DRAFT

COMPATIBILITY OF WASTES IN HAZARDOUS WASTE MANAGEMENT FACILITIES

A Technical Resource Document for Permit Writers

This document (SW-XXX) was prepared by Fred C. Hart Associates, Inc., under contract to EPA's Office of Solid Waste and Theodore P. Senger of the Hazardous and Industrial Waste Division, OSW.

This document has not been peer and administratively reviewed within EPA and is for internal Agency use/ distribution only.

Stephen A. Lingle 11/2/82
Authorized signature and date

U.S. ENVIRONMENTAL PROTECTION AGENCY/1982

PREFACE

This is one of a series of technical resource documents that provides information on standards for facilities that treat, store, or dispose of hazardous waste.

The documents are being developed to assist permit writers in evaluating facilities against standards (40 Code of Federal Regulations, Part 264) issued under Subtitle C of the Resource Conservation and Recovery Act (RCRA) of 1976, as amended. Included in these documents is detailed information about design, equipment, and specific procedures for evaluating data submitted by the permit applicant, as well as bibliographies that can be used to locate additional information.

The series, which is being produced by the Technology Branch of EPA's Office of Solid Waste, includes guidance on:

- containers
- tanks
- compatibility of wastes
- incineration

Permit writers should keep in mind when using this material that the regulations are subject to change through amendments and modifications and should incorporate any changes into their evaluations of facilities.

The material contained herein is for guidance purposes only and is not enforceable. The technical resource documents are not to be interpreted as amending the facility standards in 40 CFR Part 264.

CONTENTS

	Page
INTRODUCTION	1
WASTE-TO-WASTE COMPATIBILITY	2
Determining Compatibility through Binary Comparison of Chemical Constituents	3
Chemical classes and incompatibility tables	4
Determining compatibility: an example	8
Determining Compatibility through Trial Mixing of Wastes	9
Bench-scale tests	9
Precautions concerning trial tests	9
COMPATIBILITY OF THE WASTE WITH THE CONTAINMENT STRUCTURE	11
Corrosion of Metals	11
General corrosion	11
Localized corrosion	11
Factors influencing corrosion	12
Protection Against Corrosion	13
Soluble inhibitors	13
Paints, coatings, and linings	14
Cathodic protection	14
Evaluating and Selecting Structural and Lining Material	14
Corrosion tests	14
Structural materials	15
Lining materials	17
Corrosion-resistant piping	17
REFERENCES	20
BIBLIOGRAPHY	20
APPENDIX 1: SELECTED MATERIALS FROM CORROSION DATA SURVEY	21
APPENDIX 2: SELECTED MATERIALS ON CORROSION FROM CHEMICAL ENGINEERS' HANDBOOK	32

TABLES

1-1	Incompatible Wastes: Reactivity Group Numbers (RGNs) of Chemical Classes and Incompatible RGNs	5-7
1-2	Waste-to-Waste Comparisons	10
2-1	Compatibility Chart: Chemicals versus Structural Materials	16
2-2	Compatibility Chart: Chemicals versus Lining Materials	18
2-3	Physical Characteristics of Major Hose Stock Types	19

INTRODUCTION

This manual provides information on how to determine the compatibility of hazardous wastes with other wastes and with the various types of structures—tanks, piles, and containers—in which they are stored or treated.

"Incompatible waste" is defined in EPA's regulations (40 CFR Section 260.10) as "a hazardous waste which is unsuitable for: (1) placement in a particular device or facility because it may cause corrosion or decay of containment materials (e.g., container inner liners or tank walls); or (2) comingling with another waste or material under uncontrolled conditions because the comingling might produce heat or pressure, fire or explosion, violent reaction, toxic dusts, mists, fumes or gases, or flammable fumes or gases."

Wastes are not necessarily incompatible whenever they react with each other. Reactions involving neutralization or dissolution of one substance by another, such as metals dissolved in acid, are not generally considered to be incompatible. If, however, such reactions result in fires or explosions or generate toxic substances in amounts that are sufficient to endanger public health and safety and the environment, they are regarded as incompatible.

The standards for containers, tanks, and piles (40 CFR Part 264, Subparts I, J, and L) contain special requirements for managing wastes that are incompatible with other wastes (Sections 264.177, 264.199, and 264.257). Methods for determining compatibility of waste through analysis of waste and trial tests are discussed in Chapter 2. These standards also require that containment structures be compatible with the waste stored in or on them (Sections 264.172, 264.192(a), and 264.253). Several major sources of information on corrosion and compatibility between wastes and containment materials are referenced in Chapter 3.

This manual will assist permit writers in deciding whether adequate procedures are used at a facility for detecting incompatible wastes. It will also help the permit writer to determine if the facility owner or operator is taking proper precautions to avoid inadvertent mixing of incompatible wastes and treating or storing wastes in vessels or equipment with which the wastes are incompatible. Owners and operators of waste treatment, storage, and disposal facilities will find the manual useful in preparing waste analysis plans and determining the compatibility of wastes.

CHAPTER 1

WASTE-TO-WASTE COMPATIBILITY

Standards for facilities that treat, store, or dispose of hazardous waste require that incompatible wastes be separated unless precautions are taken to prevent reactions that:

(1) generate extreme heat or pressure, fire or explosions, or violent reactions;

(2) produce uncontrolled toxic mists, fumes, dusts, or gases in sufficient quantities to threaten human health or the environment;

(3) produce uncontrolled flammable fumes or gases in sufficient quantities to pose a risk of fire or explosions;

(4) damage the structural integrity of the device or facility; or

(5) through other like means threaten human health or the environment.

Owners and operators must document the fact that they have complied with these requirements. Such documentation may be based on references to published scientific or engineering literature, data from trial tests (e.g., bench-scale or pilot-scale tests), waste analyses (as specified in Section 264.13), or the results of the treatment of similar wastes by similar treatment processes under similar operating conditions.

Compatibility of wastes must be determined before treatment or storage to avoid uncontrolled reactions such as fires, explosions, or releases of toxic vapors. If a known waste has not previously been treated at a facility or if there is insufficient information to establish the identity of the waste, the owner or operator should test it for compatibility.

A combination of sources of information can be used to determine the composition of a waste. Among these sources are:

- a description of the waste provided by the generator,
- information of similar wastes contained in the facility operating record, and
- results of detailed analysis of the waste.

Using this information, the owner or operator should consult available references on compatibilities between waste constituents. (One valuable source of such information is discussed in this chapter.) If conclusive information is not available on the compatibility of two wastes, a trial mixing of the wastes in small amounts can be used to determine potential consequences. (Trial mixing of wastes is also discussed in this chapter.)

While the procedures described above are useful in determining the compatibilities of wastes, common sense is also important in avoiding inadvertent mixing of incompatible wastes. All wastes entering a facility should be checked for color, pH, texture, and viscosity to ensure that the waste being received is the same as the waste described on the manifest. Once the identity of the waste is confirmed, previously acquired information on the waste can be used to ensure safe management of it.

The following steps can be used to determine waste-to-waste compatibilities:

1. Request from the generator as much information as possible about the waste to be shipped, since the information required on the waste manifest is very general and of little use in determining compatibilities.

2. If that waste has not been handled previously at the facility, analyze a representative sample of the waste. The information obtained through waste analysis substantiates the generator's information and determines if additional information is needed.

3. Use the information on waste composition gathered in the first and second steps in conjunction with other available information on chemical constituents to determine waste-to-waste compatibilities (as described later in this chapter). If the information is not conclusive, potential consequences of mixing the wastes should be determined through trial tests.

4. Check the waste when it arrives at the facility. Should this check show apparent discrepancies with the information provided by the generator, further tests should be made in an attempt to resolve the discrepancies. If the particular waste is handled on a regular basis at the facility, checking the waste may be simplified.

Based on all the information gathered, the waste shipment is either refused (if discrepancies are not resolved) or accepted and managed properly. The information collected and results of testing must be kept in the operating record of the facility.

DETERMINING COMPATIBILITY THROUGH BINARY COMPARISON OF CHEMICAL CONSTRAINTS

H.K. Hatayama, et al., of the California Department of Health Services, developed a method for determining hazardous waste compatibility (A Method for Determining the Compatibility of Hazardous Wastes, EPA-600/2/80/76, April 1980).[1] The method described in this document, which is summarized here, provides a detailed, straightforward procedure for determining hazardous waste compatibility.

The method presented is based on a study of the chemical reactions that are likely to produce significant hazards to health or the environment. In this method, incompatibility is determined by identifying chemical classes occurring in specific waste streams. The possibility of mixing incompatible wastes in the same storage vessel or of uncontrolled reactions during chemical treatment can be reduced by using this information. This method, which represents a generalized approach, should serve as a guide; it should not replace the services of qualified chemists and analytical laboratories.

In the Hatayama report, the method for determining compatibility is based on the assignment of reactivity group numbers (RGNs) to chemicals typically found in waste streams. Reactivity group members are, basically, related to molecular structure and reactivity of the chemicals—information that is used to predict the compatibility of the wastes.

The method has some limitations because it is based on binary (two-way) combinations of wastes. Ternary (three-way) combinations and catalytic effects are not considered. Wastes, of course, typically contain several or many of the groups presented.

Chemical Classes and Incompatibility Tables

A list of chemical classes, the reactivity group numbers assigned to each chemical class, and examples of chemicals commonly found in wastes that are listed for each chemical class are shown in Table 1-1. The table also includes predictions concerning incompatibility of the RGNs. Forty-one reactivity group numbers are assigned. Numbers 1-34 are based on molecular structure, while numbers 101-107 are based on reaction classifications. Binary combinations of wastes are considered to be incompatible if mixing the wastes results in one or more of the following hazardous consequences:

- generation of heat from chemical reaction;
- fire resulting from extremely exothermic reaction;
- generation of toxic or flammable gases;
- explosion from detonation of unstable reaction products;
- violent polymerization reaction resulting in generation of extreme heat and, possibly, toxic and flammable gases;
- dissolution of toxic substances, including some metals.*

* This reaction is not currently defined as incompatible in EPA's hazardous waste regulations.

TABLE 1-1

INCOMPATIBLE WASTES

REACTIVITY GROUP NUMBERS (RGNs) OF CHEMICAL CLASSES AND INCOMPATIBLE RGNs

Chemical Class	Examples	Incompatible RGNs
Mineral acids, nonoxidizing	chlorosulfonic acid, difluorophosphoric acid	4-15, 17-26, 28, 30-107
Mineral acids, oxidizing	nitric acid, sulfuric acid	All except 104
Acids, organic	benzoic acid, acetic acid	2, 4, 5, 7, 8, 10, 11, 12, 15, 18, 21, 22, 24, 25, 26, 33, 34, 102, 103, 104, 105, 107
Alcohols and glycols	ethylene glycol, ethyl alcohol	1, 2, 3, 8, 18, 21, 25, 30, 34, 104, 105, 107
Aldehydes	benzaldehyde, acetaldehyde	1, 2, 3, 7, 8, 10, 12, 21, 25, 27, 28, 30, 33, 34, 104, 105, 107
Amides	acetamide, formamide	1, 2, 21, 24, 104, 105, 107
Amines	aniline, propanolamine	1, 2, 3, 5, 12, 17, 18, 21, 24, 30, 34, 104, 105, 107
Hydrazines	phenylhydrazine	1-5, 9, 11, 12, 13, 17-23, 25, 30-34, 102-107
Carbamates	ammonium carbamate	1, 2, 8, 10, 21, 22, 25, 30, 104, 107
Caustics	lye	1, 2, 3, 5, 9, 13, 17, 18, 19, 21, 22, 24-27, 32, 34, 102, 103, 107
Cyanides	potassium cyanide, ferro- and ferricyanides	1, 2, 3, 8, 17, 18, 19, 21, 25, 30, 34, 103, 104, 107
Dithiocarbamates	CDEC	1, 2, 3, 5, 7, 8, 18, 21, 25, 30, 34, 103, 104, 105, 107

Chemical Class	Examples	Incompatible RGNs
Esters	ethyl acetate, methyl butyrate	1, 2, 8, 10, 21, 25, 102, 104, 105, 107
Ethers	diethyl ether, diphenyl ether	1, 2, 104, 107
Fluorides, inorganics	sodium fluoride, potassium fluoride	1, 2, 3, 107
Hydrocarbons, aromatic	benzene, toluene, cymene	2, 104, 107
Halogenated organics	chloroacetic acid, chlorobenzenes, bromobutyric acid	1, 2, 7, 8, 10, 11, 20, 21, 22, 23, 25, 30, 104, 105, 107
Isocyanates	ethyl isocyanate	1, 2, 3, 4, 7, 8, 10, 11 12, 20, 21, 22, 25, 30, 31, 33, 104, 105, 106, 1
Ketones	acetone, MEK, benzophenone	1, 2, 8, 10, 11, 20, 21, 25, 30, 104, 105, 107
Mercaptans	ethyl mercaptan, butyl mercaptan	1, 2, 8, 17, 18, 19, 21, 22, 25, 30, 34, 104, 105 107
Metals, alkali and alkaline earth	sodium, potassium, lithium, calcium, barium	1-13, 17-20, 25, 26, 27, 30, 31, 32, 34, 101-104, 106, 107
Metals, other elements and alloys as vapors and powders	cobalt, zinc	1, 2, 3, 8, 9, 10, 17, 1 20, 28, 30, 34, 102, 103 104, 106, 107
Metals, other elemental and alloys as sheets, rods	copper, bronze, cobalt	1, 2, 8, 17, 102, 103, 104, 107
Metals and metal compounds, toxic	cadmium, mercury, beryllium, lead	1, 2, 3, 6, 7, 10, 26, 3 34, 102, 103, 106, 107
Nitrides	silver nitride	1-5, 8-13, 17-21, 26, 27 30, 31, 34, 101, 102, 10 104, 106, 107
Nitriles	acetonitrile, propionitrile	1, 2, 3, 10, 21, 24, 25, 30, 104, 105, 107
Nitrocompounds, organic	nitrobenzene, TNT, nitroaniline	2, 5, 10, 21, 25, 104, 105, 107

Chemical Class	Examples	Incompatible RGNs
Hydrocarbons, aliphatic, unsaturated	ethylene, propylene	1, 2, 5, 22, 30, 104, 10
Hydrocarbons, aliphatic, saturated	octane, butane	2, 104, 107
Peroxides, organic	benzoyl peroxide	1, 2, 4, 5, 7, 8, 9, 11, 12, 17-22, 24, 25, 26, 28, 31-34, 101-105, 107
Phenols and cresols	phenol (carbolic acid) trinitrophenol (picric acid)	1, 2, 8, 18, 21, 25, 30, 34, 102, 104, 105, 107
Organophosphates	chlorothion, malathion	1, 2, 8, 10, 21, 30, 34, 104, 105, 107
Sulfides, inorganic	mercuric sulfide, zinc sulfide, copper sulfide	1, 2, 3, 5, 8, 18, 30, 34, 102, 103, 104, 106, 107
Epoxides	ethylene oxide, cresyl diglycyl ether	1-5, 7, 8, 10, 11, 12, 20, 21, 22, 24, 25, 30, 31, 32, 33, 102, 104, 105, 107
Combustible and flammable materials, miscellaneous	cellulose, camphor oil	1, 2, 21, 25, 30, 102, 104, 105, 107
Explosives	TNT, picric acid, mercury and silver fulminates	1, 2, 3, 8, 10, 13, 21-2 30, 31, 33, 34, 101, 103 104, 105, 107
Polymerizable compounds	ethylene oxide, ethyl acrylate	1, 2, 3, 8, 10, 11, 12, 21-25, 30, 31, 33, 102, 104, 105, 107
Oxidizing agents, strong	chromic acid, potassium permanganate	1, 3-9, 11-14, 16-23, 25-34, 101, 102, 103, 105, 107
Reducing agents, strong	copper sulfide, diethyl aluminum chloride, diethyl zinc	1-8, 12, 13, 17-20, 26, 27, 30, 31, 32, 34, 101-104, 106, 107
Water and mixtures containing water	———	1, 2, 8, 18, 21, 22, 24, 25, 33, 105, 107
Water reactive substances	lithium aluminum hydride, sodium, potassium, aluminum chloride	All

The table lists for each reactivity group number (RGN) all RGNs incompatible with that particular RGN. For RGN 1, for example, the incompatible RGNs are 4-15, 17-26, 28, and 30-107. This means that a waste containing any chemical to which RGN 1 is assigned should probably not be mixed with any other waste containing chemicals in the RGNs listed in the "Incompatible RGN" column. The analyses were conducted independent of quantity and therefore the results should be regarded as precautions rather than prohibitions. The table, of course, does not apply when incompatible wastes are intentionally mixed, such as in neutralization or other treatment processes, under controlled conditions. The Hatayama report includes a color-coded chart that gives the specific reactions that result when these wastes are mixed.

Determining Compatibility: An Example

The compatibility of four different wastes arriving at a facility must be determined in this example. The generators provided the following information concerning the processes generating the wastes:

Waste A: wastewater treatment sludge from electroplating operations

Waste B: distillation bottoms from production of acetaldehyde from ethylene

Waste C: still bottoms from distillation of benzyl chloride

Waste D: spent pickle liquor from steel finishing operations

Representative samples of the wastes were analyzed with the following results:

Waste A: cadmium, chromium, and nickel were detected through atomic absorption spectrophotometry. Cyanide was detected through titration or the use of a specific ion electrode.

Waste B: chloroform, formaldehyde, methylene chloride, methyl chloride, paraldehyde, and formic acid were detected through gas chromatography.

Waste C: benzyl chloride, chlorobenzene, toluene, and benzotrichloride were detected through gas chromatography.

Waste D: pH was measured at 1.8. Iron was detected through atomic absorption. Chloride was detected through use of a specific ion electrode.

The following reactivity group numbers were assigned by using Table 1-1.

Waste A: 11, 24

Waste B: 17, 5, 3

Waste C: 16, 17

Waste D: 2

At this point, Table 1-1 (or the more complete compatibility chart included in the Hatayama report) is employed to determining compatibility of all possible pairs of wastes. The results of this comparison, which are provided in Table 1-2 show that only wastes B and C are compatible.

DETERMINING COMPATIBILITY THROUGH TRIAL MIXING OF WASTES

Bench-Scale Tests

A bench-scale test involving trial mixing of representative samples of hazardous wastes is often the least costly method for determining the compatibility of waste. A trial test, when carried out with proper safety precautions and in a controlled and monitored environment, can often determine the nature (extent and violence) of the reactions that occur between two or more wastes.

Some prior knowledge of the waste (background information or limited analysis) is necessary before trial mixing. With this information one can determine the potential consequences of the reaction.

The quantity of a sample to be used for trial mixing depends upon individual circumstances. Samples should be of sufficient size to produce clearly discernible effects of the mixing. The samples must, however, be sufficiently small to assure that any reaction can be controlled.

One can determine the extent of upper and lower explosive limits for flammable gases by carefully observing upward flame propagation through a cylindrical tube. The amounts of toxic gases produced as a result of reaction may be discovered by gas chromatography for organics and by specific ion electrodes for many inorganic gases in solution.

One method for quickly detecting the evolution of toxic gases involves the use of detector tubes, a variety of which are commercially available. To determine if toxic gases are produced by the reaction being tested, the gas is aspirated through a detector tube for the specific gas. A change of color in the tube indicates the presence of the particular gas, the concentration of which is proportional to the length of the change of color in the tube. A single tube can detect the presence of more than 20 gases.

Precautions Concerning Trial Tests

The mixing of two wastes for which only limited information is available can result in highly violent and dangerous reactions. Safety precautions must therefore be taken to protect laboratory personnel. They should wear explosion-proof hoods and safety glasses and the surroundings should be fire resistant. Safety showers, eyewash stations, and first-aid kits should be available. All personnel should, of course, be famililar with fire and emergency procedures.

The reactions between two wastes in a small-scale test may not accurately reflect the results of large-scale mixing. In large-scale operations, reactions that appeared insignificant or were undetectable in the laboratory can have significant consequences (such as generation of large amounts of heat or toxic fumes). It is obvious, therefore, that extreme care and adequate safety precautions should always be used when mixing or treating large quantities of hazardous waste.

TABLE 1-2

WASTE-TO-WASTE COMPARISONS

Using Reactivity Group Numbers

Wastes A and B

A \ B	17	5	3
11	I		I
24			(I)

Wastes A and C

A \ C	16	17
11		I
24		

Wastes A and D

A \ D	2
11	I
24	(I)

Wastes B and C

B \ C	16	17
17		
5		
3		

Wastes B and D

B \ D	2
17	I
5	I
3	I

Wastes C and D

C \ D	2
16	I
17	I

I - Incompatible
(I) - Consequence is the solubilization of toxic models which is not currently defined by EPA as an incompatible reaction.

CHAPTER 2

COMPATIBILITY OF THE WASTE WITH THE CONTAINMENT STRUCTURE

The standards for treatment, storage, and disposal facilities (40 CFR, Part 264) require that wastes be compatible with their containment structure. In this context, "compatible" means that the waste will not cause accelerated corrosion or deterioration of the containment structure and will not impair the ability of the structure to contain the waste. "Containment structure" includes containers, tanks, pile bases and liners, and surface impoundment liners. None of these structures, of course, has an infinite lifetime and some corrosion and deterioration are expected over time. Consequently, only wastes that significantly accelerate corrosion or deterioration are considered incompatible with the containment material.

General information on corrosion, corrosion rates, inner liners used to prevent corrosion, and the resistance of liners to chemical attack is provided in this chapter. Also included are references to valuable sources on rates of corrosion and on liners. Corrosion inhibitors, used to protect structures and equipment, are also discussed, and some examples of common inhibitors are provided. Cathodic protection which is primarily used to protect a tank from reaction with surrounding soil is discussed briefly.

CORROSION OF METALS

General Corrosion

Corrosion is a complex phenomenon that is usually confined to the metal surface. The complete corrosion reaction is divided into an anodic (positive) portion and a cathodic (negative) portion, occurring simultaneously at discrete points on metallic surfaces. Flow of electricity from the anodic to the cathodic areas may be generated by local cells set up either on a single metallic surface (because of local point-to-point differences on the surface) or between dissimilar metals. Corrosion cells, which derive their driving voltage from the interaction of two different metals, are called bimetallic cells. Such cells are created when two dissimilar metals are connected.

Localized Corrosion[2]

Intergranular Corrosion. Selected corrosion in the grain boundaries of a metal or alloy without appreciable attack on the grains or crystals themselves is called intergranular corrosion. When severe, this attack causes a loss of strength and ductility out of proportion to the amount of metal actually destroyed by corrosion. Alloys such as the austenitic stainless steels and some aluminum-copper alloys, when improperly heated, become susceptible to intergranular corrosion because of the precipitation of intergranular compunds.

The austenitic stainless steels that are not stabilized or that are not of the extra-low carbon types, when heated in the temperature range of 850°-1550°F, have chromium-rich compounds (chromium carbides) precipitated in the grain boundaries. This leads to susceptibility to intergranular corrosion in many environments.

When improperly heat treated, some aluminum-copper alloys become susceptible to selective grain-boundary attack. This attack is attributed to precipitation of relatively large particles of the $CuAl_2$ constituent at the grain boundaries, which results in depletion of copper from the grain boundaries of adjacent aluminum-copper solid-solution materials. Depletion of copper in the grain-boundary material causes the affected metal to become anodic to both the $CuAl_2$ precipitate and the Al-Cu solid solution, and intergranular corrosion will progress in some environments by galvanic behavior.

Pitting Corrosion. Pitting is a form of corrosion that develops in highly localized areas on a metal surface. Chloride ions enhance pitting corrosion of stainless alloys.

Stress-Corrosion Cracking. Corrosion can be accelerated by stress, either by an internal or external force.

Galvanic Corrosion. Galvanic corrosion is the excess corrosion rate that is associated with electrons flowing from an anode to a cathode in the same environment. Galvanic corrosion is an important consequence of coupling two metals that are widely separated in the galvanic series. The result is an accelerated attack on the more active metal.

Crevice Corrosion. Crevice corrosion occurs within or adjacent to a crevice formed by contact with another piece of metal. This phenomenon is associated with a deficiency of oxygen in the crevice, acidity changes in the crevice, or buildup of ions in the crevice.

Factors Influencing Corrosion

pH. Acid solutions are, in general, more corrosive than neutral or alkaline solutions. With amphoteric metals, however, such as aluminum and zinc, highly alkaline solutions may also be quite corrosive.

Oxidizing Agents. Most of the corrosion observed in practice occurs under conditions where the oxidation of hydrogen (to form water) is an unavoidable part of the corrosion process. For this reason, oxidizing agents are often powerful accelerators of corrosion. The oxidizing potential of a solution is therefore an important property affecting corrosion.

Temperature. The rate of corrosion tends to increase with rising temperature, since chemical reaction rates always increase with increases in temperature.

Chlorides. Chlorides generally accelerate corrosion of iron and steel, since even small amounts of chlorides can break down the passive oxide film on stainless steels.

Stray Currents. Stray electrical currents that come from power lines or from improperly constructed electrical systems and travel through the soil before returning to the source cause differentials in electrical potential leading to rapid corrosion.

Soluble Inhibitors

Soluble inhibitors are substances that can be added to the contents of a waste storage tank to inhibit corrosive reactions. The choice of a particular chemical to be used as an inhibitor is highly dependent on the composition of the tank contents.

In order to understand the action of soluble inhibitors, it is important to know the mechanism by which corrosion is created. Corrosion occurs at anodic points on the surface where iron goes into a solution:

$$Fe \longrightarrow Fe^{++} + 2e^- \text{ (anodic)}$$

At the nearest cathodic point, the reaction usually occurring is:

$$2H^+ + 2e^- \longrightarrow H_2 \text{ (hydrogen evaluation in acidic solution, cathodic)}$$

$$\text{or } 1/2\ O_2 + H_2O + 2e^- \longrightarrow 2OH^- \text{ (oxygen reduction in alkaline solution, cathodic)}$$

Since the anodic and cathodic reactions occurring during corrosion are mutually dependent, it is possible to reduce corrosion by reducing the rates of either reaction. Corrosion inhibitors function by interfering with either the anodic or cathodic reactions, or both.

Certain organic compounds can function as inhibitors by forming an impervious film on the metal surface or by interfering with either the anodic or cathodic reactions. High molecular weight amines retard the cathodic hydrogen evolution reaction ($2H^+ + 2e \quad H_2$) and therefore reduce the corrosion rate. Arsenic and antimony ions specifically retard the hydrogen evolution reaction. They are therefore effective in acid solutions but are ineffective in environments where other reduction processes, such as oxygen reduction, are the controlling cathodic reactions. Conversely, some inhibitors work effectively in solutions where oxygen reduction is the controlling cathodic reaction. These inhibitors (such as sodium sulfite or hydrazine) act by removing oxygen from the solution; they are not, however, effective in strong acid solutions.

Chromate and nitrite are primarily used to inhibit the corrosion of metals and alloys that demonstrate active-passive transitions, such as iron and its alloys and stainless steels. (Passivity refers to the loss of chemical reactivity of certain metals and alloys under particular environmental conditions. Metals that possess an active-passive transition become corrosion resistant in moderate-to-strong-oxidizing environments.)

Paints, Coatings, and Linings

Paints and coatings are widely used as corrosion inhibitors, particularly for the prevention of corrosion owing to exposure to the elements. Paint helps to exclude water and oxygen from the metal surface, thus preventing formation of rust. Paint and varnish films are not, however, entirely impervious to water and oxygen.

Inhibitive pigments, such as chromates or red lead, are commonly used in paints for protection of metal from corrosion. Inhibition of corrosion occurs because of several factors: the pigment neutralizes acids, catalyzes the formation of protective ferric oxide films at the iron surface, and (in the case of red lead) serves to destroy sulfur dioxide, which is a very corrosive constituent in the ambient air of urban and industrial areas.

A superior alternative to coating the tank with paint is lining it with a highly impervious material. Linings are applied to the walls of the tank or container and serve to protect the wall from contact with the liquid contents. Examples of common lining materials are rubbers, epoxies, and silicones.* (A discussion of the resistance of lining to chemical attack is included in the following section on evaluating and selecting structural and lining materials.)

Cathodic Protection

Cathodic protection minimizes corrosion by establishing an electrochemical cell in which the metal to be protected is the cathode. Two methods are:

1. The sacrificial anode method uses zinc, magnesium, or aluminum as anodes in electrical contact with the metal. The required current is generated by corrosion of the sacrificial anode material.

2. The impressed electromotive force method provides direct current by external sources, which is passed through the system by use of anodes (such as carbon, noncorrodible alloys, or platinum) buried in the ground or suspended in the electrolyte in an aqueous system.

EVALUATING AND SELECTING STRUCTURAL AND LINING MATERIAL

Corrosion Tests

When information on experience with similar wastes and material (structural material and linings) is not available, corrosion tests are highly recommended.

---

* For additional material on coatings and liners, see EPA's Lining of Waste Impoundment and Disposal Facilities (SW-870) and the permit writers' guidance manual on storage of hazardous waste in containers (SW-XXX).

Exposure time is very important in testing of metal samples. In a batch-treatment process, test time should equal the expected batch time. In continuous treatment processes, test time can be determined as a function of the corrosion rate as follows:

$$\text{Minimum exposure time (hours)} = \frac{2000}{\text{Corrosion rate in mils per year}}$$

(1 mil = .001 in)

In addition to weighing, the corrosion rate can be determined by inspecting samples for pitting, crevice corrosion, or stress-corrosion cracking. A corrosion rate of over 20 mils per year is generally considered poor and is only justified in special circumstances. (For additional information on corrosion tests see reference 4.).

With polymers, long-term effects may be accelerated by testing at elevated temperatures. Solvent attack of polymers is measured in terms of swelling, loss of strength, change in color, and deterioration. In a 1-month test, a 15 percent loss of tensile strength or 1.5 percent change in weight indicates poor resistance. For rubber, a 5 percent change in weight or 25 percent change in volume after 30 days indicates poor resistance.

Structural Materials

Since steels are the principal construction material for tanks and containers, this discussion of resistance to corrosion of structural materials is limited to steels. Information on some other materials is summarized in Table 2-1. (Additional information can be obtained from the National Association of Corrosion Engineers, the American Concrete Institute, and the Chemical Engineers' Handbook, (cited in reference 2). Examples of the types of information available are provided in Appendices 1 and 2.

Carbon Steel.[2] Carbon steel is a low alloy or mild steel. Carbon steel should not be used in contact with dilute acids. It can be used effectively as construction material for tanks holding organic solvents. In addition, carbon steel is relatively inexpensive, and it exhibits excellent ductility.

Stainless Steel.[2] There are more than 70 standard types of stainless steel and many special alloys. Stainless steels are iron-based, with 12 to 30 percent chromium, 0 to 22 percent nickel, and minor amounts of carbon, niobium, copper, molybdenum, selenium, tantalum, and titanium. Stainless steels are divided into the following three groups:

a. Martensitic alloys contain 12 to 30 percent chromium with small amounts of carbon and other additives. Corrosion resistance is inferior to other groups of stainless steel. Martensitic steels can be exposed to organic materials.

b. Ferritic stainless steel contains 15 to 30 percent chromium, with low carbon content. Corrosion resistance is good, although ferritic alloys are attacked by hydrochloric acid. Ferritic alloys can be used with mildly corrosive acids and some oxidizing media.

TABLE 2-1

COMPATIBILITY CHART: CHEMICALS VS STRUCTURAL MATERIALS

Construction Material	Incompatible Chemicals
Steel	Mineral acids; nitric, hydrochloric, sulfuric acids
Aluminum	Alkalies; potassium hydroxide, sodium hydroxide, mineral acids
Magnesium	Mineral acids
Lead	Acetic acid, nitric acid
Copper	Nitric acid, ammonia
Nickel	Nitric acid, ammonia
Zinc	Hydrochloric acid, nitric acid
Tin	Organic acids, alkalies
Titanium	Sulfuric acid, hydrochloric acid

c. Austenitic stainless steels are the most corrosion-resistant stainless steels. These steels contain 16 to 26 percent chromium and 16 to 22 percent nickel. Carbon content is very low. Austenitic stainless steels have excellent resistance to nitric acid. Chloride ions, however, will cause significant corrosion.

Lining Materials

A brief summary of information on the compatibility of lining materials is presented in Table 2-2. Additional information is available from the National Association of Corrosion Engineers and the Chemical Engineers' Handbook (reference 2). Information on lining materials used for pile bases and surface impoundments is contained in EPA's Lining of Waste Impoundment and Disposal Facilities.[3]

Corrosion-Resistant Piping

A brief summary of information on the durability of "rubber" hose is contained in Table 2-3 and the article "Beat Corrosion with Rubber Hose."[5]

TABLE 2-2

COMPATIBILITY CHART: CHEMICALS
VERSUS LINING MATERIALS

Lining Materials	Incompatible Chemicals
Alkyds	Strong mineral acids, strong alkalies, alcohols, ketones, esters, aromatic hydrocarbons
Vinyls (polyvinyl-chloride-PVC)	Ketones, esters, aromatic hydrocarbons
Chlorinated Rubbers	Organic solvents
Epoxy: (amine-cured, polyamide cured, or esters)	Oxidizing acids (nitric acid), ketones
Coal Tar Epoxy	Strong organic solvents
Latex	Oxidizing acids, ketones, esters
Polyesters	Oxidizing acids, strong alkalies, mineral acids, ketones, aromatic hydrocarbons
Silicones	Strong mineral acids, strong alkalies, alcohols, ketones, aromatic hydrocarbons

TABLE 2-3

PHYSICAL CHARACTERISTICS OF MAJOR HOSE STOCK TYPES

Hose Compound / ;trength nd lesistance	Natural Rubber (and Styrene Butadiene*)	Butyl (IIR)	Ethylene Propylene (EPDM)	Hypalon (CSM)	Neoprene (CR)	Buna N (NBR)	Tufflex†	Gatron†	Fluoro-elastomer (FPM)	Epi-chloro-hydrin	Polyester Elastomer	Nylor
'ensile trength	Excellent	Fair to good	Good	Good	Good	Fair to good	Good	Good	Fair	Good	Good	Good
'earing	Good to excellent	Good	Good	Fair	Good	Fair to good	Good	Fair	Fair	Good	Good	Good
braslon	Excellent	Fair to good	Good	Good	Good to excellent	Fair to good	Good	Fair	Good	Fair to good	Good	Good
lame	Poor	Poor	Poor	Good	Very good	Poor	Fair to good	Poor	Good	Poor	Poor	Good
etroleum, oil nd commercial asoline	Poor	Poor	Poor	Good	Good	Good to excellent	Fair	Excellent	Excellent	Excellent	Good	Excel
as permeation	Fair	Out-standing	Fair to good	Good to excellent	Good	Good	Good	Good	Good	Good	Good	Excel
eathering	Poor	Excellent	Excellent	Very good	Good to excellent	Good** to poor	Excellent	Excellent	Excellent	Very good	Good	Excel
zone	Poor	Excellent	Out-standing	Very good	Good to excellent	Good** to poor	Excellent	Excellent	Excellent	Very good	Good	Excel
eat	Poor	Excellent	Excellent	Very good	Good	Good	Fair	Fair	Out-standing	Excellent	Excellent	Good
ow temperature	Good	Very good	Good to excellent	Poor	Fair to good	Poor to fair	Excellent	Fair to good	Good	Excellent	Excellent	Excel
eneral	Good	Good	Good	Good	Good	Fair to good	Good	Excellent	Excellent	Fair to good	Good	Excel

*Styrene butadiene polymer (SBR) has properties very similar to natural rubber.
**Good to poor depending on requirements and compounding.
†Trademarks of Gates Rubber Co.

ource: Reprinted by special permission from Chemical Engineering, R. Gallapher, Sept. 8, 1980, McGraw-Hill, Inc., New York, NY 10020.

REFERENCES

1. Municipal Environmental Research Laboratory, A Method for Determining the Compatibility of Hazardous Waste (EPA-600/2-80-076) (Cincinnati, OH: MERL, 1980). (Copies are available from the National Technical Information Service, Springfield, VA 22161.)

2. Robert H. Perry and Cecil H. Chilton, Chemical Engineers' Handbook, 5th Ed. (New York: McGraw Hill, 1973).

3. U.S. Environmental Protection Agency, Office of Solid Waste, Lining of Waste Impoundment and Disposal Facilities (SW-870) (Washington, DC: U.S. EPA, 1980).

4. For additional Information on the selection of structural and lining materials for containment structures used to store or treat liquid hazardous waste see Gary N. Kirby, "How to Select Materials," Chemical Engineering, November 1980: 86-131. (Order number: reprint 046)

5. R. Gallagher, "Beat Corrosion with Rubber Hose," Chemical Engineering (New York: McGraw Hill, 1980).

BIBLIOGRAPHY

N.E. Hamner, Corrosion Data Survey—Metals Section; Corrosion Data Survey—Nonmetals Section, 5th Ed. (Houston, TX: National Association of Corrosion Engineers, 1974; 1975).

ACI Committee 515, "Guide for the Protection of Concrete Against Chemical Attack by Means of Coatings and Other Corrosion-Resistant Materials," ACI Journal, Proceedings, 63(1966):1305-1392.

APPENDIX 1

Selected Pages from Corrosion Data Survey, 5th Edition (Houston, Texas: National Association of Corrosion Engineers, 1974). Pages 22-31 are reprinted with permission of the National Association of Corrosion Engineers.

In the development of new chemical processes, questions invariably are raised concerning the choice of materials for certain equipment. However, as available corrosion information is scattered widely through the technical literature, these questions frequently are not easy to answer.

This survey summarizes published data in a group of charts for ready reference in order that possible materials for use may be recognized quickly and unsuitable ones rapidly eliminated. These charts act only as a guide and it is to be expected that in most cases additional corrosion testing and pilot plant experience may be necessary. The charts have been checked against actual plant conditions and a good correlation has been found. In cases of doubt, representatives of metal and other material suppliers often can be helpful in supplying additional information. In any event, the services of a Corrosion Engineer for a precise interpretation of the data, combined with supplemental information will be most beneficial.

References on the graphs have not been acknowledged. They have been collected from a wide variety of sources,[1] but have been taken for the most part from the following publications:

Title	Author
Book of Stainless Steels	E. E. Thum
Chemical Engineering	McGraw-Hill Publishing Company
Combatting Corrosion in Process Industries	Crane Company
Corrosion	National Association of Corrosion Engineers
Corrosion Guide	E. Rabald
Corrosion Handbook	H. H. Uhlig
Corrosion Catalog	Pacific Foundry Company
Dechema Werkstoff-Tabelle	E. Rabald and H. Bretschneider
Duriron Catalog	Duriron Company
Industrial and Engineering Chemistry	American Chemical Society
Interstate Commerce Commission Regulations	I.C.C.
Korrosionstabellen metallischer Werkstoffe	F. Ritter
Lead	Lead Industrie
Materials of Construction for Chemical Process Industrie	James A. Lee
Materials Protection	National Association of Corrosion Engineers
Meehanite Catalog	Meehanite Corporation
Metals and Alloys	Reinhold Publishing Company
Metals and Alloys Data Book	S. L. Hoyt
Metals Handbook	American Society for Metals
Nickel and Nickel Alloys	International Nickel Company
Oil and Gas Journal	Petroleum Publishing Company
Silver in Industry	L. Addicks, A. Butts, J. M. Thomas

In using the charts, reference should be made to the code on Page x. This illustrates the method by which concentration and temperature are compared against corrosion rates.

The following comments enlarge on the means used to present the data and emphasize the importance of many additional factors in determining the corrosion resistance of a material. All factors involved in the proper selection of a material for a given service cannot be expressed in such a simple, graphical form. Consequently, IT IS IMPORTANT THAT THE FOLLOWING NUMBERED SECTIONS BE READ CAREFULLY.

1. Corrosives

Although the major arrangement of corrosives is alphabetical, a series of charts listed in the Table of Contents present additional information on special topics and on certain generally encountered corrosives. Experience with previous reports has revealed that a grouping of corrosion rates by similar compounds is helpful. When information on the particular corrosive under consideration is meager or lacking, there may be others in the same general group which could be expected to react with materials in a similar manner.

2. Materials of Construction

Materials of construction available at reasonable cost and in a wide variety of forms have been selected for general corrosion rating. In special cases, other materials also are plotted.

This schedule of materials and their analyses illustrates one of the drawbacks of a collection of data such as this. It would be difficult, if not impossible, to accommodate information laboriously compiled over the years to changed alloys. For example, Carpenter 20 Alloy, formerly with 29 percent nickel, was changed to 34 percent nickel five years ago. Thus data relating to this alloy compiled before 1962 obviously cannot be used with confidence in considering the alloy currently bearing this designation. Similarly, a whole host of new data has been accumulated since 1960 on such metals as gold, platinum and tantalum, now grouped under one heading in the tables. The new data permit precise discrimination among these materials which cannot be displayed in the tables as now arrayed.

Materials have been grouped under general classification headings according to the major base metal. Within each classification are a number of materials frequently considered to have comparably similar corrosion resistances. For example:

a. In carbon steels, carbon content up to 0.30 is not considered to alter appreciably the corrosion rate.
b. Copper, red brass, silicon bronze, aluminum bronze, tin bronze and the cupronickels are considered to have similar corrosion

resistances in most media, but it is recognized they can differ markedly in specific environments.

c. In stainless steels, Types 302, 304, 304L, 321 and 347 are expected to have similar corrosion resistance and are grouped as 18-8 stainless in the corrosion tables.

d. In aluminum alloys, the following types are expected to have equivalent corrosion resistance: 1100, 3003, 3004, 5052, 6061, 6062; and cast 43, B214, 356 and 406. No aluminum alloy containing over 1.0 copper should be considered to have corrosion resistance equal to those previously listed.

Thus, where data on any of the above are shown on the charts, other materials in the same group usually can be expected to perform in a like manner.

3. Concentration of Corrosives

Concentration in all cases (except in certain solutions and gases either desiccated or essentially so) are considered to be water dilutions of pure compounds. Although it is fully understood that small quantities of contaminants may have a profound effect on corrosion rates, this factor is not ordinarily taken into account, usually (but not always) because the specific contaminants are not reported in the references from which data are taken. In instances when a metal was designated as being unaffected by a chemical and no mention was made of concentration or temperature, the charts show the metal as satisfactory at the 100 percent line at room temperature. This indicates that the metal has a possible use and could be tried.

Ratings for dry, or essentially dry, material also have been noted because, among other uses, such notations are helpful in selecting materials to be used as shipping or storage containers.

4. Temperature

The effect of temperature on corrosion reactions does not satisfactorily fit the usual rate equations. The temperature effect is rarely exponential, as it would be for most chemical reactions and it is rarely linear as it would be if influenced by physical changes alone. Rate increases of 100 to 200 percent per 10 C increments are typical of chemical reactions and rate increases of 20 to 30 percent per 10 degree rise are typical of diffusion-controlled processes. Some experimental corrosion rates increase with temperature whereas others decrease and in some cases maxima are observed. In general, the effect of temperature on the corrosion rate depends on its influence on the factors controlling the corrosion reaction and the electrochemical potential of the metal.

Temperature may affect the corrosion rate through its effect on oxygen solubility and availability. As temperature rises oxygen solubility in an aqueous solution decreases and at the boiling point all oxygen is removed. Opposed to this is the fact that the diffusion rate of oxygen increases with temperature. It is rather common, therefore, to find that the corrosion rate increases with temperature to some maximum and then decreases to some low value at the boiling point.

Temperature may affect corrosion through its effect on pH. Because dissociation of water increases with temperature, pH decreases with temperature. At 60 C, the "neutral" pH is 6.4. The corrosion rate of steel in water at 22 C is constant from pH 4 to pH 10 but it rises on the acidic side and decreases on the alkaline side. At 40 F the plateau is narrower, extending from pH 4.5 to 8.5. This reflects the enhanced activity of the hydrogen ion in increasing the corrosion rate on the low pH side and the increased activity of the hydroxyl ion in passivating the steel on the alkaline side.

Temperature also may affect corrosion rates through its effect on films. It may increase the solubility of protective corrosion products, as in the case of lead in hydrochloric acid. Lead chloride is insoluble and protective in cold, but is soluble and non-protective in hot acid. A change in temperature also may bring about changes in the physical nature or the chemical composition of corrosion products which may make them considerably more, or less, protective. The behavior of zinc in water is an example. Another effect of rising temperatures on films is caused by precipitation of protective coatings on metallic surfaces, as in waters containing calcium sulfate and calcium carbonate.

In solutions under pressure at temperatures above their normal boiling points, corrosion rates may increase quite rapidly with temperature, possibly because many of the factors (such as diffusion, which normally acts to limit corrosion) are no longer controlling. The limiting effect of diffusion also can be overcome by rapid movement.

The effect of heat flux on the corrosion rate must be recognized. Maintaining a liquid at a bulk temperature of 120 C in a vessel can produce no corrosion, whereas the same temperature on the heating side of a metal surface can result in catastrophic corrosion.

Also, certain materials may have chemical stability in an environment beyond the temperature at which they are structurally stable. The physical and mechanical properties of the material then need to be fully appraised before making a choice.

Temperatures are plotted in degrees Fahrenheit from 75 to 800 degrees on the left and in the corresponding degrees Centigrade on the right. Where information is available at temperatures above 425 C, a figure indicating this datum is added to the graph. This method permits evaluation of information in the most commonly used range below the boiling point and also permits plotting of high temperature data.

5. Corrosion Rates

An arbitrary set of corrosion rates has been established to meet the requirements of instrument, design and maintenance engineers. While it is desirable that chemical plants be constructed of materials which will be free from corrosion, this is not always possible nor economically attractive so it is recognized that the most economical overall procedure is to provide for a small losses of metal and keep the plant maintained by constant inspection and repair of corroded and wornout parts.

The ideal rating (a solid circle) has been assigned when corrosion is less than 0.002-in (2 mils) per year, representing materials that would suffer essentially no dimensional change during the life of the process. Many materials have this property and may be used for some pieces of equipment, although they may be ruled out for others because of other failings, such as contamination of product, brittleness, temperature limitations, or unavailability in suitable form.

When this highest degree of corrosion resistance cannot be indicated, a second rating (an open circle) representing less than 0.020-in per year corrosion rate is used. In the development of this category, considerable difficulty has been encountered owing to the various methods of reporting corrosion data. It has been found that many excellent materials will be reported as "Recommended" or "Completely Resistant". It is believed that some of these materials may have corrosion rates less than 0.002-in per year. However, without actual figures, they have been placed in the second category rather than the ideal one. For the majority, corrosion rates probably will be below 0.005-in per year. The rating of 0-020-in per year indicates those materials which normally would be specified where a corrosion allowance of 1/16 to 1/8-in is added for protection against possible mild corrosion.

A third classification (an open square) is provided to indicate a corrosion rate between 0.020 and 0.050-in per year. These materials can be used only in special cases where such a rate can be tolerated, but are not considered adequate for general plant construction.

The final rating (a cross) is given where the corrosion rate is probably too high to merit consideration (over 0.050-in per year).

It is conceded that deterioration of most non-metallic materials should not be expressed in the same manner as the corrosion of metals. However, the same rating code has been used in this publication to allow presentation of the data in compact form. When reviewing the data for the non-metallic materials, consider the solid dot to indicate fully satisfactory resistance, the unshaded circle to indicate useful resistance with some loss of properties, the square to signify doubtful utility of the material with testing definitely required, and the X to show severe attack of the material.

6. Additional Factors Influencing Corrosion Rates

There are many factors besides concentration and temperature which influence corrosion rates and, while they are often extremely important, it is impossible to list them all in a survey of this type. For example, velocity, aeration, heat flux, the presence of oxidizing agents and other chemical contaminants can either increase or decrease the corrosion rate, so where possible, rates have been added to graphs indicating these effects.

The effect of galvanic coupling is also important in assessing the useful life of a piece of equipment and Tables 1 and 2 are expositions of the galvanic series in sea water. While minor shifts in the position of alloys may be expected in other electrolytes, the sea water series is a good guide to the behavior of alloy groups when coupled. Normally when alloys close together in the series are in contact they will not cause a significant increase in corrosion rate of the metal higher in the series.

TABLE 1 — Galvanic Series in Sea Water (1)

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]		[illegible]

TABLE 2 — Galvanic Series for Oilwell Materials in Artificial Sea Water

[illegible]	
[illegible]	[illegible]
	[illegible]
	[illegible]
	[illegible]
[illegible]	
[illegible]	
[illegible]	
[illegible]	
[illegible]	
[illegible]	
[illegible]	
[illegible]	

Welding is another factor which may influence service life. Aside from intergranulo. corrosion, which is discussed later in Section 8, there are instances where as-deposited weld metal is attacked in preference to the base metal; conversely, there are occasions when the weldment is more resistant. Additionally, localized stresses due to welding often make zones adjacent to welds susceptible to stress corrosion cracking. For these reasons, selection of correct welding material is as important as selection of base material.

Many alloy systems show variations in corrosion resistance as a result of being heated or cooled in a certain way. It is important that fabrication and heat treatment are such that an alloy's corrosion resistance is not impaired if the fabricated part is intended for corrosive service. Generally the solution annealed condition is preferred, but the manufacturer of the alloy should be consulted for his recommendations.

7. Effect of Stress on Corrosion Rates

Generally, stressing metals at less than their elastic limit does not markedly increase corrosion rates. Under some circumstances and under special conditions of temperature and with some corrosives, this may not be true. It is true also in some environments that alternating stresses result in faster corrosion rates than static stress in one direction alone. Markedly different corrosion rates have been experienced with certain metals when they were stressed after exposure in an environment than when they had been stressed before exposure. There also may be a differential in corrosion rates between that side of a material under compressive stress and the one under extension.

The whole subject of corrosion of materials under stress is exceedingly complex, so no brief explanation can be adequate. The engineer seeking data on corrosion performance needs to be aware of the fact that stresses on materials are important factors in performance. If any indecision exists concerning the behavior of a given material under stress, the services of a competent corrosion metallurgist will prove helpful.

There are very important instances when stress and corrosion operating simultaneously will not cause increased general attack but will produce fracture. These are called corrosion fatigue and stress corrosion cracking. While corrosion fatigue may occur in any corrosive medium, stress corrosion cracking requires a specific combination of alloy and environment.

Quite often the stress which causes stress corrosion cracking is due not only to operating conditions but also to locked-in stress due to fabrication. Welding, in particular, often induces stresses sufficient to cause failure. For this reason, post-fabrication heat treatments often are specified.

While stress cracking is indicated on the graphs, the materials definitely should be stress relieved after fabrication, or a metal not susceptible to stress cracking should be selected. For stress relieving times and temperatures, the manufacturer of the alloy should be consulted.

8. Intergranular Corrosion

Intergranular corrosion attacks grain boundaries of materials and can be particularly aggressive when in certain chemical solutions are in contact with austenitic stainless steels which have precipitated carbides at grain boundaries (sensitization). This precipitation is produced when the steel has been subjected to temperatures between 800-1400 F and is often present adjacent to welded areas. Various methods have been developed to eliminate this undesirable condition. However, because intergranular corrosion is not produced by all corrosive media, special heat treatments or specification of stabilized types of 18-8 often are unnecessary.

Certain other metals and alloys are subject to intergranular attack when exposed to specific media under some environmental conditions and others after an adverse heat treatment. In such cases the manufacturer should be consulted for information relating to his product.

9. Corrosion Inhibitors

Because the proper use of inhibitors requires good understanding of electrochemical and chemical factors involved in both the metal to be protected and the corrosive, they are not considered in this tabulation except in a very few instances. An example is the percentage of water required in a solution of hydrochloric acid and methanol to prevent corrosion of titanium and zirconium. The technology of inhibition is well developed and the literature voluminous.

Not considered among the data either are the electrical techniques of cathodic and anodic protection, both of which have benefits under some conditions when applied by persons with the necessary experience and skill. Those who are interested in investigating these techniques may get good advice from consultants in these fields.

(1) Reprinted from "Galvanic Corrosion in Oil and Gas Well Fluids" by F. L. LaQue. Corrosion, 5, No. 3, 86-91 (1949) March.

Main Tables

The following pages have been designated "main" data pages mainly for convenience in identification and not to denote that the information they contain is different from that appearing in tables elsewhere. The data displayed is of the same kind and reliability and comes from the same sources as other data.

It is advisable to examine the matrix below before attempting to use the tables. A replica of this matrix appears on all left hand pages. Note that both Fahrenheit and Centigrade scales are used in the ordinate while the abscissa scale denotes concentration percent in water. "Concentration percent" in this scale is not necessarily the same as "percent solution" because in many instances data are given for mixtures which exceed the solubility limits of the chemicals in water. Although the original sources do not always make it clear, it can be assumed that when solubility limits are exceeded, a mixture or slurry is inferred.

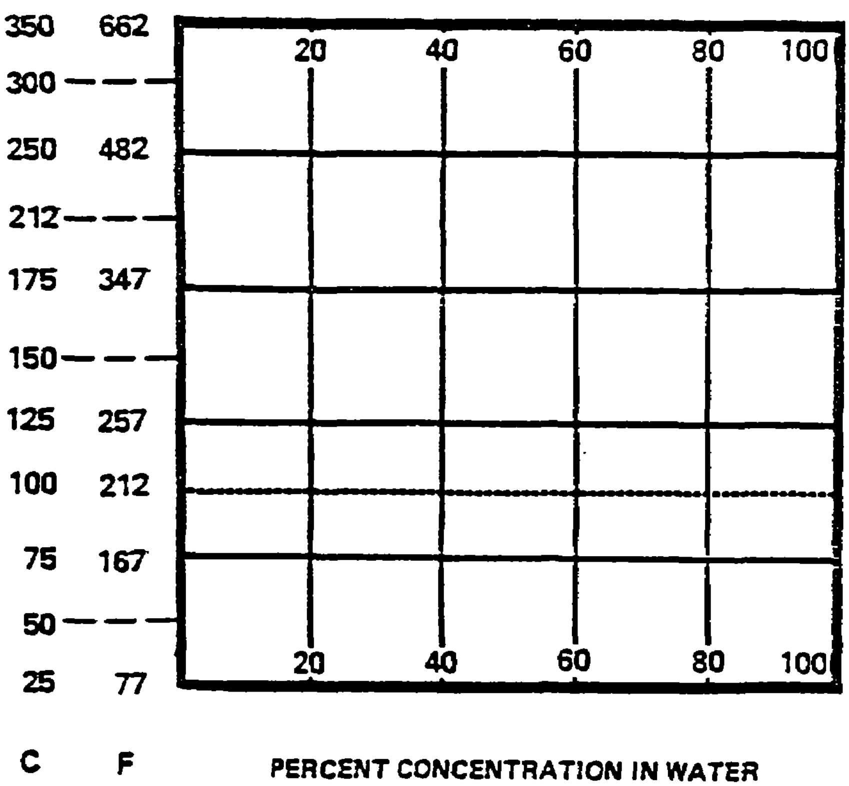
Likewise, in many instances, reactions are given at temperatures which exceed those at which the solutions at the concentrations posted usually boil. Because there are few pressure data in the sources from which the information is taken, it has been assumed that pressures exist which permit reactions at the temperatures posted. Vapor phase attack may or may not be assumed except in those instances when this factor has been noted in the original source and posted as a footnote in the matrix.

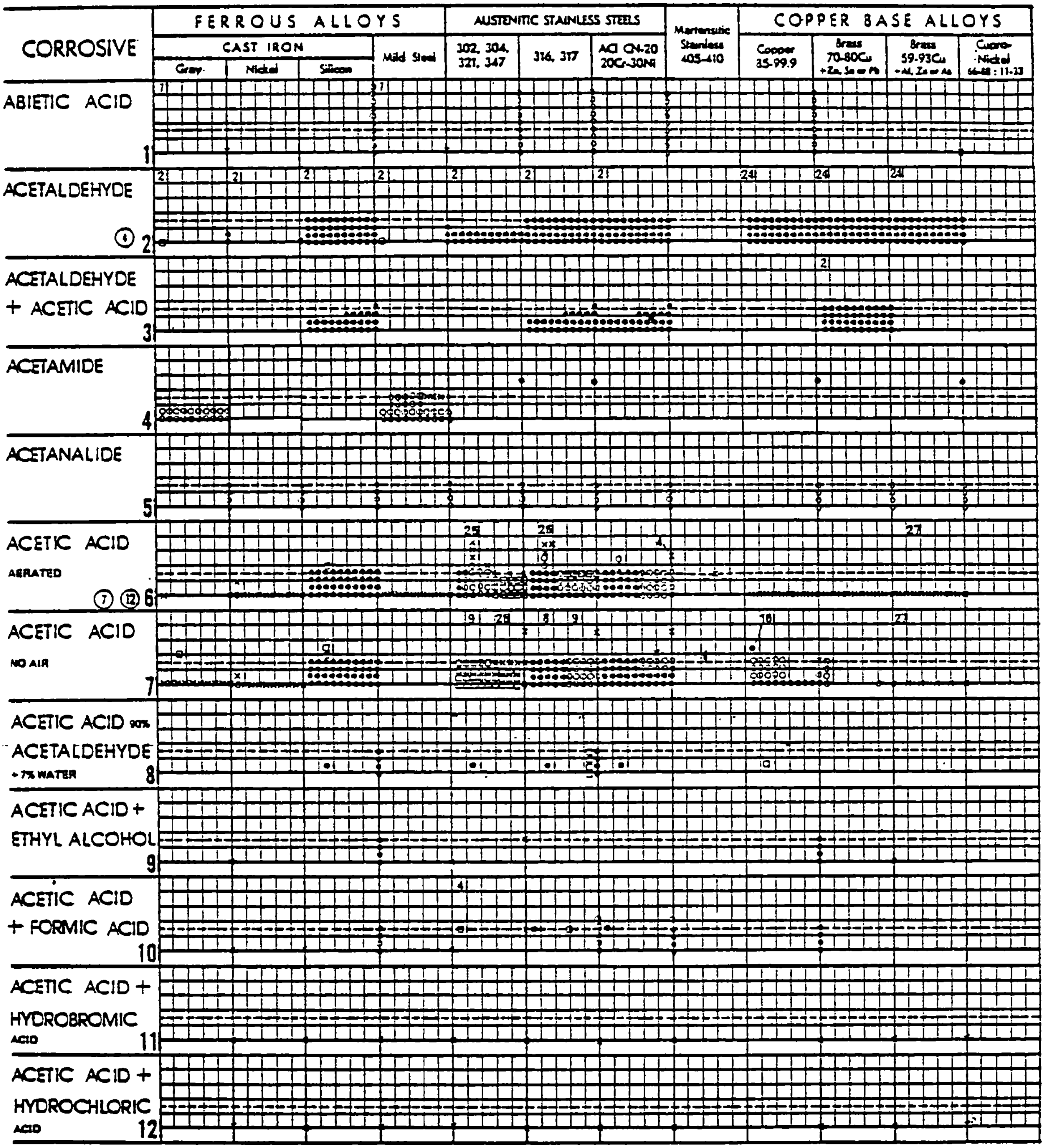
Intervals in the Centrigrade temperature scale used in the ordinate are as given below:

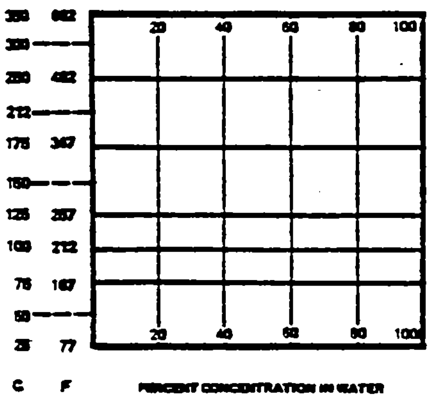
Degrees Centigrade	No. of Degrees in Interval
25 to 75	.50
75 to 125	.50
125 to 175	.50
175 to 250	.75
250 to 350	100

A table of penetration rates showing the meaning of the indicia used in the matrix in English and metric units also appears on every left hand page. A conversion table which permits a rough approximation of weight loss in some commonly used units to the penetration rates in the matrices appears on every left hand page also.

Right hand pages contain two schedules of footnotes. That in the left box pertains to the corrosives, while that in the right box pertains to data posted in the squares.







AVERAGE PENETRATION PER YEAR

Code		Mils	[illegible]	[illegible]
●	<	2	0.002	50.8
○	<	20	0.020	508.0
□	{	20- 50	0.020 0.050	508.0 1270.0
x	>	50	0.050	1270.0

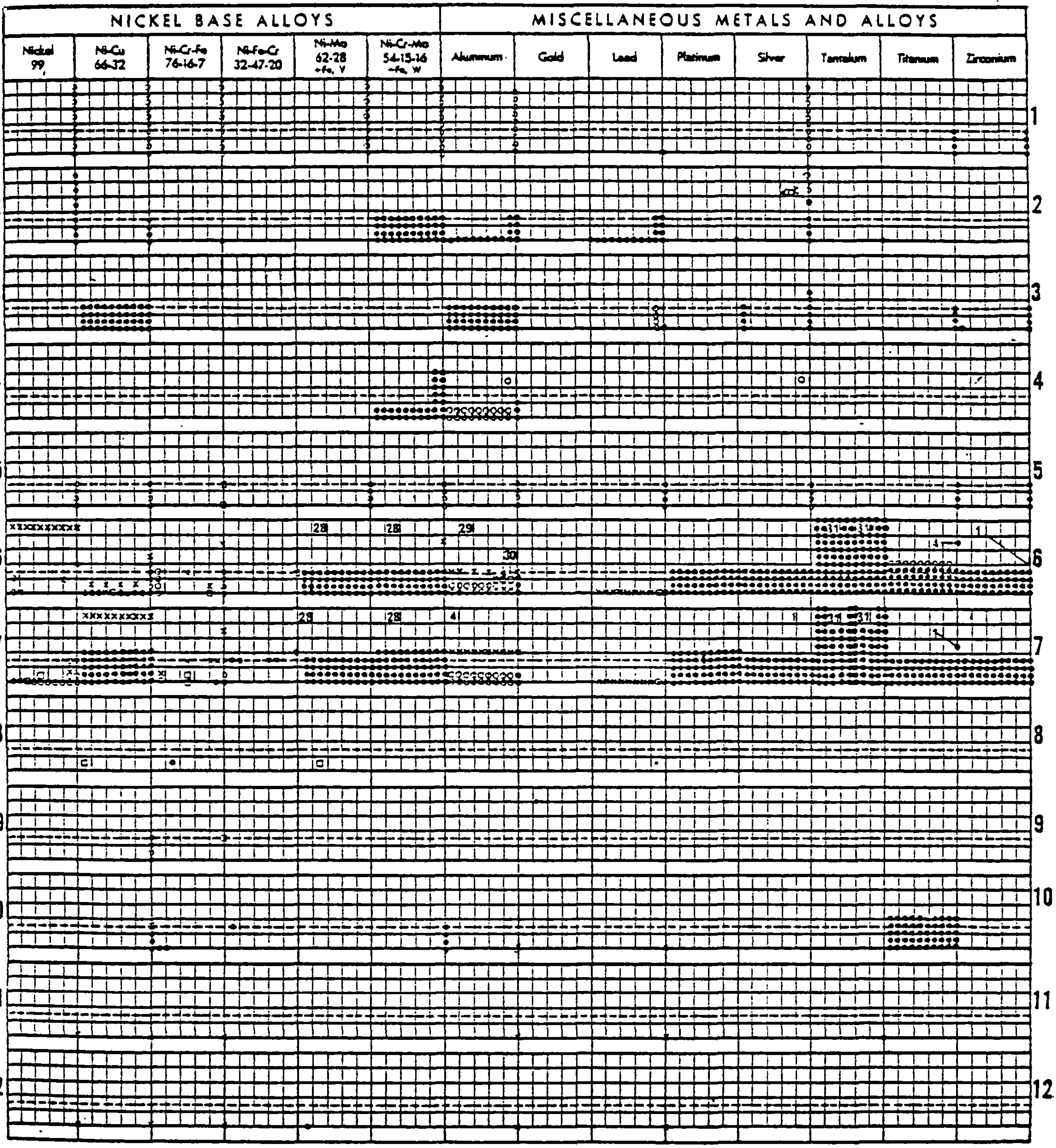
SOME CONVERSION FACTORS

Steel: mpy = lb/ft²/yr x 24.5
ipy x 696 x density = mdd
g/m²/d x 0.0146 ÷ density = ipy
1 micron = 0.03937 mil
Parts per million = 0.001 g/liter
Normal = 1 g [illegible]. liter ([illegible])

AVERAGE PENETRATION RATE/YR COMPARED TO WEIGHT LOSS

CODE	[illegible]	[illegible]	[illegible]
ALUMINUM			
●	<3.79	<138	<0.0284
○	<37.90	<1380	<0.284
□	37.9-945.5	1380-3450	0.284-0.71
x	>945.5	>3450	>0.71
COPPER, NICKEL or IRON			
●	<11.9	<435	<0.0896
○	<119.0	<4350	<0.896
□	119.0-297.5	4150-10875	0.896-2.24
x	>297.5	>10875	>2.24

CODE	[illegible]	[illegible]	[illegible]
LEAD			
●	<15.75	<576	<0.1178
○	<31.50	<5760	<1.178
□	31.5-393.75	5760-14,400	1.178-2.945
x	>393.75	>14,400	>2.945
TANTALUM			
●	<23.06	<843	<0.172
○	<230.6	<8430	<1.72
□	230.6-576.5	8430-21,075	1.72-4.3
x	>576.5	>21,075	>4.3



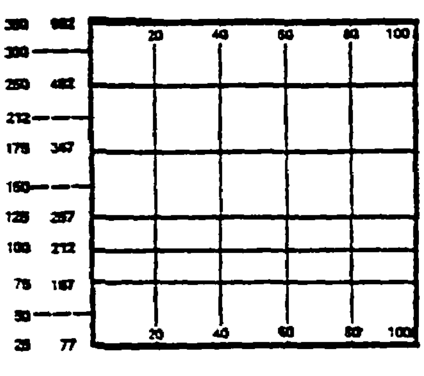
FOOTNOTES FOR CORROSIVES

1. Poison
2. Toxic
3. Explosive
4. Flammable
5. Ingestion poison
6. Inhalant poison
7. Attacks skin
8. Irritant
9. Vapor harmful
10. Ignites organics
11. Fuming liquid
12. Hygroscopic

FOOTNOTES FOR DATA SQUARES

1. No water
2. No air, oxygen
3. Low air, oxygen
4. Pits
5. Stress cracks
6. Stress corrosion
7. Discolors
8. Crevice attack
9. Intergranular attack
10. No chlorides
11. May discolor
12. May catalyze
13. May pit
14. May stress crack
15. Transgranular attacl
16. Vapor
17. Aerated
18. Catalyzes
19. Static
20. Agitated
21. ~ 7 pH
22. < 7 pH
23. > 7 pH
24. No acetylides
26. No HCl, H_2SO_4, NaCl
27. Dealloys
28. No ferric chloride
29. No Cu, Sn, Pb
30. < 2% anhydride
31. Up to 390 C.

CORROSIVE	FERROUS ALLOYS				AUSTENITIC STAINLESS STEELS			Martensitic Stainless 405-410	COPPER BASE ALLOYS			
	CAST IRON			Mild Steel	302, 304, 321, 347	316, 317	ACI CN-20 20Cr-30Ni		Copper 85-99.9	Brass 70-80Cu +Zn, Sn or Pb	Brass 59-93Cu +Al, Zn or As	Cupro-Nickel 66-88 : 11-33
	Gray	Nickel	Silicon									
ACETIC ACID VAPOR 1						9						
ACETIC ANHYDRIDE IN ACETIC ACID ④⑦③ 2												
ACETONE ④ 3												
ACETOACETIC ACID 4												
ACETONE CYANOHYDRIN ① 5												
ACETONITRILE ④ 6												
ACETOPARA-TOLUIDINE 7	1			1								
8												
ACETIC ACID + MERCURY SALTS 9									14	14	14	
ACETIC ACID + SALICYLIC ACID VAPORS 10					9							
ACETIC ACID + SULFURIC ACID 11												
ACETO-PHENETIDIN 12												



AVERAGE PENETRATION PER YEAR

[illegible]		Mils	[illegible]	Microns
●	<	2	0.002	50.8
○	<	20	0.020	508.0
□	{	20- 50	0.020 0.050	508.0 1270.0
x	>	50	0.050	1270.0

SOME CONVERSION FACTORS

Steel: mpy = lb/ft²/yr x 24.5
ipy x 696 x density = mdd
g/m²/d x 0.0144 ÷ density = ipy
1 micron = 0.03937 mil
Parts per million = 0.001 g/liter
Normal = 1 g equiv. liter (wt)

AVERAGE PENETRATION RATE/YR COMPARED TO WEIGHT LOSS

[illegible]	[illegible]	[illegible]	[illegible]
ALUMINUM			
●	<3.79	<138	<0.0284
○	<37.90	<1380	<0.284
□	37.9-945.5	1380-3450	0.284-0.71
x	>945.5	>3450	>0.71
COPPER, NICKEL or IRON			
●	<11.9	<435	<0.0896
○	<119.0	<4350	<0.896
□	119.0-297.5	4350-10875	0.896-2.24
x	>297.5	>10875	>2.24

[illegible]	[illegible]	[illegible]	[illegible]
LEAD			
●	<15.75	<576	<0.1178
○	<31.50	<5760	<1.178
□	31.5-393.75	5760-14,400	1.178-2.945
x	>393.75	>14,400	>2.945
TANTALUM			
●	<23.06	<843	<0.172
○	<230.6	<8430	<1.72
□	230.6-576.5	8430-21,075	1.72-4.3
x	>576.5	>21,075	>4.3

book. A supply of worksheets can be obtained by writing to:

Corrosion Data Survey — Nonmetals Section
NACE
P. O. Box 1499
Houston, TX 77001

Miscellaneous

Additional useful information will be found in Appendix 9—Trade Names of Materials Rated in Book.

References

1. Corrosion Data Survey—Metals Section. Fifth Edition. N. E. Hamner, compiler. NACE, Houston, TX.
2. Chemical Resistant Data Sheets. L. T. Nutt, J. Pacitti, and J. R. Scott, editors. Rubber and Plastics Research Association of Great Britain, Shawbury, Shrewsbury, Shropshire, England.

Hawley, reviser. VanNostrand Reinhold Co., New York, N. Y.

Bibliography

Testing and Evaluation of Reinforced Polyester for Corrosion Control Applications. NACE Liberty Bell Corrosion Course, 1966. Walter A. Szymanski, Hooker Chemical Corp., N. Tonawanda, N. Y.

NBS Voluntary Standard PS-15-69. Custom Contact-Molded Reinforced Polyester Chemical-Resistant Process Equipment. U.S. Government Printing Office, Washington, D. C. 20402. No. C13-20 2:15-69. 30 cents.

Standard Method of Test for Resistance of Plastics to Chemical Reagents. ASTM D543-07. Per copy, $1.50.

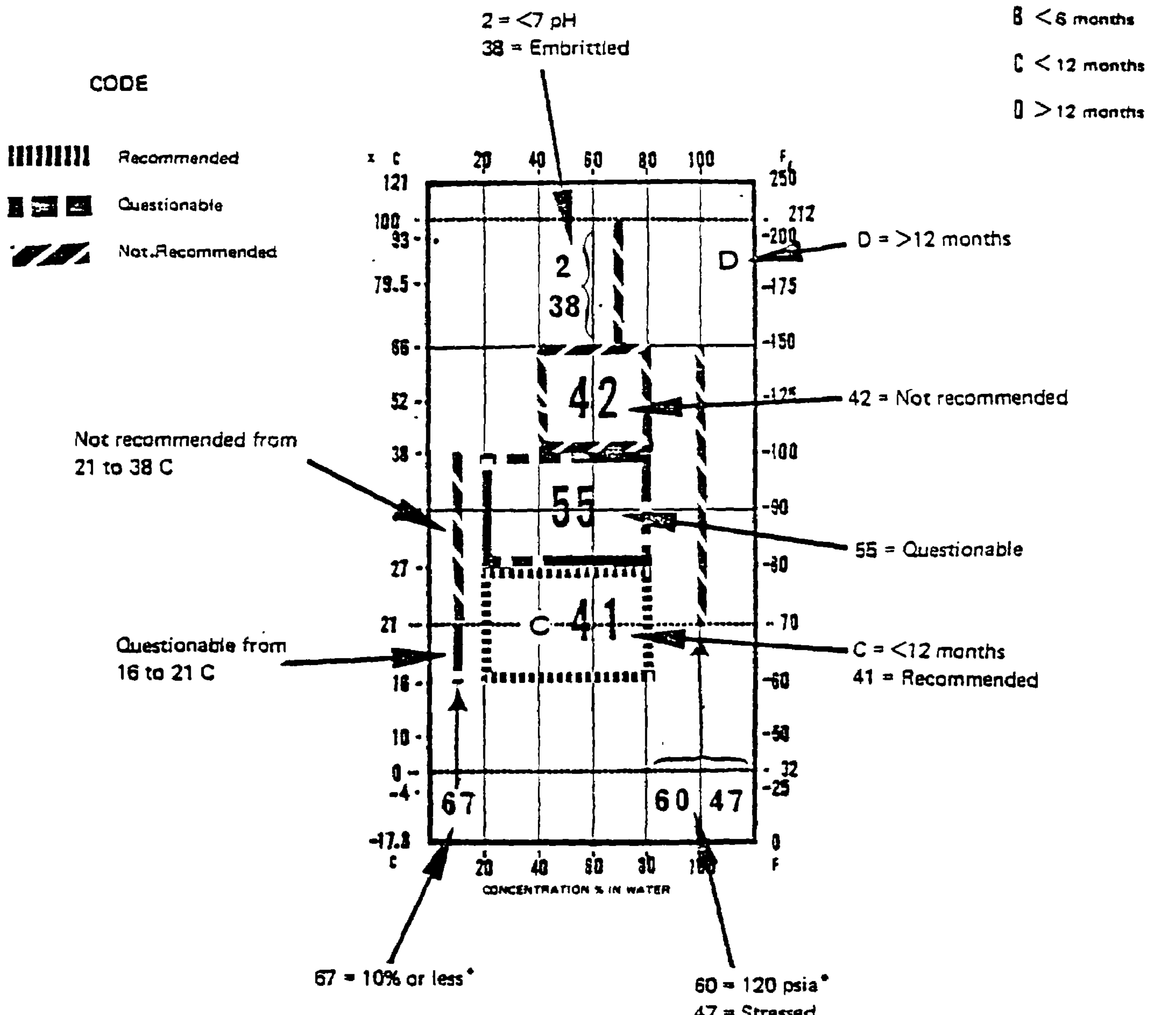
Standard Method of Test for Environmental Stress-Cracking of Ethylene Plastics. ASTM-D1693-70. Per copy, $1.50.

APPENDIX 1

Explanation of conventions, notations, and footnotes for bar graphs:

EXPOSURE TIME

A <1 month
B <6 months
C <12 months
D >12 months



*Footnotes specific for this graph. Remainder are from standing footnotes.

APPENDIX 2

Standing Footnotes

STANDING FOOTNOTES FOR ALL PAGES

ENVIRONMENTAL FACTORS

1. ~7 pH
2. < 7 pH
3. > 7 pH
4. Aerated
5. Agitated
6. Brief exposure
7. Cyclic immersion
8. Immersed
9. Intermittent exposure
10. No air, oxygen
11. Splash zone
12. Static
13. Pressure
14. Vacuum
15. Vapor
16. Velocity
17. Vibration
18. No water
19. Wet
20. Aqueous solution
21. Gas
22. Saturated
23. Liquid
24. Dilute
25. Crystals, powders, solids
26. < 134 C (275 F)
27. < 148 C (300 F)
28. Explosive
29. Poison
30. % conc. in air

MATERIALS' FACTORS

35. Compressed
36. Discolored
37. Disintegrated
38. Embrittled
39. Flex. str. loss
40. Leached
41. Recommended
42. Not recommended
43. Liquid-gas interface
44. Perforated
45. Softened
46. May stress crack
47. Stressed
48. Stretched
49. Swollen
50. Weight gain
51. Weight loss
52. Permeable
53. Strength loss
54. Blistered
55. Questionable
56. May dissolve

Footnotes specific to a page are located at the bottom of the page to which they refer.

STANDING FOOTNOTES FOR ALL PAGES

ENVIRONMENTAL FACTORS

1. ~7 pH
2. < 7 pH
3. > 7 pH
4. Aerated
5. Agitated
6. Brief exposure
7. Cyclic immersion
8. Immersed
9. Intermittent exposure
10. No air, oxygen
11. Splash zone
12. Static
13. Pressure
14. Vacuum
15. Vapor
16. Velocity
17. Vibration
18. No water
19. Wet
20. Aqueous solution
21. Gas
22. Saturated
23. Liquid
24. Dilute
25. Crystals, powders, solids
26. < 134 C (275 F)
27. < 148 C (300 F)
28. Explosive
29. Poison
30. % conc. in air

MATERIALS' FACTORS

35. Compressed
36. Discolored
37. Disintegrated
38. Embrittled
39. Flex. str. loss
40. Leached
41. Recommended
42. Not recommended
43. Liquid-gas interface
44. Perforated
45. Softened
46. May stress crack
47. Stressed
48. Stretched
49. Swollen
50. Weight gain
51. Weight loss
52. Permeable
53. Strength loss
54. Blistered
55. Questionable
56. May dissolve

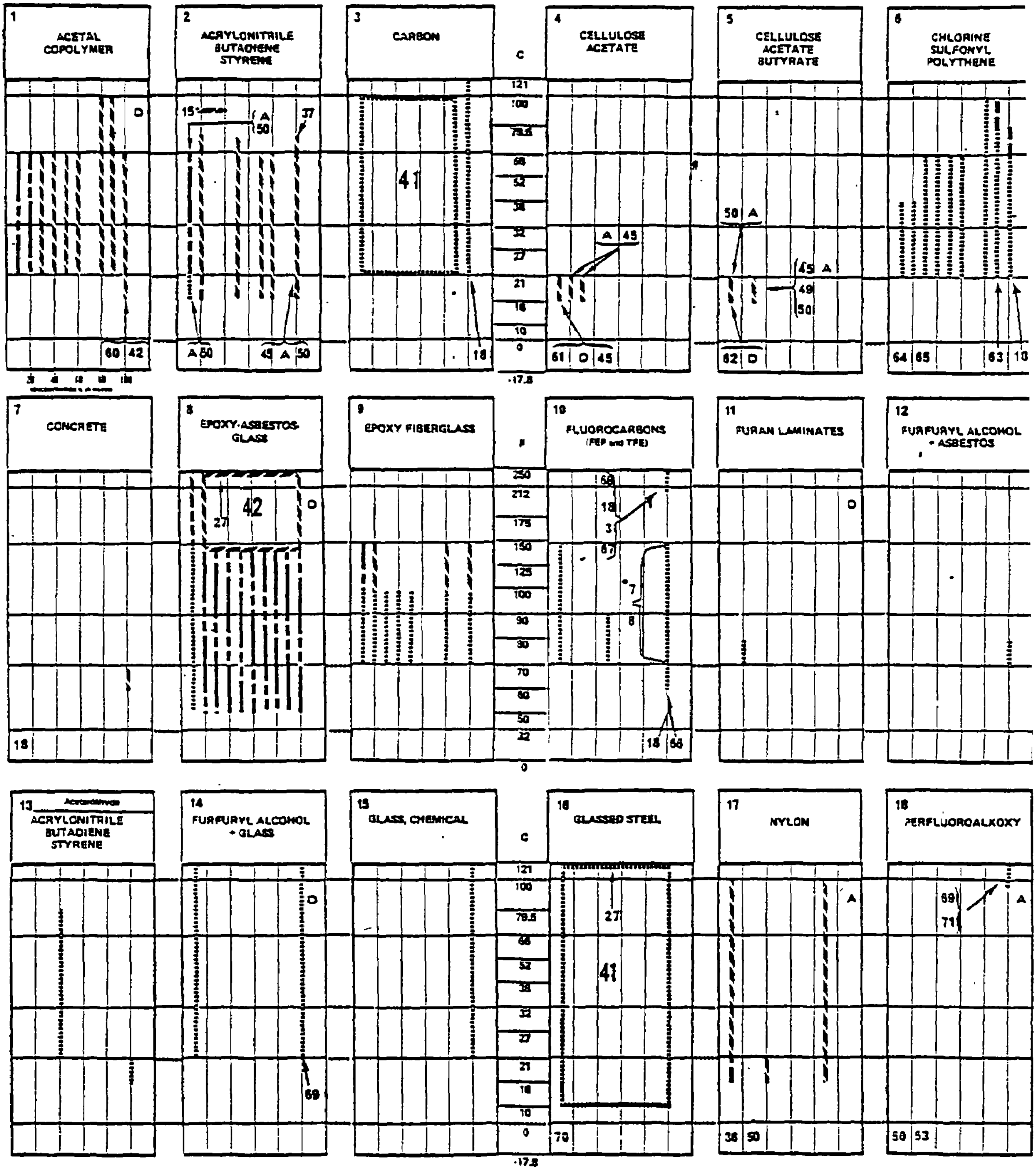
Acetic Acid

PERFORMANCE CODE

- Recommended
- Questionable
- Not Recommended

EXPOSURE TIME

A = < 1 month
B = < 6 months
C = < 12 months
D = > 12 months



FOOTNOTES

60. Anhydride or crude.
61. 5 percent.
62. <5% recommended.
63. 85 percent.
64. Not recommended for glacial.
65. Recommended for crude 95% to 40 C.
66. Wet.
67. 150 C.
68. Rating for FEP only.
69. Glacial.
70. <5%, 125-150 C questionable.
71. Anhydride also.

APPENDIX 2

Selected pages from Chemical Engineers' Handbook, 5th Edition, Robert H. Perry and Cecil H. Chilton, Copyright, 1973 (New York, NY: McGraw-Hill, 1973). Pages 33-38 are used with permission of McGraw-Hill Book Company.

TABLE 1

GENERAL CORROSION PROPERTIES OF SOME METALS AND ALLOYS

Ratings: 0 unsuitable. Not available in form required or not suitable for fabrication requirements or not suitable for corrosion conditions.
1 poor to fair.
2 fair. For mild conditions or where periodic replacement is possible. Restricted use.
3 fair to good.
4 good. Suitable when superior alternatives are uneconomic.
5 good to excellent.
6 normally excellent.
Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Material	Liquids: Non-oxidizing or reducing media				Liquids: Oxidizing media			Liquids: Natural waters				Gases: Common industrial media				
	Acid solutions, excluding hydrochloric, e.g., phosphoric, sulfuric, most conditions, many organics	Neutral solutions, e.g., many non-oxidizing salt solutions, chlorides, sulfates	Alkaline solutions, e.g.: Caustic and mild alkalies, excluding ammonium hydroxide	Alkaline solutions, e.g.: Ammonium hydroxide and amines	Acid solutions, e.g., nitric	Neutral or alkaline solutions, e.g., persulfates, peroxides, chromates	Pitting media,† acid ferric chloride solutions	Fresh-water supplies: Static or slow-moving	Fresh-water supplies: Turbulent	Sea water: Static or slow-moving	Sea water: Turbulent	Steam: Moist, condensate	Steam: Dry at high temp., promoting slight dissociation	Furnace gases with incidental sulfur content: Reducing, e.g., heat-treatment furnace gases	Furnace gases with incidental sulfur content: Oxidizing, e.g., flue gases	Ambient air, city or industrial
Cast iron, flake graphite, plain or low alloy	1	3	4	5	0	4	0	4	3	4	2	4	4	1	1	3
Ductile iron (higher strength and hardness may be attained by composition and heat-treatment or both)	1	3	4	5	0	4	0	4	4	4	3	4	4	1	1	3
Ni-Resist corrosion-resistant cast iron, type 1 (14 Ni; 7 Cu; 2 Cr; bal. Fe)	4	5	5	5	0	5	0	5	5	5	5	5	5	3	2	4
Ni-Resist corrosion-resistant cast iron, type 2 Cu free (20-30 Ni; 2-3 Cr; bal. Fe)	4	5	5	6	0	5	0	5	5	5	5	5	5	3	2	4
Ni-Resist corrosion resistant cast iron, ductile (24 Ni; bal. Fe)	4	5	5	6	0	5	0	5	5	5	5	5	5	3	2	4
14% silicon iron	6	6	2	5	6	6	3	5	5	5	5	6	4	4	3	6
Mild steel, also low-alloy irons and steels	1	3	4	5	0	4	0	4	3	4	2	4	4	1	1	3
Stainless steel, ferritic 17% Cr type	2	4	4	6	5	6	0	4	6	1	4	5	6	3	2	4
Stainless steel, austenitic 18 Cr; 8 Ni type	3	4	5	6	6	6	0	6	6	2	5	6	6	2	3	5
Stainless steel, austenitic 18 Cr; 12 Ni; 2.5 Mo type	4	5	5	6	5	6	1	6	6	3	5	6	6	2	4	6
Stainless steel austenitic 20 Cr; 29 Ni; 2.5 Mo; 3.5 Cu type	5	6	5	6	5	6	2	6	6	4	6	6	6	2	4	6
Ni-o-nel nickel iron-chromium alloy (40 Ni; 21 Cr; 3 Mo; 1.5 Cu; bal. Fe)	6	6	5	6	5	6	2	6	6	4	6	6	6	2	5	6
Hastelloy alloy C[a] (55 Ni; 17 Mo; 16 Cr; 6 Fe; 4 W)	5	6	5	6	4	6	5	6	6	6	6	6	6	3	4	6
Hastelloy alloy B[b] (61 Ni; 28 Mo; 6 Fe)	6	5	4	4	0	3	0	6	6	4	4	6	5	3	2	5
Hastelloy alloy D (82 Ni; 9 Si; 3 Cu)	6	6	3	4	2	5	1	6	6	6	6	6	6	4	2	6
Inconel nickel-chromium alloy (78 Ni; 15 Cr; 7 Fe)	5	6	6	6	3	6	1	6	6	4	6	6	6	2	4	6

[a] Also Chlorimet 3. [b] Also Chlorimet 2.

From: Chemical Engineers' Handbook, 5th Ed., Robert H. Perry and Cecil H. Chilton, McGraw-Hill, pg. 23-34, 1973. Copyright, 1973. Used by permission of McGraw-Hill Book Co.

TABLE 1 (Continued)

Ratings. 0 unsuitable. Not available in form required or not suitable for fabrication requirements or not suitable for corrosion conditions.
1 poor to fair.
2 fair. For mild conditions or where periodic replacement is possible. Restricted use.
3 fair to good.
4 good. Suitable when superior alternatives are uneconomic.
5 good to excellent.
6 normally excellent.
Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Material	Liquids											Gases				
	Non-oxidizing or reducing media				Oxidizing media			Natural waters				Common industrial media				
	Acid solutions, excluding hydrochloric, e.g., phosphoric, sulfuric, most conditions, many organics	Neutral solutions, e.g., many non-oxidizing salt solutions, chlorides, sulfates	Alkaline solutions, e.g.		Acid solutions, e.g., nitric	Neutral or alkaline solutions, e.g., persulfates, peroxides, chromates	Pitting media, acid ferric chloride solutions	Fresh-water supplies		Sea water		Steam		Furnace gases with incidental sulfur content		Ambient air, city or industrial
			Caustic and mild alkalies, excluding ammonium hydroxide	Ammonium hydroxide and amines				Static or slow-moving	Turbulent	Static or slow-moving	Turbulent	Moist, condensate	Dry at high temp., promoting slight dissociation	Reducing, e.g., heat-treatment furnace gases	Oxidizing, e.g., flue gases	
Copper-nickel alloys up to 30% nickel	4	5	5	0	0	4	1	6	6	6	6	6	5.	2	2	5
Monel 400 nickel-copper alloy (66 Ni; 30 Cu; 2 Fe)	5	6	6	1	0	5	1	6	6	4	6	6	6	2	3	5
Alloy 505 nickel copper cast alloy (66 Ni; 30 Cu; 4 Si)	5	6	6	1	0	5	1	6	6	4	6	6	6	2	3	5
Monel K-500 age hardenable Ni-Cu alloy (67 Ni; 30 Cu; 3 Al)	5	6	6	1	0	5	1	6	6	4	6	6	6	2	3	5
A nickel—commercial (99.4 Ni)	4	5	6	1	0	5	0	6	6	3	5	6	6	2	2	4
Copper and silicon bronze	4	4	4	0	0	4	0	6	5	4	1	6	5	2	2	5
Aluminum brass (76 Cu; 22 Zn; 2 Al)	3	4	2	0	0	3	0	6	6	4	5	6	5	2	2	5
Nickel aluminum-bronze (80 Cu; 10 Al; 5 Ni; 5 Fe)	4	4	2	0	0	3	0	6	6	4	5	6	5	2	3	5
Bronze, type A (88 Cu; 5 Sn; 5 Ni; 2 Zn)	4	5	4	0	0	4	0	6	6	5	5	6	5	2	2	5
Aluminum and its alloys	1	3	0	6	0-5	0-4	0	4	5	0-5	4	5	2	5	4	5
Lead, chemical or antimonial	5	5	2	2	0	2	0	6	5	5	3	2	0	4	3	5
Silver	4	6	6	0	0	2	0	6	6	5	5	6	5	4	4	4
Titanium	3	6	2	6	6	6	6	6	6	6	6	6	5	3	5	6
Zirconium	3	6	2	6	6	6	2	6	6	6	6	6	6	3	5	6

TABLE 1 (Continued)

Ratings: 0 unsuitable. Not available in form required or not suitable for fabrication requirements or not suitable for corrosion conditions.
1 poor to fair.
2 fair. For mild conditions or where periodic replacement is possible. Restricted use.
3 fair to good.
4 good. Suitable when superior alternatives are uneconomic.
5 good to excellent.
6 normally excellent.
Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Material	Gases (Cont'd) — Halogens and derivatives				Available forms	Cold formability in wrought and clad form	Weld-ability	Max. strength annealed condition × 1000 lb./sq. in.	Coeff. of thermal expansion, millionths per °F. 70°-212°F.	Remarks¶
	Halogens		Halide acids, moist, e.g., hydrochloric hydrolysis products of organic halides	Hydrogen halides, dry,‡ e.g., dry hydrogen chloride, °F.						
	Moist, e.g., chlorine below dew point	Dry, e.g., fluorine above dew point								
Cast iron, flake graphite, plain or low alloy	0	2	0	2 < 400 1 < 750	Cast	No	Fair§	45	6.7	
Ductile iron (higher strength and hardness may be attained by composition and heat-treatment or both)	0	2	0	2 < 400 1 < 750	Cast	No	Good§	67	7.5	
Ni-Resist corrosion-resistant cast iron, type 1 (14 Ni; 7 Cu; 2 Cr; bal. Fe)	0	2	3	3 < 400 2 < 750	Cast	No	Good§	22-31	10.3	
Ni-Resist corrosion-resistant cast iron, type 2 Cu free (20-30 Ni; 2-3 Cr; bal. Fe)	0	2	3	3 < 400 2 < 750	Cast	No	Good§	22-31	9.6	Type 3 Ni-Resist has same corrosion resistance
Ni-Resist corrosion-resistant cast iron, ductile (24 Ni; bal. Fe)	0	2	3	3 < 400 2 < 750	Cast	No	Good§	56	10.4	
14% silicon iron	0	0	4	1 < 400	Cast	No	No	22	7.4	Very brittle, susceptible to cracking by mechanical and thermal shock
Mild steel, also low-alloy irons and steels	0	3	0	3 < 400 1 < 750	Wrought, cast	Good	Good	67	6.7	High strengths obtainable by alloying, also improved atmospheric corrosion resistance. See A.S.T.M. specifications for particular grade
Stainless steel, ferritic 17% Cr type	0	2	0	2 < 400	Wrought, cast, clad	Good	Good§	78	6.0	A.I.S.I. type 430 A.S.T.M. corrosion- and heat-resisting steels
Stainless steel, austenitic 18 Cr; 8 Ni types	0	2	0	3 < 400	Wrought, cast, clad	Good	Good	90	9.6	A.I.S.I. type 304 A.S.T.M. corrosion- and heat-resisting steels. Stabilized or ELC types used for welding
Stainless steel, austenitic 18 Cr; 12 Ni; 2.5 Mo type	0	3	2	4 < 400 3 < 750	Wrought, cast, clad	Good	Good	90	8.9	A.I.S.I. type 316 A.S.T.M. corrosion- and heat-resisting steel. ELC type used for welding
Stainless steel, austenitic 20 Cr; 29 Ni; 2.5 Mo; 3.5 Cu type	1	3	3	4 < 400 3 < 750	Wrought, cast	Good	Good	90	9.4	A.C.I. CN-7M. Good resistance to sulfuric, phosphoric, and fatty acids at elevated temperatures
Ni-o-nel nickel iron-chromium alloy (40 Ni; 21 Cr; 3 Mo; 1.5 Cu; bal. Fe)	2	3	3	4 < 400 3 < 750	Wrought, cast, clad	Good	Good	100	7.3	Special alloy with good resistance to sulfuric, phosphoric, and fatty acids. Resistant to chlorides in some environments
Hastelloy alloy C[a] (55 Ni; 17 Mo; 16 Cr, 6 Fe; 4 W)	5	4	4	4 < 750 3 < 900	Wrought, cast, clad	Fair	Good	145	6.3	Excellent resistance to wet chlorine gas and sodium hypochlorite solutions
Hastelloy alloy B[b] (61 Ni; 28 Mo; 6 Fe)	1	3	5	4 < 750 3 < 900	Wrought, cast, clad	Fair	Good	135	5.6	Resistant to solutions of hydrochloric and sulfuric acids
Hastelloy alloy D (85 Ni; 9 Si; 3 Cu)	1	1	2	3 < 400 2 < 750 1 < 900	Cast	No		90-110	6.1	Greatest application in hot concentrated solutions of sulfuric acid
Inconel nickel-chromium alloy (78 Ni; 15 Cr; 7 Fe)	2	5	3	5 < 400 4 < 900	Wrought, cast, clad	Good	Good	90	6.9	Wide application in food and pharmaceutical industries

[a] Also Chlorimet 3. [b] Also Chlorimet 2.

TABLE 1 (Concluded)

Ratings: 0 unsuitable. Not available in form required or not suitable for fabrication requirements or not suitable for corrosion conditions.
1 poor to fair.
2 fair. For mild conditions or where periodic replacement is possible. Restricted use.
3 fair to good.
4 good. Suitable when superior alternatives are uneconomic.
5 good to excellent.
6 normally excellent.
Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Material	Gases (Cont'd)				Available forms	Cold formability in wrought and clad form	Weldability	Max. strength annealed condition × 1000 lb./sq. in.	Coeff. of thermal expansion, millionths per °F, 70°-212°F.	Remarks¶
	Halogens and derivatives									
	Halogens		Halide acids, mold, e.g., hydrochloric, hydrolysis products of organic halides	Hydrogen halides, dry,† e.g., dry hydrogen chloride, °F.‡						
	Moist, e.g., chlorine below dew point	Dry, e.g., fluorine above dew point								
Copper-nickel alloys up to 30% nickel	1	5	3	4 < 400 3 < 750	Wrought, cast, clad	Good	Good	38-62	9.3-8.5	High-iron types excellent for resisting high-velocity effects in condenser tubes
Monel 400 nickel copper alloy (66 Ni; 30 Cu; 2 Fe)	3	6	3	6 < 400 3 < 750 2 < 900	Wrought, cast, clad	Good	Good	77	7.5	Widely used for sulfuric acid pickling equipment. Also for propeller shafts in motor boats. Take precautions to avoid sulfur attack during fabrication
Alloy 505 nickel copper cast alloy (66 Ni; 30 Cu, 4 Si)	3	4	3	6 < 400 3 < 750 2 < 900	Cast	No	No	100	8.6	Non-galling characteristics. Excellent for bearings or bushings. High strength developed by heat-treatment
Monel K-500 age hardenable Ni-Cu alloy (67 Ni; 30 Cu; 3 Al)	3	6	3	6 < 400 3 < 750 2 < 900	Wrought, cast	Fair	Good	99-155	7.4	High strength obtainable by heat-treatment. Take precautions to avoid sulfur attack during fabrication
A nickel—commercial (99.4 Ni)	3	6	2	6 < 400 5 < 750 4 < 900	Wrought, cast, clad	Good	Good	54	6.6	Widely used for hot concentrated caustic solutions. Take precautions to avoid sulfur attack during fabrication
Copper and silicon bronze	0	5	2	3 < 400 2 < 750	Wrought, cast, clad	Excellent	Fair	29	9.3-9.5	Unsuitable for hot concentrated mineral acids or for high-velocity HF
Aluminum brass (76 Cu; 22 Zn; 2 Al)	0	4	2	3 < 400	Wrought, cast	Good	Fair	60	10.3	May develop localized corrosion in sea water
Nickel aluminum-bronze (80 Cu; 10 Al; 5 Ni; 5 Fe)	0	4	3	3 < 400 2 < 750	Wrought, cast	Good	Fair	60-80	9.4	Ship propellers an excellent application
Bronze, type A (88 Cu; 5 Sn; 5 Ni; 2 Zn)	0	4	3	3 < 400 2 < 750	Cast	No	§	45	11.0	High strengths obtainable by heat treatment. Not susceptible to dezincification
Aluminum and its alloys	0	4	0	3 < 400 1 < 750	Wrought, cast, clad	Good	Good	9-90	11.5-13.7	Extent of corrosion dependent upon type and concentration of acid ions. Wide range of mechanical properties obtainable by alloying and heat-treatment
Lead, chemical or antimonial	0	1	3	0	Wrought, cast, clad	Excellent	Good	3	16.4-15.1	High purity "chemical lead" preferred for most applications
Silver	5	5	3	4 < 400 3 < 750	Wrought, cast, clad	Excellent	Good	21	10.6	Used as a lining
Titanium	4	0	1	0	Wrought, cast	Fair	Good§	6-90	5.0	Red fuming HNO_3 may initiate explosions. Good resistance to solutions containing chlorides
Zirconium	6	1	6	0	Wrought, cast	Fair	Good§			

*Data courtesy of International Nickel Co.
†On unsuitable materials these media may promote potentially dangerous pitting.
‡Temperatures are approximate.
§Special precautions required.
¶Many of these materials are suitable for resisting dry corrosion at elevated temperatures.

TABLE 2

PROPERTIES AND CHEMICAL RESISTANCE OF ORGANIC COATINGS[a]

	Alkyd								Cellulose			Epoxy					
	Alkyd	Alkyd-amine	Alkyd-phenolic	Alkyd-silicone	Alkyd-urea	Styrenated alkyd	Acrylic	Bituminous	Nitro-cellulose	Buty-rate	Ethyl cellulose	Epoxy-amine	Epoxy-ester	Epoxy-furane	Epoxy-melamine	Epoxy phenolic	Epoxy-urea
Chemical resistance:																	
Exterior durability	E	E	E	E	E	F	E	F	E	E	E	G	E	E	E	E	VG
Salt spray	E	VG	E	E	G	G	E	E	E	E	......	VG	E	E	E	E	E
Solvents, alcohols	F	G	G	G	G	G	F	P	G	G	F	G	F	E	E	E	E
Solvents, gasoline	G	E	E	E	E	F	G	P	G	G	P	E	E	E	E	E	E
Solvents, hydrocarbons	G	E	E	G	E	E	F	P	F	F	F	E	VG	E	E	E	E
Solvents, esters, ketones	P	P	F	P	F	P	P	P	P	P	P	VG	F	G	VG	E	VG
Solvents, chlorinated	P	P	P	P	P	P	P	P	P	P	P	G	F	E	E	E	E
Beverages, food	F	G	VG	G	G	VG	VG	E	G	G	E	E	VG	E	E	E	E
Salts	VG	E	E	VG	E	E	VG	G	G	VG	G	E	E	E	E	E	E
Ammonia	P	P	P	P	P	P	P	......	P	P	G	G	P	E	P	F	P
Alkalis[b]	F, P	VG, G	F, P	VG, G	G, G	G, VG	G, F	E	F, P	F, P	G, G	E, E	E, E	E	E, E	E, E	E, E
Acids, mineral[c]	F, F, P	G, F, P	VG, G, F	G, F, F	F, F, P	G, F, F	G, F, P	G, -, -[e]	E, G, F	G, F, P	G, F, P	E, VG, G	G, F, F	G	E, VG, G	F, F, E	E, VG, F
Acids, oxidizing[c]	F, F, P	F, P, P	G, F, F	F, F, P	F, F, P	F, F, P	F, F, P	......	F, P, P	F, P, P	F, F, P	G, P, P	F, P, P	F	G, P, P	E, VG, P	P, P, P
Acids, organic (acetic, formic, etc.)[c]	F, F, P	P, F, P	F, P, P	F, F, P	F, F, P	P, F, P	F, P, P	E, -, -[f]	F, P, P	P, P, P	G, -, -	P, F, P	P, F, P	F, G	G, F, F	E, E, VG	F, P, P
Acids, organic (oleic, stearic, etc.)	F	G	VG	G	F	F	F	P	F	F	......	F	E	E	E	E	E
Acid, phosphoric	P	P	P	P	P	P	P	E	P	P	......	G	F	E	G	E	G
Water (salt, fresh)	F	G	G	G	F	G	E	E	G	E	E	G	VG	E	G	E	G
Physical properties:																	
Sward rocker hard. (8th day)	24	30	34	16-30	23	28	24	......	30	26	25-30	36	30	24	36	44	34
Flexibility	E	VG	G	VG	VG	G	E	E	E	E	E	F	E	E	VG	VG, E	VG
Abrasion resistance, cycles[d]	3500	>5000	>5000	4000	>5000	>5000	2500	......	2500	2500	......	>5000	>5000	......	>5000	>5000	>5000
Max. svc. temp., °F	200	250	250	450[f]	225	200	180	200	180	180	300	400	300	350	400	400	400
Toxicity	None	Slight	None	None	Slight	Slight	None	......	None	None	None	None	None	None	None	None	None
Impact resistance	VG	E	G	G	E	G	E	E	E	E	E	G	E	G	VG	VG	G
Dielec. properties	G	G	VG	E	G	G	VG	......	F	G	E	VG	VG	G	VG	VG	VG
Adhesion to:																	
Ferrous metals	E	E	E	VG	E	F	VG	E	VG	VG	P	E	E	E	E	E	E
Nonferrous metals	F	E	E	VG	VG	F	VG	E	G	G	P	E	E	E	E	E	E
Old paints	VG	G	G	E	G	VG	P	......	P	P	P	G	VG	E	P	P	P

[a]These data are intended only as a preliminary selection guide. Final selections should be made after consulting with coating formulator.

Key: E = excellent; VG = very good; G = good; F = fair; P = poor.

[b]Two ratings are for dilute (20%) and concentrated, respectively

[c]Three ratings are for dilute (10%), medium (10-30%), and concentrated, respectively.

[d]Taber CS-10 wheel.

[e]Not recommended with nitric acid.

[f]Not recommended with strong acetic acid solutions.

From: Chemical Engineers' Handbook, 5th Edition, Robert H. Perry and Cecil H. Chilton, McGraw-Hill, 1973, pg. 23-64. Used by permission, McGraw-Hill Book Co.

TABLE 2 (Concluded)

	Chlorinated polyether	Chlorinated polypropylene	Fluorocarbon (air-dried)	Furane	Phenolic	Polyamide (nylon)	Polyester	Polyethylene	Rubber: Chlorinated rubber	Rubber: Neoprene	Rubber: Hypalon	Rubber: Viton	Silicone	Urethane	Vinyl	Vinyl-alkyd (approx. 1:1)
Chemical resistance:																
Exterior durability	E	E	E	G	E	P	E	P	E	E	E	E	E	E	E	E
Salt spray	E	E	E	G	E	F	E	VG	E	E	E	E	E	E	E	E
Solvents, alcohols	E	G	E	E	E	G	G	E	E	E	....	E	F	F-E	F	G
Solvents, gasoline	E	G	E	E	E	G	E	P	G	F	F	E	F	F-G	E	E
Solvents, hydrocarbons	E	P	E	E	E	....	E	P	P	P	....	E	VG	F-E	G	P
Solvents, esters, ketones	E	F	P	G	F	....	P	G	P	G	F	P	F	F	F	P
Solvents, chlorinated	E	P	E	E	F	....	P	F	P	P	F	G	F	F-E	F	P
Beverages, food	E	G	E	E	E	....	G	E	G	F	F	E	F	VG	E	F
Salts	E	E	E	E	E	....	G	E	E	E	E	E	G	E	E	G
Ammonia	E	G	E	E	P	G	P	E	G	E	P	E	P	F	E	P
Alkalis[a]	E	VG, VG	E, E	E	F, P	G, G	P	P, G	E, E	E, E	E, F	E, E	E, F	VG, F	E, E	G, P
Acids, mineral[b]	E, E, E	E, G, G	E, E, E	G	G, F, P	F, F, P	F	....	E, E, G	E, G, P	E, E, E	E, E, E	G, G, F	G, F, F	E, E, G	VG, G, F
Acids, oxidizing[c]	E, E, E	E, E, G	E, E, E	P	G, F, F	....	P	VG, VG, VG	E, E, P	F, P, P	G, F, P	G, F, F	F, F, F	G, F, F	E, VG, G	P, P, F
Acids, organic (acetic, formic, etc.)[c]	E, E, E	G, F, F	E, E, E	F, G	G, F, P	F, F, F	P	VG, F, F	G, P, P	P, P, P	F, P, P	E, E, E	F, F, F	G, F, F	E, F, P	G, F, P
Acids, organic (oleic, stearic, etc.)	E	G	E	E	E	VG	P	G	F	P	P	E	G	E	E	E
Acid, phosphoric	E	G	E	E	F	....	F	VG	G	VG	E	E	F	E	E	P
Water (salt, fresh)	E	E	E	E	E	F	G	E	E	E	E	E	E	E	E	E
Physical properties:																
Sward rocker hard. (8th day)	....	24	<10	28	38	....	30	....	24	<10	<10	<10	16	35-45	20	26
Flexibility	F	VG	G	F	G	G	G	E	VG	E	E	G	F	E	E	E
Abrasion resistance, cycles[d]	>5000	5000	1000	....	>5000	....	3500	....	>5000	5000	5000	1000	2500	>5000	>5000	2500
Max. svc. temp., °F	300	250	550	300	350	300	200	225	200	200	250	550	550	300	150	160
Toxicity	None	Slight	Slight	None	None	....	None	None	Slight	None	....	Slight	None	Slight	None	None
Impact resistance	F	G	E	F	G	VG	F	E	G	E	E	E	F	E	E	E
Dielec. properties	E	E	E	F	E	G	G	E	E	F	VG	E	E	E	E	G
Adhesion to:																
Ferrous metals	VG	G	VG	F	E	VG	F	E	F	VG	VG	VG	F	E	G	VG
Non-ferrous metals	G	VG	VG	F	E	VG	F-P	E	VG	VG	VG	VG	E	E	VG	G
Old paints	P	E	P	E	G	....	P	P	F	....	F	P	E	G	F	P