature limitations.

Small-size (less than about 120 gallons) hot water heaters should be glass lined and cathodically protected on the waterside using properly sized sacrificial anodes for a ten year anode life (Obrecht and Myers, April 1973). For water resistivities less than about 2000 ohm-cm, the zinc anode material should satisfy the chemical composition requirements of ASTM Standard Specification B418 for High-Purity Zinc. Magnesium alloy anodes satisfying the chemical composition requirements of MIL-A-21412 should be used when the water resistivity exceeds about 2000 ohm-cm. Aluminum alloy anodes are not recommended because of the tendency to passivate in many waters; in other waters, their rapid corrosion can cause pit initiation of copper in hot waters. All components for the pressure/temperature relief valves on the hot water heaters must be fabricated using appropriate copper-based alloys.

All large size steel hot water heaters should be cylindrically shaped and lined internally using a properly specified applied and cured hydraulic cement (Obrecht and Myers, December 1976). A calcium oxide cement containing not more than 35 percent calcium oxide and not less than 25 percent silica should be used for waters having a pH greater than about 7. An aluminum silicate cement containing no free calcium oxide and not less than 25 percent silica should be used for soft waters having a pH of less than about 7.

All cold water storage tanks (house tanks) should be coated internally and cathodically protected (Obrecht and Myers, January 1977).

Coatings in conjunction with cathodic protection should also be used in those rare occurrences when copper tubes might possibly be exposed to unusually-aggressive soils (Myers and Cohen 1984).

The same corrosion mitigation technique should be used when cement-mortar lined ductile iron pipe are exposed to aggressive soils (soils having a resistivity of less than about 5000 ohm-cm, especially if they contain appreciable amounts of sulfate). Loose wrappings of PE are not a viable option for mitigating the underground corrosion of ductile iron pipe. Similarly, nonmetallic conduits or sleeves cannot be expected to mitigate the corrosion of underground copper tubes unless the nonmetallics are impermeable to water or water vapor and the ends of the sleeves or conduits are perfectly sealed to prevent the ingress of groundwater.

3.13 Elevated Steel Water Tanks, Steel Standpipes, and Ground-Storage Reservoirs

(See also UFGS 13210A, UFGS 13206A, and TM 5-813-4.)

All of the underground pipes and fittings should be cement-mortar lined ductile iron that is externally coated using the guidelines presented in Section 3.10.4. If the soils have a resistivity of less than 5000 ohm-cm, the pipes and fittings should be cathodically protected using the guidelines presented in Sections 3.16.1 and 3.16.3.

Guidelines for coating steel water storage tanks are presented in Table 17.

Table 17. Coating selection and application guidelines for steel water storage structures.

Surface/ Exposure	Surface Preparation/ Pretreatment	Finish Type	1st Coat	2nd Coat	3rd Coat
Steel tank Exteriors	Commercial blast-cleaning, SSPC-SP-6	Vinyl, white or colored	SSPC Paint 9 (Four coats to obtain a minimum total dry film thickness of 5.0 mils.)		
		Vinyl, aluminum	SSPC Paint 9 (3 coats)	SSPC Paint 8 (1 coat)	
			(Minimum total dry film thickness of 5.0 mils.)		
		High-performance urethane	MIL-P-38336 or MIL-P-26915 Type I, Class A	MIL-P-24441	MIL-C-83286
			(Minimum total dry film thickness of 5.0 mils.)		
		Red lead/ alkyd	TT-P-86 Type II	TT-P-1593 or TT-E-490	TT-P-1593 or TT-E-490
Steel tank interiors	Near white blast-cleaning, SSPC-SP-10	Epoxy	MIL-P-24441 (Two or more coats as necessary to obtain a minimum total dry film thickness of 5.0 mils.)		
	Near white blast-cleaning, SSPC-SP-10 Pretreat with SSPC Paint 27	Vinyl, white or colored	SSPC Paint 9 (Four coats with a minimum total dry film thickness of 5.0 mils.)		
		Vinyl, aluminum	SSPC Paint 9 (3 coats)	SSPC Paint 8 (1 coat)	
			(Minimum total dry film thickness of 5.0 mils.)		

* Unless otherwise indicated, coatings should be applied at the spreading rate or DFT recommended by the coating manufacturer.

The waterside surfaces of all steel tanks, standpipes, and reservoirs (including large diameter risers) should be cathodically protected using mixed metal oxide activated titanium anodes (see Sections 3.16.1 and 3.16.2.

3.14 Cooling Systems

3.14.1 Central Refrigeration System (for Air Conditioning System); Refrigeration System

(See also UFGS 15651N, UFGS 15652A, and TM 5-670.)

The copper fins on air-cooled condensers are not acceptable for most severely corrosive environments because the thin fin material corrodes rapidly (Hock et al. 1988). If the copper fins are coated to inhibit general corrosion the result is a reduction in heat transfer capability, and corrosion will actually accelerate where there are holidays or similar coating defects. Aluminum fin/copper tube fabrication also is not a viable option because galvanic corrosion generally occurs at the fin/tube interfaces in high-humidity atmospheres. For coastal and other aggressive atmospheres, aluminum tube/aluminum fin fabrication should be selected. It is important that no ferrous- or copper-based alloys are in contact with the aluminum tubes at locations were moisture can accumulate (Segan et al. 1990).

The copper fins on existing air-cooled condensers can be somewhat protected from rapid deterioration by filtering the salt-laden air before it enters the units. One technique that has reportedly been successful involves 2 in. thick close ferrous metal mesh air filters that are sprayed with an oil after installation to capture the salt particles from the incoming air (Segan et al. 1990). Theoretically, these filters should also mitigate the galvanic corrosion of the aluminum fins attached to copper tubes.

Aluminized steel should be used instead of galvanized steel or aluminum alloys for the ductwork associated with refrigeration systems. Atmospherically exposed fans associated with the refrigeration equipment should be aluminum alloy. Stainless steel 316 alloy may also be used, but this practice is considerably more expensive than the use of aluminized steel.

Corrosion control recommendations for other components of a refrigeration system are presented in related sections of this report. These include (1) plumbing (see Section 3.12), (2) insulation (see Section 3.8.3), (3) Painting (see Section 3.2.3), and (4) water-cooled condensers (see Section 3.9 for “closed” chilled water systems and Section 3.9.2 for “open-cycle” condenser water systems).

3.14.2 Air-Conditioning System (Unitary Type)

(See also UFGS 15730N.)

Air-cooled condensers in coastal locations should not use copper fins because the material corrodes rapidly (see Section 3.14). If the copper fins are coated to inhibit general corrosion the result is a reduction in heat transfer capability, and corrosion will actually accelerate where there are holidays or similar coating defects. Aluminum fin/copper tube fabrication also is not a viable option because galvanic corrosion generally occurs at the fin/tube interfaces in high-humidity coastal exposures. For such locations, air-cooled condensers should use aluminum tubes and aluminum fins to avoid the problems associated with dissimilar metal construction and corrosion-resistant coatings.

Corrosion control methods for air-conditioning systems at severely corrosive locations are presented in other sections of this report. These include (1) field painting (see Section 3.2.3), (2) air-cooled condensers and fins (see Section 3.14), (3) ductwork (see Section 3.14.3), (4) insulation (see Section 3.14.3), (5) closed-water systems (see Section 3.9), (6) plumbing (see Section 3.12), and (7) open-cycle water systems (see Section 3.9.2).

3.14.3 Air Supply and Distribution System for Air Conditioning

Hot-dipped, aluminized steel should be used for the ductwork associated with air-conditioning systems. This material combines the strength of steel with the corrosion resistance of aluminum. Further, aluminized steel is only slightly more expensive than galvanized steel and considerably less expensive than aluminum-alloy sheet. The superior corrosion resistance of aluminized-steel compared to galvanized-steel in most atmospheres is well documented (Hock et al. 1988).

Although glass-fiber ductwork does not deteriorate by electrochemical corrosion, it is susceptible to vibrational (fatigue) and other mechanical (impact) damage. Worker experience is required to repair or alter the ductwork.

Where copper water tubes are exposed to aggressive soils, they should be coated and cathodically protected. Copper tube systems should be installed using industry-standard practices (see Section 3.12). When insulation is applied to cold-air ducts or chilled-water pipes/tubes, it is important that a proper vapor barrier exists over the insulation and that the insulation not be hygroscopic or contain any leachable species such as chlorides that are aggressive/corrosive to the metallic tubes/pipes/ducts.

Aluminum tube-aluminum fin coil fabrication should be the standard for environmental conditions where these components will be exposed to unfiltered air containing aggressive species (e.g., sulfur dioxide and/or chlorides) in conjunction with high humidities. If there is assurance that the environmental conditions will be non-aggressive, copper tubes and fins or copper tubes with aluminum fins can be used.

If there is reason to believe that the steam-to-water or water-to-water heat exchangers will involve water temperatures greater then about 150°F and the water will contain dissolved oxygen, the U-bend tubes for these units should be fabricated using Copper Alloy No.C70600. Otherwise, these components can be Copper Alloy No. C12200.

The closed-water system expansion tanks should be nitrogen blanketed with the circulated water chemically treated using the guidelines presented in Section 3.9.1. Guidelines for cooling coil fabrication for air-cooled condensers is presented in Section 3.14.1.

All field painting should be accomplished using the guidelines presented in Section 3.2.3.

3.15 Water Desalination Plant

(See also TM 5-813-8.)

Stainless steels should not contact stagnant brine and/or seawater. Naturally weathering steels should also be avoided for use in salt-laden atmospheres.

Exposed steel at desalination plants should be sandblasted to a white metal finish (SSPC-SP-10 or NACE 1) and coated using an inorganic zinc vinyl topcoat system (see Section 3.2.3). If interior steel will be exposed to temperatures up to 400 and 1200 °F, the steel should be abrasive-blasted to a white metal finish and coated with TT-E-496 and TT-P-28, respectively (Lampo et al. 1984). Exterior steel exposed to temperatures up to 1400 °F should be sandblasted to a white metal finish and coated with MIL-P-14105. All heat-resistant coatings must be suitably cured before they are exposed to aggressive atmospheres.

Water lines for desalination plants should be installed according to Sections 3.12 and 3.10.4.

The seawater intake should be fabricated using Copper Alloy No. C70600, and the mist eliminator for the evaporator condenser should be Monel 400. Other materials that are advantageous for desalination plant applications include Copper Alloys No. C70600 and C71500 for the brine heaters, Type 317L stainless steel for the vacuum system, and FRP for the walkways and gratings.

Preferably, the product water from a desalination plant would be chemically treated to a saturation (Langelier) index of about +0.6 (with the addition of lime) in order to reduce the characteristics that are naturally aggressive to most plumbing materials.

Pumps for desalination plants can be selected using the guidelines presented in Sections 3.10.1 and 3.10.2.

3.16 Cathodic Protection

3.16.1 Sacrificial Anodes

(See also UFGS 13110A.)

Sacrificial/galvanic anode cathodic protection systems generate protective currents through the naturally occurring potential differences that exist between metals and alloys. Only zinc, magnesium, and aluminum-based materials are available for the sacrificial cathodic protection of commonly used metallic materials (ferrous-based alloys, copper, and copper alloys). Basically, the sacrificial anode materials available are high-purity zinc (ASTM B418, Type II) and a zinc alloy (ASTM B418, Type I), two magnesium alloys (standard potential and high-potential magnesium alloys) and four aluminum alloys (Myers 1996). General guidelines for sacrificial anode use in soil and water are presented in Table 18. When using the information presented here, it should be understood that anodes used in soil are almost always surrounded by special backfills containing bentonite clay, gypsum, and sodium sulfate.

Table 18. Typical resistivity-range criteria for sacrificial-anode usage in soil and water.

Anode Material	Environment	Resistivity Range, ohm-cm
Aluminum Alloys	Water	Up to 150
High-Ampere Zinc	Water	Up to 500
Standard-Potential Magnesium Alloy	Water	Over 500
High-Ampere Zinc	Soil	Not Recommended
Aluminum Alloys	Soil	Not Recommended
High-Purity Zinc*	Soil and Water	Up to 2000
Standard-Potential Magnesium Alloy*	Soil	Up to 4000
High-Potential Magnesium Alloy*	Soil	Over 4000

*With backfill for soil installations (Myers 1996).

The resistivity ranges reported do not infer that the anodes cannot be used at higher resistivities or lower resistivities; it depends on the current required for protection or the life expectancy desired for the cathodic protection system. For example, well coated structures in relatively high-resistivity soil may require only a small amount of total current for adequate protection; zinc anodes may be capable of providing this current.

General guidelines for the design of sacrificial anode type cathodic protection systems are presented in the text "Cathodic Protection Design" (Myers 1996.). These systems can be readily designed for a structure if information is available regarding the electrical resistivity of the environment and the total current required for protection. The design is important and must include instructions on the proper location of the anodes in order to ensure desired distribution of the protective current. It is advantageous to have the design phase completed by a qualified corrosion engineer.

It is important to have a qualified inspector available at the project site between the time that the components for a sacrificial anode system are delivered and the time when the system is completed and commissioned (Myers July/August 1997; Myers September/October 1997; Myers January/February 1998). The materials used during the installation of a sacrificial anode type cathodic protection system must be in compliance with the specifications and components must be installed according to the engineering drawings. Otherwise, the cathodic protection system may not achieve its intended objective.

In general, cathodic protection is achieved when the polarized potentials for iron and steel in aerobic and anaerobic environments, respectively are more negative than -0.85 and -0.95 volt relative to a copper/copper sulfate reference electrode. Lead, copper, copper alloys, aluminum, and aluminum alloys are considered to be adequately protected when the structure-to-environment potentials are more negative than -0.60, -0.50, and -0.95 volt, respectively relative to a copper-copper sulfate reference electrode. The measurement of all structure-to-environment potentials must be done using a high-resistance voltmeter and an uncontaminated reference electrode, the validity of which is routinely checked with at least two other electrodes.

In general, there is little concern regarding the effect of IR (the component of the measured structure-to-environment potential associated with the flow of cathodic current in the environment) for sacrificial anode type cathodic protection systems. This is understandable because sacrificial anodes typically produce relatively small amounts of current (I is small) and they are usually used only in relatively low-resistivity environments with the anodes being located relatively close to the protected structure (R is small).

Similarly, there is almost never any concern regarding the overprotection of amphoteric metals (lead/lead alloys and aluminum/aluminum alloys) when they are cathodically protected using sacrificial anodes. If there is concern, it can be eliminated by ensuring that the polarized potentials do not exceed -1.2 volts relative to copper-copper sulfate for aluminum/aluminum alloys and -0.85 volt for lead/lead alloys.

Other advantages of sacrificial anode type cathodic protection systems are that they almost never cause any overprotection related damage to the modern coatings applied to the structures being protected. They are rarely associated with stray current corrosion and do not require the availability of electrical power.

3.16.2 Cathodic Protection: Steel Water Tanks

(See also UFGS 13111A and TM 5-811-7.)

Cathodic protection should be used for the mitigation of corrosion on the waterside surfaces of steel storage tanks because many waters are corrosive to steel. Even well coated tanks require cathodic protection because all practical coatings will contain and/or develop holidays where corrosion of the steel can occur. Because of safety and water availability concerns associated with the corrosion of these structures, it is understandable that cathodic protection is mandatory according to TM 5-811-7 for all Army water storage tanks having a capacity of greater than 250,000 gallons (Hock et al. 1998). The design life for these cathodic protection systems should be 20 years.

Guidelines for the design of cathodic protection systems for water storage tank interiors are presented in the text "Cathodic Protection Design" (Myers 1996). A cathodic protection system for a water storage tank can be readily designed if data are available regarding the resistivity of the water, the dimensions of the tanks, and the current required for protection. Only relatively small and well coated tanks typically can be cost effectively protected using sacrificial anodes. Sacrificial anodes should only be used for larger sized tanks when electrical power is not available and cannot be made economically available.

The primary concern in cathodically protecting an elevated, pedestal type water storage tank is to ensure there will be proper distribution of current to the wetted surfaces of the bowl (the elliptic bottom, the sidewall, and the elliptic top) and its associated riser. Usually this requires three anode circuits. One circuit, the main column anodes, involves the placement of anode strings (almost always with more than one anode on each string) on a circle around the tank for protecting the top, the sidewall, and a portion of the bottom of the bowl. A second circuit, the stub anodes, involves the placement on anode strings (generally with one anode on each string) at its lower end on an inner circle around the tank for protecting the balance of the elliptic bottom of the bowl. The third circuit involves the placement of a centrally positioned anode string down the tank riser.

Only mixed metal oxide activated titanium anodes should be used for the cathodic protection of water storage tanks. Usually, this will involve the use of tubular or rod type anodes wherein the anode vendor will be advised that the anodes will be used in fresh water. The anode strings should be vendor assembled.

When three electrical circuits are involved in cathodically protecting a water storage tank, it is generally most cost effective to use a modular type rectifier with a module for each circuit. Unless the atmospheric conditions are especially dusty, the rectifiers can be air-cooled and, depending upon economics, have either silicon or selenium rectifying elements. If the current required for cathodic protection will vary significantly during operation of the cathodic protection system, the rectifier potential should be automatically controlled with the permanently installed reference electrodes inside the tank being properly positioned and with a life expectancy of at least five years.

Electrical cable for the cathodic protection system should be high molecular weight polyethylene (HMPE) insulated copper. There must be no underwater cable splices.

A qualified inspector must be available to ensure that the materials and components delivered to the project site are in compliance with the approved engineering drawings and specifications. The inspector must also ensure that the cathodic protection system is installed according to the engineering drawings.

For coated steel water storage tanks, the criterion for cathodic protection can be a structure-to-water potential that is at least as negative as -0.85 volt relative to a copper-copper sulfate electrode. Any concern for IR associated with this potential measurement due to the flow of current through the water can be eliminated by placing the reference electrode within about one inch of the steel at each measurement site. Alternatively, if cathodic protection is applied to a rust covered tank, the 100 millivolt polarization criterion can be used.

3.16.3 Cathodic Protection: Impressed Current

(See also UFGS 13112A and TM 5-811-7.)

An impressed current type cathodic protection system requires the availability of an external power source. The basic components of the system are (1) a direct current (DC) power source (generally a rectifier), (2) a group of auxiliary anodes with or without carbonaceous backfills (a ground bed or anode bed), (3) the structure to be protected, and (4) insulated electrical cable used to connect the power source to the ground bed and the structure to be protected. It is important to connect the negative terminal of the power source to the structure and the positive terminal of the power source to the anode bed.

Guidelines for the design of impressed current cathodic protection systems are presented in the text "Cathodic Protection Design" (Myers 1996). Careful attention is required in selection of the anodes, power sources, electrical cable, and groundbeds for a properly designed system. Concerns about overprotection related coating damage to the structure being protected and stray current corrosion (interference) to other underground/submerged metallic structures in the area must be considered during the design and operation of impressed current type cathodic protection systems.

A number of anode materials with a wide variety of shapes and sizes are available. These include graphite, high-silicon cast iron, platinum coated titanium and niobium, and mixed metal oxide activated titanium. When selecting an anode material, note that graphite and high-silicon cast iron anodes are heavy, brittle, and difficult to handle; platinum coated anodes (because of the ultra-thin platinum coating applied) have a history of premature failure when installed in mud and water storage tanks. Impressed current type cathodic protection systems should be designed using mixed-metal oxide activated titanium anodes. These anodes are available in a variety of shapes and sizes including solid cylinders, tubes, expandable springs, ribbons, wires, discs, and probes.

Three basic groundbeds are available for the cathodic protection of metallic structures in soil. These are: (1) conventional (relatively shallow) point type surface groundbeds, (2) deep groundbeds where the top of the activated anode column is at least 50 feet from the surface of the earth, and (3) distributed groundbeds wherein the anodes are distributed along and relatively close to the structure to be protected. Each groundbed type has certain advantages and limitations. For example, distributed groundbeds and deep groundbeds often minimize the stray current corrosion concerns associated with conventional point-type groundbeds. Deep groundbeds are useful in the protection of aboveground storage tank bottoms where the steel contacts potentially aggressive soil.

The anodes are almost always backfilled with a carbonaceous material in a designed amount and configuration when used in soil. The purpose of the carbonaceous backfill is to extend the life expectancy of the anodes, decrease the anode-to-earth resistance, and assist in the release of gases generated at the anodes. Commonly used carbonaceous backfill materials include metallurgical coke, delayed calcined petroleum coke, and calcined fluid petroleum coke. Carbonaceous backfills must be selected with care; otherwise, the cathodic protection system may not achieve its intended objective. For example, calcined fluid petroleum coke should be used for deep groundbeds because the particles have a spherical shape that facilitates self compaction of the carbonaceous backfill downhole. For the same application the other carbonaceous materials are undesirable because, for example, the delayed calcined petroleum coke particles are not spherical and their inherent porosity allows them to float. Flake graphite is not used for deep groundbeds because leafing of the flakes impedes the release of gases generated downhole.

The power sources for impressed current type cathodic protection systems are almost always rectifiers having either selenium or silicon rectifying elements. Silicon rectifying elements are usually advantageous where high output voltages are required. Selenium rectifying elements, however, are less expensive and more reliable. Often rectifier selection is based upon output power. Below 500 volt-amperes of DC output, single-phase selenium rectifiers are selected; above 1000 volt-amperes, silicon rectifiers are usually more economical for both single phase and three phase circuits. The most commonly used circuit is the single phase bridge circuit. Automatic potential controlled rectifiers should be used where the current required for protection can vary during the year.

Factors that must be considered in selecting the electrical cable for a cathodic protection system include (1) current carrying capacity, (2) voltage drop, (3) the insulation's dielectric strength, (4) abrasion resistance, (5) chemical resistance, (6) impermeability to water, and (7) the cable's mechanical strength. For impressed current systems the cable almost always consists of suitably insulated, single conductor stranded annealed copper rated at 600 volts. The most popular insulation for direct burial cathodic protection systems cable is HMPE manufactured according to ASTM Standard Specification D1248, Type I, Grade J-3, Class C; Category 5. Note that HMPE is not resistant to certain chemicals including chlorine, hydrochloric acid, and most petroleum hydrocarbons.

Dual insulations are available for impressed current cathodic protection systems when aggressive environments exist or will be generated. The outer HMPE insulation for these cables provides the abrasion resistance required for cable installation and backfilling while the inner insulation provides the required chemical resistance. Two widely used chemically resistant inner insulations are ethylene chlorotrifluorethylene (ECTFE) and PVF. Dual insulation cables typically consist of 0.020 to 0.040 in. of ECTFE or PVF extruded over the tinned-copper conductor over which is extruded a 0.065 to 0.080 in. thickness of HMPE.

It is important that a qualified corrosion engineer reviews and approves the design and materials/components used in the installation of an impressed current type cathodic protection system. Equally important, a qualified inspector must ensure that the design materials and components are delivered to the project site and installed according to the engineering drawings and associated specifications. Substitutions, in general, are unacceptable.

For underground/submerged steel structures, cathodic protection is considered to be satisfactory when the instant-off (immediately after the rectifier is deenergized) structure-to-environment potential is at least as negative as -0.85 volt relative to a copper-copper sulfate electrode. Cathodic protection can be assumed to be adequate when the polarized potential at a given location is at least 100 millivolts more negative than the natural potential of the structure (Myers 1996). The latter criterion (the 100 mV polarization) is also normally used for copper and copper alloys as well as aluminum alloys.

3.17 Fueling System for Motor Vehicles: Service-Station Type

(See also UFGS 13202A and UFGS 13203A.)

One of the four EPA-mandated requirements for the installation of new USTs is that the tanks and associated pipes be protected from corrosion. The other requirements provide for leak detection, the avoidance of spills and overfills, and certification that the tanks are installed according to industry codes.

The preferred system for underground fuel storage for tanks up to about 20,000 gallons is horizontal double wall with full 360-degree secondary containment, glass fiber reinforced polyester tanks and accessories manufactured according to ASTM Standard Specification D4021. The tank design should include bottom deflector gauge plates to prevent tank damage from dipstick abuse. The pipe system between the tank and the station pump or between tanks should be double wall FRP (e.g., a 2 in. diameter pipe inside a 3 in. diameter pipe) manufactured according to the guidelines presented in, for example, ASTM Standard Specification for Filament Wound "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Pipe. With the use of FRP anchoring straps and other nonmetallic accessories, the FRP tanks system requires no protective coatings, routine coating maintenance, cathodic protection, or cathodic protection monitoring and maintenance.

Alternatively, underground fuel storage at service stations can be installed using horizontal double wall steel tanks that are coated both internally and externally. These tanks should have factory installed splash plates under the fill tubes in order to avoid premature erosion corrosion induced leaks at these locations. Guidelines for coating the interior and exterior surfaces of these tanks and their associated steel pipes are presented in Table 19.

Table 19. Coating selection and application guidelines for steel fuel-storage tanks at service stations.

Surface/ Exposure	Surface Preparation/ Pretreatment	Finish Type	1st Coat	2nd Coat	3rd Coat
Exterior steel under-ground fuel storage tanks	Near white metal blast-cleaning, SSPC-SP-10	Coal-tar epoxy, high-performance	SSPC Paint 16	SSPC Paint 16	
			(Two or more coats as required for an average total DFT of 16 mils.)		
		Fiberglass/ resin (for maximum protection in very aggressive soils)	Factory applied using fiberglass that meets MIL-Y-1140 and a grade of corrosion-resistant polyester resin meeting MIL-R-7575, grade B, for strength.		
		Coal-tar enamel (minimum protection)	MIL-C-18480	MIL-C-18480	
Interior steel fuel storage tanks fitted with manholes	White metal blast-cleaning, SSPC-SP-5	Epoxy	MIL-C-4556 (primer)	MIL-C-4556 (topcoat)	
			(Minimum of two coats to an average DFT of 7.5 mils.)		
		Urethane	MIL-P-23236, Type 1, Class 4	MIL-P-23236, Type 1, Class 4	
			(Two or three coats to a minimum DFT of 6 to 8 mils, depending on coating system manufacturer's recommendations.)		
Exterior above-ground steel fuel storage tanks	Commercial blast-cleaning, SSPC-SP-6 minimum; near white cleaning, SSPC-SP-10, is better	High-performance urethane	MIL-P-38336 or MIL-P-26915	MIL-P-24441	MIL-C-83286 (two coats)
	Commercial blast-cleaning, SSCP-SP-6	General Purpose	TT-P-86, Type II	TT-E-1593 or SSPC Paint 21, Type I	TT-E-1593 or SSPC Paint 21, Type I

Guidelines for the cathodic protection of underground, steel storage tanks are presented in Sections 3.16.1 and 3.16.3.

The guidelines for coating the exterior surfaces of aboveground steel fuel storage tanks are also included in Table 19. These tanks must also be coated internally. The outside surfaces where these tanks might contact soil should be cathodically protected (see Section 3.16).

4 Conclusion

The purpose of this report was to specify cost-effective corrosion control measures to help ensure the operational readiness of Army facilities located in highly corrosive environments. The discussion addressed technical aspects of severely corrosive environments and described different types of corrosion that may affect metal components of Army infrastructure.

The report focused on corrosion mitigation guidance related to building components and systems that are most heavily impacted by exposure to a severely corrosive environment. Although discussed previously, it is worth noting again that the materials selection guidelines offered here are intended specifically for applications in which established Army guidance does not address severely corrosive conditions. Pertinent guide specifications and TMs are cross-referenced throughout the text, and their full citations are provided in Appendices A and B, respectively.

In all cases, the relevant existing Army guidance should be consulted before finally determining the suitability of the guidelines presented in the text.

References

Abbott, William, "Corrosion Monitoring of Air Force Field Sites," *Proceedings of the Triservices Corrosion Conference*, November 1999.

Ailor, W.H., "ASTM atmospheric corrosion testing: 1906 to 1976," "Atmospheric Factors Affecting the Corrosion of Engineering Metals, ASTM STP 646," S.K. Coburn, Ed., American Society for Testing and Materials, pp 129-151, 1978.

Benarie, M., "Air Pollution Damage Function Reconciliation-Effects on Materials," Interim report to Brookhaven National Laboratory, unpublished, 1983.

Bernarie, M., and F.W. Lipfert, "A General Corrosion Function In Terms of Atmospheric Pollutant Concentrations and Rain pH," *Atmospheric Environment,* vol 20, no.10, 1986.

Blake, Richard T., *Water Treatment for HVAC and Potable Water Systems* (McGraw-Hill, NY 1980).

Byrnes, G., "Preparing New Steel for Coating." *Materials Performance*, vol 33, no. 10 (October 1994).

Carew, J., A. Al-Hashem, W.T. Riad, M. Othman, et al., "Performance of Coating Systems in Industrial Atmospheres on the Arabian Gulf." *Materials Performance*, vol 33, no. 12 (December 1994).

Chorley, D.M., "Halt Pesky Termites' Attack on Buildings—Use Stainless Mesh," *Nickel*, vol 8, no. 1 (September 1992).

Cohen, A., and J. R. Myers, "Overcoming Corrosion Concerns in Copper Tube Systems," *Materials Performance*, vol 35, no. 9 (October 1996), pp. 53-55.

——— "Mitigating Copper Pitting Through Water Treatment," *Journal of the American Water Works Association*, vol 79, no. 2 (February 1987).

Cotton, I. J., "Oxygen Scavengers—The Chemistry of Sulfite Under Hydrothermal Conditions," *Material Performance*, vol 26, no. 3 (March 1987).

Dean, S.W., "Corrosion Testing of Metals Under Natural Atmospheric Conditions," *Corrosion Testing and Evaluations: Silver Anniversary Volume* ASTM STP 1000, R. Baboian and S. W. Dean, American Society for Testing Materials, Philadelphia, PA, 1990.

Dittmer, C.K., R.A. King, and J.D.A. Miller, "Bacterial Corrosion of Iron Encapsulated in Polyethylene Films," *British Corrosion Journal*, vol 10, no. 1 (1975).

Drisko, R.W., "Coatings for Tropical Exposures," *Journals of Protective Coatings and Linings*, vol 16, no. 3 (March 1999).

Hock, V.F., R.G. Lampo, S.A. Johnson, and J.R. Myers, *Corrosion Mitigation and Materials Selection Guide for Military Construction in a Severely Corrosive Environment*, Technical Report [TR] M-88/03/ADA199921 (U.S. Army Construction Engineering Research Laboratory [CERL]), July 1988).

Hock, V., V. Shea, R. Lampo, and J. R. Myers, *Corrosion Protection for Military Construction in the Middle East*, Interim Report [IR] M-85/16/ADA162258 (CERL, September 1985).

Jones, B. L., and A. J. Sansum, "Review of Protective Coating Systems for Pipe and Structures in Splash Zones in Hostile Environments," *Corrosion Management*, no. 14 (October/November 1996).

Kumar, A., and D. Wittmer, "Coatings and Cathodic Protection of Pilings in Saltwater: Results of Five-Year Exposure," *Materials Performance*, vol 18, p 9, 1979.

Lampo, R., A. Kumar, V. Hock, V. Healy, et al., *Corrosion and Coatings Review of Specifications and Drawings of Facilities for the Oman Military Construction Program at Masirah Insland, Oman*, Special Report [SR] M-85/07/ADA149739 (CERL, December 1984).

Leong, R., "Design Criteria for Construction in the U.S. Army Kwajalein Atoll," Memorandum CEPOD-ED-MP(415-1°F) (U.S. Army Construction Engineering Research Laboratory [CERL], 24 June 1991).

Lipfert, F. W., M. Bernarie, and M. L. Daum, "Derivation of Metallic Corrosion Functions for Use in Environmental Assessments," Brookhaven National Laboratory, BNL 51896, 1985.

Merritt, F. S. and J. T. Rickets, eds., *Building Design and Construction Handbook,* (McGraw Hill, Inc. 1994).

Myers, J. R., "Corrosion of Galvanized Steel, Potable Water Pipes," *Australian Corrosion Engineering*, vol 17, no. 5 (May 1973).

——— "Cathodic Protection Design," (University of Wisconsin Press, July 1996).

——— "Inspector's Guide for Sacrificial-Anode-Type Cathodic Protection: Checklist, Part 1," *Underground Tank Technology Update*, vol 11, no. 4 (July/August 1997), pp. 8-9.

——— "Inspector's Guide for Sacrificial-Anode-Type Cathodic Protection: Checklist, Part 2," *Underground Tank Technology Update*, vol 11, no. 5 (September/October 1997), pp. 9-12.

——— "Inspector's Guide for Sacrificial-Anode-Type Cathodic Protection: Checklist, Part 3," *Underground Tank Technology Update,* vol 12, no. 1 (January/February 1998), pp. 10-12.

Myers, J. R., H. B. Bomberger, and F. H. Froes, "Corrosion Behavior and Use of Titanium and Its Alloys," *Journal of Metals*, vol 36, no. 10 (October 1984).

Myers, J. R., and A. Cohen, "Conditions Contributing to Underground Copper Corrosion," *Journal of the American Water Works Association*, vol 76, no. 8 (August 1984).

——— "Behavior of Copper Water Tube Exposed to Natural Carboneceous Granular and Cellulosic Insulation Materials," Corrosion of Metals Under Thermal Insulation: STP 880 (ASTM 1985), pp. 132-142.

——— "Soldering Flux-Induced Pitting of Copper Water Lines," *Materials Performance*, vol 33, no. 10 (October 1994).

——— "Pitting Corrosion of Copper in Cold Potable Water Systems," *Materials Performance*, vol 34, no. 10 (October 1995).

——— "Erosion-Corrosion of Copper Tube Systems by Domestic Waters," *Materials Performance*, vol 37, no. 11 (November 1998).

NCI Information Systems, Inc., "Final Report for Air Force Base Environmental Corrosion Severity Ranking," F09603-95-D-0053; November 1998.

Obrecht, M. F., and J. R. Myers, "Potable Water Systems: Recognition of Cause Vital in Minimizing Corrosion," *Materials Protection and Performance*, vol 11, no. 4 (April 1972), pp. 41-46.

——— "Performance and Selection of Materials for Potable Hot Water Service," *Materials Protection and Performance,* vol 12, no. 4 (April 1973).

——— "Potable Water Systems in Buildings: Deposit and Corrosion Problems," *Heating/Piping/Air Conditioning*, vol 45, no. 5 (May 1973).

——— "The Forms of Corrosion in Potable Water Piping," *Heating/Piping/Air Conditioning*, vol 45, no. 6 (June 1973).

——— "Performance and Selection of Materials for Potable Hot Water Service," *Heating/Piping/Air Conditioning*, vol 45, no. 9 (August 1973).

——— "How Corrosion Engineers Can Aid Designers of Potable Water Systems," *Heating/Piping/Air Conditioning*, vol 45, no. 10 (September 1973).

——— "Corrosion Control for Potable Water Storage Tanks: Linings," *Heating/Piping/Air Conditioning*, vol 48, no. 12 (December 1976).

——— "Corrosion Control for Potable Water Storage Tanks: Cathodic Protection," *Heating/Piping/Air Conditioning*, vol 49, no. 1 (January 1977).

Pettibone, J. S., "Stainless Lampposts Should Last 100 Years," *Nickel*, vol 9, no. 2 (December 1993).

Rogers, W., "Report on the Statistical Analysis of Corrosion Failures Unprotected Underground Steel Tanks," paper presented to the American Petroleum Institute, c. 1981.

Ross, R. W. Jr., and A. H. Tuthill, "Practical Guide to Using Marine Fasteners." *Materials Performance*, vol 29, no. 4 (April 1990).

Rossiter, W. J., W. E. Roberts, and M. A. Streicher, "Corrosion of Metallic Fasteners in Low-Sloped Roofs." *Materials Performance*, vol 31, no. 2 (February 1992).

Rozenfeld, I.L., "Atmospheric corrosion of metals," B.H. Tytell, transl., National Association for Corrosion Engineers, Houston, TX, 1972.

Segan, E. G., D. Larson, J. Myers, T. Race et al., *Materials Selection for Vandenberg AFB*, Report CECER-EM 70-1y (CERL, January 1990).

Smith, W. Harry, *Corrosion Management in Water Supply Systems* (Van Nostrand-Reinhold, New York, NY, 1989).

Stephenson, L. D., *Leak Potential Index Model for Use in Priority Ranking of Underground Storage Tanks at Formerly Used Defense Sites*, USACERL Technical Report 98/50/ADA341068 (CERL, March 1998).

Summitt, Frank, and Fred Fink, "PACER LIME: An Environmental Corrosion Severity Classification System," AFWAL-TR-8-410, Materials Laboratory Air Force Wright Aeronautical Laboratories, 1980

Treseder, R. S., ed., "Corrosion Engineer's Reference Book," (National Association of Corrosion Engineers, 1991).

Vernon, L. S., "The Art of Coating Specification Writing," *Materials Performance*, vol 35, no. 4 (January 1997).

Walker, A. J., "Coal-Tar Coatings," *Industrial Corrosion*, vol 11, no. 5 (August/September 1993).

Appendix A: Unified Facility Guide Specifications (UFGS) Cited in This Report

Note: UFGS are available through the TECHINFO web page published by the U.S. Army Engineering and Support Center, Huntsville, AL.

UFGS No.	***Title***
02456A	Steel H-Piles
02464A	Metal Sheet Piling
02510A	Water Distribution System
02552N	Pre-Engineered Underground Heat Distribution System
02821A	Fencing
03414A	Pre-cast Roof Decking
05090A	Welding, Structural
05093A	Welding Pressure Piping
05120N	Structural Steel
05210A	Steel Joists
05300A	Steel Decking
05500A	Miscellaneous Metal
07412A	Non-Structural Metal Roofing
07413A	Metal Siding
07600A	Sheet Metalwork, General

UFGS No.	*Title*
08110	Steel Doors and Frames
08120	Aluminum Doors and Frames
08165A	Sliding Metal Doors
08510	Steel Windows
08520A	Aluminum and Environmental Control, Aluminum Windows
08710	Door Hardware
09900A	Painting, General
10260A	Wall and Corner Protection
11181A	Incinerators, General Purpose
11211A	Pumps: Water, Centrifugal
11212A	Pumps: Water, Vertical Turbine
11310A	Pumps, Sewage and Sludge
13100A	Lightning Protection System
13110A	Cathodic Protection System (Sacrificial Anode)
13111A	Cathodic Protection System (Steel Water Tanks)
13112A	Cathodic Protection System (Impressed Current)
13120A	Standard Metal Building Systems
13121A	Metal Building Systems (Minor requirements)
13202A	Fuel Storage System
13203A	Tightness Testing of Underground Fuel Systems
13206A	Steel Standpipes and Ground Storage Reservoirs
13210A	Elevated Steel Water Tank
13211A	Pressure Vessels for Storage of Compressed Gases

UFGS No.	*Title*
15400A	Plumbing, General Purpose
15561A	Central Steam Generating System- Combination Gas and Oil Fired
15562A	Heating and Utilities System, Central Steam
15565A	Heating System, Gas Fired Heaters
15601N	Central Refrigeration Equipment for Air-Conditioning
15652A	Cold Storage Refrigeration Systems
15730N	Unitary Air-Conditioning Equipment
16113A	Underfloor Duct System
16115A	Underfloor Raceway System (Cellular Steel Floor)
16375A	Electrical Distribution System, Underground
16415A	Electrical Work, Interior
16528A	Exterior Lighting Including Security and CCTV Applications
16710A	Premises Distribution System

Appendix B: Army Technical Manuals (TMs) Cited in This Report

Editor's note: Army Technical Manuals are available through the TECHINFO web page published by the U.S. Army Engineering and Support Center, Huntsville, AL.

TM 5-652	Steam, Hot-Water and Gas Distribution Systems: Repairs and Utilities
TM 5-653	Steam, Hot-Water and Gas Distribution Systems: Inspection and Preventive Maintenance Services
TM 5-660	Maintenance and Operation of Water Supply, Treatment and Distribution Systems
TM 5-670	Repairs and Utilities for Refrigeration, Conditioning, Mechanical Ventilation and Evaporative Cooling
TM 5-671	Repairs and Utilities: Preventive Maintenance for Refrigeration, Conditioning, Mechanical Ventilation and Evaporative Cooling
TM 5-682	Facilities Engineering: Electrical Facilities Safety
TM 5-683	Facilities Engineering: Electrical Interior Facilities
TM 5-684	Facilities Engineering: Electrical Exterior Facilities
TM 5-805-14	Roofing and Waterproofing
TM 5-810-1	Mechanical Design, Heating, Ventilating and Air Conditioning
TM 5-811-1	Electric Power Supply and Distribution
TM 5-811-2	Electrical Design: Interior Electrical System

TM 5-811-3	Electrical Design: Lightning and Static Electricity Protection
TM 5-811-7	Electrical Design: Cathodic Protection
TM 5-813-1	Water Supply: Sources and General Considerations
TM 5-813-3	Water Supply, Water Treatment
TM 5-813-4	Water Supply: Water Storage
TM 5-813-5	Water Supply, Water Distribution
TM 5-813-9	Water Supply: Pumping Station
TM 5-814-1	Sanitary and Industrial Wastewater Collection- Gravity Sewers and Appurtenances
TM 5-814-2	Sanitary and Industrial Wastewater Collection- Pumping Stations and Force Mains
TM 5-815-3	Heating, Ventilation and Air Conditioning (HVAC) Control Systems

Abbreviations and Acronyms

ABS: acrylonitrile-butadiene-styrene

AC: alternating current

ASM: American Society for Metals

ASTM: American Society for Testing and Materials

AWWA: American Water Works Association

BT: benzotriazole

CIP: clean-in-place or cast-iron pipe

CPVC: chlorinated polyvinyl chloride

DC: direct current

DFT: dry film thickness

ECTFE: ethylene-chlorotrifluoroethylene

FRP: fiberglass-reinforced plastic

HDPE: high-density polyethylene

HMPE: high molecular weight polyethylene

HTHW: high-temperature hot water

HVAC: heating/ventilation/air conditioning

IR: infrared

IRH: International Rubber Hardness

LSI: Langelier Saturation Index

LTHW: low-temperature hot water

MBT: mercaptobenzothiozole

MIC: microbiologically-influenced corrosion

NACE: National Association of Corrosion Engineers

PB: polybutylene

PE: polyethylene

PLA: Predicted Leak Age

PVC: polyvinyl chloride

PVF: polyvinyl fluoride

SCC: stress-corrosion cracking

SSPC: Steel Structures Painting Council

TDS: total dissolved solids

TT: tolyltriazole

UL: Underwriters Laboratories

UV: ultraviolet

Note: A complete listing of abbreviated terms for plastics is available in ASTM Standard Terminology D1600 for Abbreviated Terms Relating to Plastics.

CERL Distribution

Chief of Engineers
ATTN: CEHEC-IM-LH (2)
ATTN: CECW-EE

Engineer Research and Development Center (Libraries)
ATTN: ERDC, Vicksburg, MS
ATTN: Cold Regions Research, Hanover, NH
ATTN: Topographic Engineering Center, Alexandria, VA

Defense Tech Info Center 22304
ATTN: DTIC-O

7
2/02

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 3-2002

2. REPORT TYPE Final

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Materials Selection Guide for Army Installations Exposed to Severely Corrosive Environments

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ashok Kumar and L.D. Stephenson

5d. PROJECT NUMBER
4A162784AT41

5e. TASK NUMBER

5f. WORK UNIT NUMBER
CF-C20

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center (ERDC)
Construction Engineering Research Laboratory (CERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL TR-02-5

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Joseph P. Hartman
U.S. Army Corps of Engineers
441 G Street NW
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)
CECW-EI

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

14. ABSTRACT

Corrosion is the most pervasive maintenance and repair problem faced today by Army facilities managers and engineers. To successfully manage corrosion in Army structures, including electrical/mechanical systems, utility distribution networks, etc., due consideration must first be given to site-specific environmental corrosivity factors. When local corrosivity conditions are properly understood, Army engineers, builders, and managers can make more informed decisions about selecting construction materials.

This report presents guidelines for properly selecting building materials for use on Army installations located in severely corrosive environments. The text includes a discussion of the various corrosion-severity indices available, and also presents material-selection guidelines for metal infrastructure components as diverse as sheet pile, roof decks, electrical utilities, and heat distribution lines. The guidance presented here is intended to be used in conjunction with related Army engineering documents such as Unified Facility Guide Specifications and Army Technical Manuals.

15. SUBJECT TERMS
maintenance and repair, corrosion, corrosion control, corrosion mitigation, Unified Facility Guide Specification (UFGS), Army Technical Manual (TM)

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			L.D. Stephenson
Unclassified	Unclassified	Unclassified	SAR	94	19b. TELEPHONE NUMBER (include area code) (217) 352-6511 X6758

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18