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Alternative Containers for Low-Level Wastes Containing Large Amounts of Tritium

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Brookhaven National Laboratory

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ABSTRACT

High-activity tritiated waste generated in the United States is mainly composed of tritium gas and tritium-contaminated organic solvents sorbed onto Speedi-Dri which are packaged in small glass bulbs. Low-activity waste consists of solidified and adsorbed liquids. In this report, current packages for high-activity gaseous and low-activity adsorbed liquid wastes are emphasized with regard to containment potential.

Containers for low-level radioactive waste containing large amounts of tritium need to be developed. An integrity may be threatened by: physical degradation due to soil corrosion, gas pressure build-up (due to radiolysis and/or biodegradation), rapid permeation of tritium through the container, and corrosion from container contents. Literature available on these points is summarized in this report.

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NOTE ADDED IN PROOF

After completion of this manuscript in May of 1981, it was discovered that the information included in Section 2 concerning the characteristics of NEN's tritium wastes contains certain inaccuracies in the package description obtained from NEN. Inclusion of an accurate package description would substantially alter the results of the analyses given in this section, particularly with respect to the gas generation expected in the NEN package due to radiolysis (Section 2.2.1). A more detailed discussion of the NEN waste in which these inaccuracies have been corrected is to be found in Gause et al., "Characterization of the Class B Stable Radioactive Waste Packages of the New England Nuclear Corporation," NUREG/CR-3018. This work also provides an analysis of the gas generation rates expected in the NEN waste package.

ALTERNATIVE CONTAINERS FOR LOW-LEVEL WASTE CONTAINING LARGE QUANTITIES OF TRITIUM

Introduction

A low-level waste survey described in U.S. Nuclear Regulatory Commission I & E Bulletin No. 79-19, dated August 10, 1979, required licensees to supply information (for all of 1978 and the first half of 1979) on the following inquiries: number of shipments, total volume, total curies, major isotopes content, and solidification technique if liquid waste was generated. An evaluation of the responses indicates that (1) the majority of tritium disposed of each year in licensed disposal sites is contained in a few hundred drums of waste (maximum content per drum 1000 Ci) and (2) waste is generated during the production of illuminated signs, watchdials, and isotope labelled chemicals. The waste consists mainly of tritium gas and contaminated organic solvents.

Packaging of low-level waste containing large quantities of tritium is preferred to waste forms on the basis of practical considerations:

- relatively small volume, but diverse chemical and physical properties, of wastes generated by individual facilities.
- likely high expense and difficulty, for small scale waste generators, to maintain and operate a waste processing system; which would be limited to occasional use, and
- a "high integrity" container (or overpack) could also serve as a radiation shield, thus considerably reducing the exposure to waste handlers and operating personnel.

With the goal of identifying containers which have the potential of maintaining their structural integrity for 100 to 200 years (approximately ten half-lives of tritium), the following divisions with their corresponding subtask number(s) are made in this study:

- A selection of candidate metals or alloys based on observed pitting rate in soil groups corresponding to those at operating disposal sites and on available data for corrosion in concrete.

  (Subtask 1a: "Compile a data base from the literature on corrosion of candidate container metals in soil and concrete".)

- Calculations, based on a source term for probable contents, of maximum internal pressure sustainable by the container and the corresponding limits on tritium and gas-generating organic content in the waste.

(Subtask 1b: "Compile a data base from the literature on gas pressures generated through radiolysis and biodegradation".) (Subtask 2: "Report the internal pressures which the containers could be expected to withstand; identify limits on tritium and organic contents for container pressure limits and for pressure limits; also evaluate the limits on tritium and organic content for pressure limits of 50 psig and 1.5 of 50 psig and 1.5 atmospheres".)

- An estimation of the amount of tritum gas diffusing through the package.

  (Subtask 1c: "Compile a data base from the literature on tritium diffusion through metals".)

- An evaluation of physical modifications (e.g., container thickness) and supplemental measures (e.g., sealing, backfilling, coating, use of additives) needed to optimize potential integrity and associated costs.

  (Subtask 3: "Provide a general evaluation of alternatives including disposing of the waste container with a cement or cement-grout backfill, varying the container thickness, coating the container-externally and/or internally, and using additives to reduce the potential for gas generation and corrosion form within waste containers; estimate minimum cost; identify problems associated with the alternatives".) Note that some topics in this subtask, such as container thickness and use of additives are covered in previous applicable sections. Also included in this section is a portion of Subtask 2: "As test cases, estimate the expected lifetimes and cost of stainless steel and copper overpacks for 55-gallon drums of waste disposed of in soil; the overpacks shall be 1/4 inch thick and the options of mechanical or weld sealing the containers shall be evaluated."

1. CORROSION OF CANDIDATE CONTAINER METALS IN SOIL AND CONCRETE

1.1 Corrosion of Metals in Soil

1.1.1 Introduction

Metals have been utilized for underground installations, such as pipelines, utility cables, culverts, water mains, etc., for a long time. Thus, substantial data are available for metals commonly used for underground structures, such as low alloy steel and cast iron. For instance, underground corrosion failures have been recorded since 1898 in the city of Philadelphia.(1) There exist some data for underground corrosion of nonferrous metals such as copper and its alloys, lead, zinc, and aluminum. The underground corrosion data for stainless steels are also available. Metals like titanium, tantalum, and zirconium have been in short supply and therefore expensive for underground installations. Consequently, they have not been sufficiently investigated under practical exposure conditions.

For the rather common underground installation such as pipelines and underground residential distribution equipment, a currently adequate solution to the corrosion problem has been achieved through the use of cathodic protection by means of externally applied electric current. However, for the nuclear waste canister this kind of cathodic protection is not a practical choice because of the required lifetime of the canister and the necessity of maintaining and checking the cathodic protection. Because of the necessity of the maintenance-free canister, cathodic protection will not be discussed further in this report.

Underground corrosion behavior of various metals will be reviewed and possible methods for improving the corrosion resistance will be discussed. At the end of this chapter, several metals will be recommended for each commercial low level waste site in operation in 1981.

The rates of corrosion of metals in soil vary to a marked degree with the kind or type of soil. For example, a cast iron pipe may last 50 years in New England soil, but only 20 years in the more corrosive soil of Southern California.(2)

Due to the very large influence of different factors on the rate of corrosion of metals in soil, only experimental data obtained for different metals under uniform exposure conditions (i.e., simultaneous experiments in the same site) can be compared, and these data are valid only for the prediction of the corrosion behaviors of the metals in that soil.

Predicting the corrosion behavior or estimating the life of a metal component in certain soil using the corrosion data from similar soil can only be approximate, and is not always sufficiently reliable. However, with very conservative calculations or estimations, safe recommendations can be made.

1.1.2 Soil Types

The corrosion behavior of metals in soil is generally dependent on the characteristics of the soil (corrosion rate is also affected by climatic factors, such as the amount of rainfall, temperature, air movement, and sunlight on the soil).

Marbut[3] divided the soils of the continental United States into 11 groups, based on obvious gross differences, such as color. These are shown in Figure 1.1.

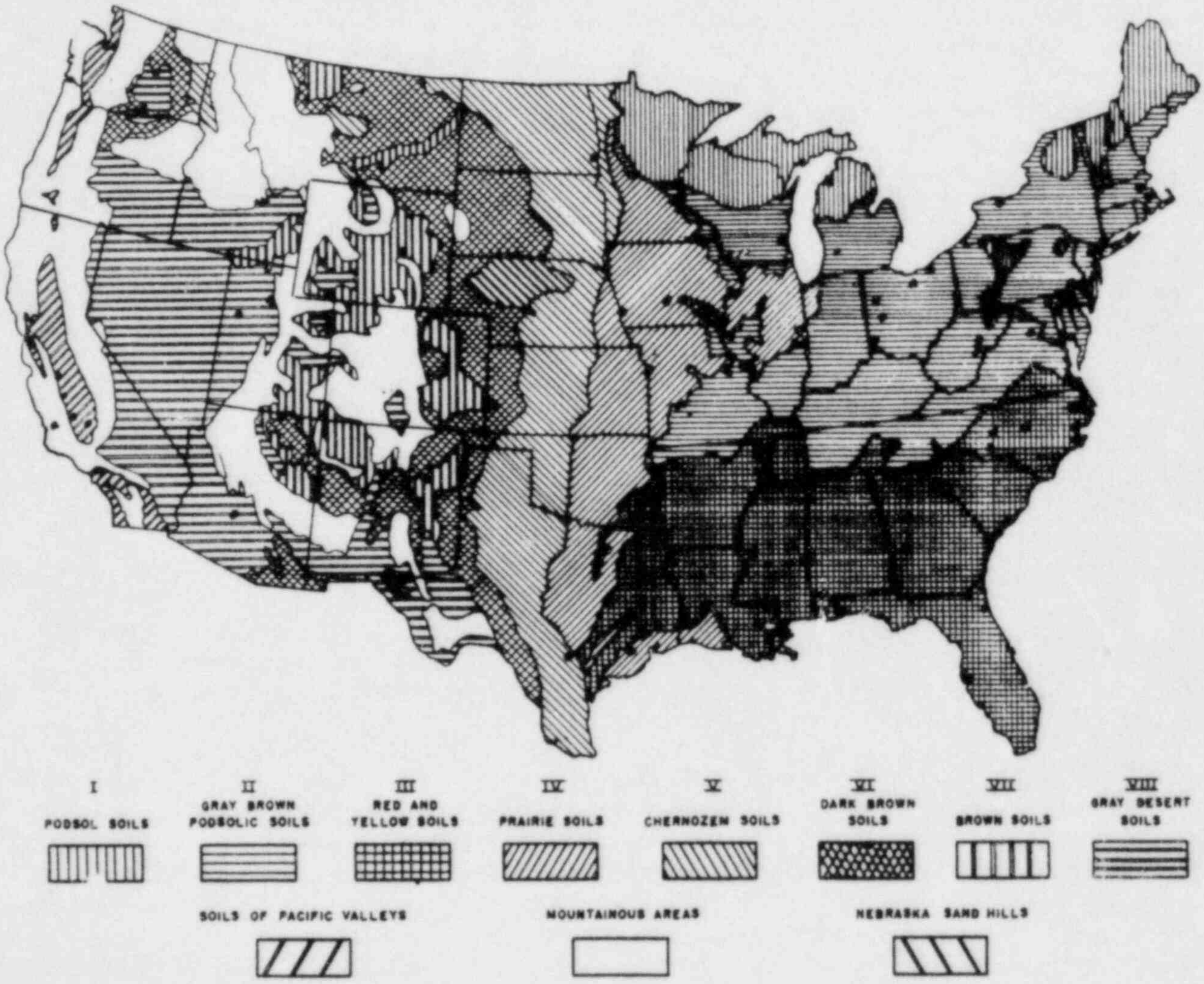

Figure 1.1 Soil groups of the United States [Marbut[3]]. The dots show the location of the National Bureau of Standards test sites.

From stratigraphic examination within a particular soil group, soil series ranging in number from 9 to 60 are identified by names chosen by the discovers for these localized similarities in the layering of soil zones (i.e., profiles). There are more than 200 soil series designations in the United States, although this does not imply the existence of 200 unique layerings.

Soils are also classified by the texture of the top layer of the soil, usually less than a foot in depth. The United States Department of Agriculture(4) has graphically presented the various textures by composition, as shown in Figure 1.2.

A soil type is obtained by adding the class name of the texture to the soil series. Examples of names of soil types are Sassafras silt loam, Susquehanna clay, and Miami clay loam.

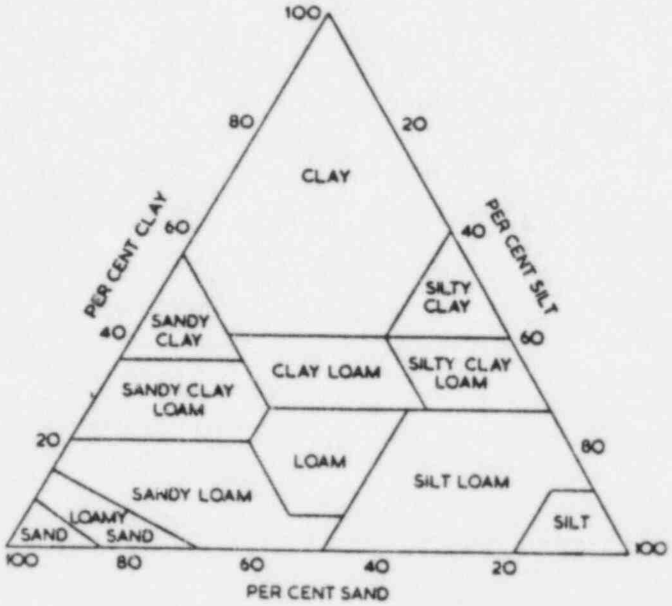

Figure 1.2 Diagram showing the percentages of clay, silt, and sand by means of which the textured name of a soil may be determined from a mechanical analysis.(4)

1.1.3 Prediction of Corrosion Behavior of Metals in Soil

Factors affecting corrosiveness of soils are moisture, alkalinity, acidity, permeability of water and air (compactness of texture), oxygen, salts, stray electrical currents, and biological organisms.(5) Most of these factors affect electrical resistance, which can be used as a measure of corrosivity.

Many attempts have been made to correlate the corrosive value of different soils with their resistivity or pH values.(6-9) Resistivity is the property most often used to approximate the aggressiveness of a soil. The measurement of pH may supplement electrical resistivity measurements. Table 1.1 shows the general relationship between soil resistivity and corrosion of ferrous metals, and Table 1.2 shows the corrosion of pipelines as affected by soil acidity and resistivity. However, because of other factors this relationship may not always be valid. Romanoff(12) considered the correlation of corrosion theory with practice as follows: "Many attempts at correlation emphasize again that underground corrosion is affected by a number of specific and interrelated factors, that the localized or pitting type of corrosion is much more serious than general corrosion and is harder to control, and that underground corrosion of any kind seldom proceeds at a uniform rate throughout the exposure. Enough data are available to differentiate between very mildly corrosive and severely corrosive soils and soil environments. The lack of fundamental knowledge in this field is such that even when much more data is (sic) available than is normally reported for corrosion studies, it is sometimes difficult to explain and often difficult to predict results in corrosive soil environments. Such predictions are most reliable when they are based on a combination of laboratory and controlled field tests with actual experience in industrial installations, all exposed to the same soil environment."

Table 1.1

General Relationship Between Soil Resistivity and Corrosion of Ferrous Metals(10)

Soil Resistivity, ohm-cm	Classification
< 700	very corrosive
700-2000	corrosive
2000-5000	moderately corrosive
>5000	mildly corrosive to non-corrosive

Table 1.2

Corrosion of Pipelines as Affected by Soil Acidity and Resistivity(11)

Soil Type	Total Acidity	Proportion of Pipeline Requiring Repairs
	Influence of Acidity - Soil Resistivity 4,000 to 5,000 ohm-cm	
	mg-eq[a]	Percent
Wauseon fine sandy loam	7.5	6.3
Caneadea silt loam	12.2	13.3
Miami silt loam	16.8	22.8
Mahoning silt loam	18.1	20.9
Trumball clay loam	21.1	20.0
Crosby silt loam	22.0	30.8
Soil Type	**Total Resistivity**	**Requiring Repairs**
	Influence of Resistivity -Total Acidity 15 to 18 mg-eq[a]	
	ohm-cm	Percent
Lordstown fine sandy loam	11,450	3.3
Wooster loam	8,002	6.0
Volusia silt loam	5,473	13.6
Mahoning silt loam	4,903	20.9
Miami silt loam	3,982	22.8
Nappanee clay loam	1,009	57.0

[a] Milligram-equivalents of hydrogen ion per 100 g of soil.

1.1.4 The Effect of the Burial Depth

The accessibility of the air and moisture to the soil surrounding the buried metal is a function of the burial depth.

Figure 1.3 shows the resistivity of one soil as a function of the depth. The resistivity ranges from 2000 ohm-cm at 60 cm from the surface to 200 ohm-cm at 450 cm from the surface, which indicates that the corrosion rate of the buried metal is probably a function of the burial depth.

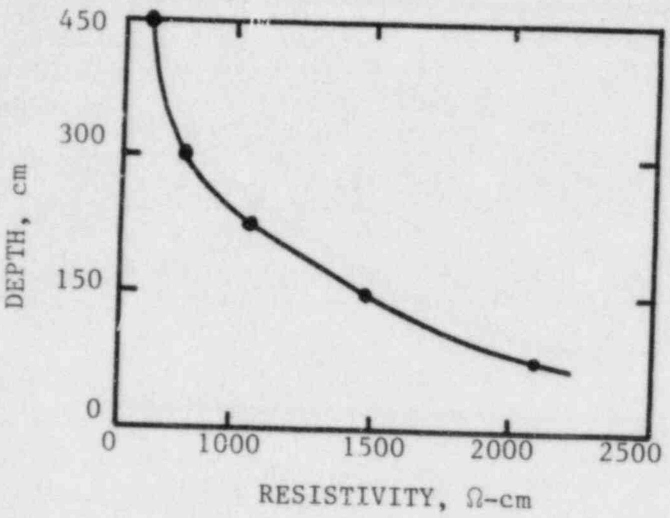

Figure 1.3 Variation of soil resistivity with depth for a light brown clay aggressive to ferrous metals.(13)

1.1.5 Characteristics of Soil Corrosion

In most soils, underground corrosion takes the form of pitting. This kind of localized corrosion becomes more important in predicting the life of an underground installation. For this reason, the underground corrosion rate must be expressed as a maximum penetration rate as well as a weight loss. Especially in the selection of nuclear waste canister material, the maximum penetration rate (pitting rate) is the main criterion when judging the corrosion resistance of the metal.

The reported pitting rates represent minimum rather than maximum values because of the small sizes (length <30 cm) of the specimens. Uhlig(14) discussed this fact as follows: "Actual depth of pits in a given time is found to increase slightly with size of test specimen, probably because cathodic area per pit increases, thus accounting for higher current densities at the pits. In addition to this factor, long-line currents or macrocells, if present, increase pit depth over the values obtained on small specimens where such cells do not operate."

1.1.6 National Bureau of Standards Tests

The most extensive underground corrosion tests were begun in 1910 by K. H. Logan of the National Bureau of Standards (NBS), and lasted until 1955. They exposed more than 36,500 specimens, representing 333 varieties of materials, in 128 test sites throughout the United States. Tested metals are listed in Table 1.3. For material compositions and more details, refer to Reference 12. The chemical and physical properties of the soils at the 128 are listed in Table 1.4. Some of the test sites are shown as dots in Figure 1.1.

Table 1.3

Metals Included in the NBS Tests

Ferrous metals	Plain irons and steel High strength low alloy steels (HSLA) High-chromium steels High-chromium-nickel and manganese steel Cast iron
Nonferrous metals	Copper and copper alloys Lead Zinc Aluminum
Coated metals	Metallic coatings Bituminous coatings Other coatings

The NBS data were summarized by the National Association of Corrosion Engineers (NACE),(15) and are shown in Table 1.5. Pitting data were selected arbitrarily for metals in five ranges of resistivities without considering other factors.

As shown in Table 1.5, copper on the average corrodes at about one-sixth the rate of iron except in tidal marsh (resistivity of 60 ohm-cm) where the corrosion rate is one-half that of iron.

Stainless steels showed high resistance to soil corrosion, and titanium was not attacked at all. This table should be used only for a rough comparison, and detailed discussion will appear in the next section.

1.1.7 Soil Corrosion of Various Metals

The soil corrosion of various metals will be discussed in more detail using the results from various references including those of the NBS field tests.

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Table 1.4

Chemical and Physical Properties of the Soils at the NBS Test Sites[a]

Soil		Location	Internal drainage of test site[c]	Resistivity at 60°F	pH	Composition of water extract, mg-eq per 100 g of soil								Mean temperature[e]	Annual precipitation[e]	Moisture equivalent	Air-pore space	Apparent specific gravity	Volume shrinkage
No.[b]	Type					Total acidity[d]	Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4						
				Ohm-cm										*°F*	*Inches*	*Percent*	*Percent*		*Percent*
1	Allis silt loam	Cleveland, Ohio	P	1,215	7.0	11.4	0.72	0.25	0.43	0.00	0.09	0.09	0.83	49.2	33.8	28.6	1.1	-----	6.6
2	Bell clay	Dallas, Tex.	P	684	7.3	3.5	.28	1.09	.13	.00	1.18	.04	.18	65.5	36.2	37.6	2.0	1.95	23.0
3	Cecil clay loam	Atlanta, Ga.	G	30,000	5.2	11.5	-----	-----	-----	-----	-----	-----	-----	61.2	48.3	29.1	18.2	1.60	7.0
4	Chester loam	Jenkintown, Pa.	F	6,670	5.6	7.6	-----	-----	-----	-----	-----	-----	-----	54	40	22.2	7.0	1.78	2.2
5	Dublin clay adobe	Oakland, Calif.	P	1,345	7.0	6.5	.93	.48	.10	.00	0.69	.03	.25	56.4	23.4	28.8	4.9	2.00	22.6
6	Everett gravelly sandy loam	Seattle, Wash.	G	45,100	5.9	12.8	-----	-----	-----	-----	-----	-----	-----	51.0	34.0	12.[illegible]	40.6	1.50	0.1
7	Maddox silt loam	Cincinnati, Ohio	F	2,120	4.4	29.8	-----	-----	-----	-----	-----	-----	-----	53.2	38.6	34.3	3.7	2.02	34.5
8	Fargo clay loam	Fargo, N. Dak.	P	350	7.6	A	1.42	1.72	2.55	.00	.71	.01	4.43	39	21	37.0	8.7	1.56	21.0
9	Genesee silt loam	Sidney, Ohio	P	2,820	6.8	7.2	-----	-----	-----	-----	-----	-----	-----	51.2	39.0	24.8	15.8	1.74	5.6
10	Gloucester sandy loam	Middleboro, Mass.	F	7,460	6.6	3.6	-----	-----	-----	-----	-----	-----	-----	50	41	13.0	27.8	1.58	0.2
11	Hagerstown loam	Loch Raven, Md.	G	11,000	5.3	10.8	-----	-----	-----	-----	-----	-----	-----	55.4	42.6	32.0	15.5	1.49	8.6
12	Hanford fine sandy loam	Los Angeles, Calif.	F	3,190	7.1	2.5	0.39	0.50	0.16	.00	.40	.00	0.14	62.4	15.2	12.4	33.5	-----	0
13	Hanford very fine sandy loam	Bakersfield, Calif.	F	290	9.5	A	6.23	.09	.13	.00	1.12	1.64	3.76	64.6	5.6	21.7	34.5	-----	0
14	Hempstead silt loam	St. Paul, Minn.	F	3,520	6.2	5.6	-----	-----	-----	-----	-----	-----	-----	44.2	27.2	17.2	14.4	1.76	1.0
15	Houston black clay	San Antonio, Tex.	P	489	7.5	5.0	2.18	.88	.20	.00	2.00	0.13	0.73	68.9	27.2	51.4	5.7	2.08	39.8
16	Kalmia fine sandy loam	Mobile, Ala.	F	8,290	4.4	11.8	-----	-----	-----	-----	-----	-----	-----	67.3	61.6	22.2	12.0	1.65	0.6
17	Keyport loam	Alexandria, Va.	P	5,980	4.5	19.1	-----	-----	-----	-----	-----	-----	-----	55.	42	30.8	4.4	1.72	5.4
18	Knox silt loam	Omaha, Nebr.	G	1,410	7.3	1.4	0.27	.63	.20	.00	0.94	.00	.25	50.6	27.8	28.4	16.6	1.26	1.3
19	Lindley silt loam	Des Moines, Iowa	G	1,970	4.6	10.9	.38	.32	.41	.00	.16	.03	.46	49.5	32.0	28.4	3.9	1.76	11.8
20	Mahoning silt loam	Cleveland, Ohio	P	2,370	7.5	1.5	.25	.48	.20	.00	.51	.00	.15	49.2	33.8	22.4	3.8	1.90	3.9
21	Marshall silt loam	Kansas City, Mo.	F	2,370	6.2	9.5	-----	-----	-----	-----	-----	-----	-----	54.4	37.1	31.2	10.8	1.66	6.5
22	Memphis silt loam	Memphis, Tenn.	G	5,150	4.9	9.7	-----	-----	-----	-----	-----	-----	-----	61.6	47.7	28.4	9.6	1.67	3.0
23	Merced silt loam	Buttonwillow, Calif.	F	278	9.4	A	8.38	.38	.22	.02	1.87	1.12	5.57	65	6	24.7	6.1	1.69	0.2
24	Merrimac gravelly sandy loam	Norwood, Mass.	G	11,400	4.5	12.6	-----	-----	-----	-----	-----	-----	-----	50	41	13.0	34.7	1.4	0
25	Miami clay loam	Milwaukee, Wis.	F	1,780	7.2	4.7	0.23	.70	.41	.00	1.01	0.03	0.10	46.1	30.1	25.8	9.5	1.95	7.6
26	Miami silt loam	Springfield, Ohio	G	2,980	7.3	2.6	.27	.50	.31	.00	0.70	.03	.12	53	37	16.4	20.9	1.95	1.0
27	Miller clay	Bunkie, La.	P	570	6.6	3.7	.53	1.86	1.12	.00	2.00	.08	1.54	67	56	42.6	1.9	2.01	32.5
28	Montezuma clay adobe	San Diego, Calif.	P	408	6.8	-----	1.50	0.06	0.18	.00	0.12	.99	0.89	61.0	10.3	24.6	2.5	-----	5.9
29	Muck	New Orleans, La.	VP	1,270	4.2	28.1	2.15	1.92	1.55	.00	.00	1.69	2.30	69.3	57.4	34.5	26.6	-----	5.8
30	Muscatine silt loam	Davenport, Iowa	P	1,300	7.0	2.6	0.32	0.65	0.40	.00	.71	0.09	0.24	49.9	32.1	29.4	7.2	1.81	7.5
31	Norfolk fine sand	Jacksonville, Fla.	G	20,500	4.7	1.8	-----	-----	-----	-----	-----	-----	-----	69.3	47.4	2.8	38.1	1.55	0
32	Ontario loam	Rochester, N. Y.	G	5,700	7.3	0.5	.23	.70	.12	.00	.73	.01	.42	47.6	32.8	17.8	11.7	1.85	0.1
33	Peat	Milwaukee, Wis.	VP	800	6.8	36.0	1.52	7.30	4.06	.00	-----	2.27	2.13	46.1	30.1	72.8	34.0	-----	16.9
34	Penn silt loam	Norristown, Pa.	F	4,900	6.7	7.0	-----	-----	-----	-----	-----	-----	-----	54	40	23.4	11.7	1.82	8.4
35	Romona loam	Los Angeles, Calif.	G	2,060	7.3	5.7	0.68	0.68	0.49	.00	1.10	0.06	0.35	62.4	15.2	18.0	10.9	1.86	3.1
36	Ruston sandy loam	Meridian, Miss.	G	11,200	4.5	4.6	-----	-----	-----	-----	-----	-----	-----	64.0	53.0	13.8	16.0	1.62	0
37	St. John's fine sand	Jacksonville, Fla.	P	11,200	3.8	15.3	-----	-----	-----	-----	-----	-----	-----	69.3	47.4	7.0	-----	-----	0
38	Sassafras gravelly sandy loam	Camden, N. J.	G	38,600	4.5	1.7	-----	-----	-----	-----	-----	-----	-----	54	40	3.0	32.1	1.59	0
39	Sassafras silt loam	Wilmington, Del.	F	7,440	5.6	6.6	-----	-----	-----	-----	-----	-----	-----	54	40	24.2	7.5	1.72	3.8
40	Sharkey clay	New Orleans, La.	P	970	6.0	9.4	.56	.58	.44	.00	0.93	.07	.28	69.3	57.4	33.0	2.3	1.78	16.4
41	Summit silt loam	Kansas City, Mo.	F	1,320	5.5	11.0	.30	.54	.36	.00	.78	.04	.46	54.4	37.1	33.1	6.9	1.61	14.6
42	Susquehanna clay	Meridian, Miss.	F	13,700	4.7	28.2	-----	-----	-----	-----	-----	-----	-----	64.0	53.0	34.8	14.9	1.79	4.7
43	Tidal marsh	Elizabeth, N. J.	VP	60	3.1	36.8	45.10	5.17	9.45	.00	.00	43.30	37.00	52	43	55.4	-----	-----	-----
44	Wabash silt loam	Omaha, Nebr.	G	1,000	5.8	8.8	1.05	1.08	0.66	.00	1.97	0.82	0.41	50.6	27.8	31.2	7.2	1.55	6.0
45	Unidentified alkali soil	Casper, Wyo.	P	263	7.4	A	8.15	3.70	.70	.00	0.24	.18	11.98	47.2	15.3	14.8	18.7	-----	0
46	Unidentified sandy loam	Denver, Colo.	G	1,500	7.0	-----	-----	-----	-----	-----	-----	-----	-----	50.0	14.1	7.6	23.2	-----	0
47	Unidentified silt loam	Salt Lake City, Utah	P	1,770	7.6	3.0	0.67	0.72	.39	.00	.88	.06	0.48	51.6	16.1	25.7	2.6	1.72	3.7
51	Acadia clay	Spindletop, Tex.	P	190	6.2	13.2	10.27	15.55	5.03	.00	.56	5.75	22.00	69	49	47.1	1.4	2.07	37.9
52	Lake Charles clay loam	League City, Tex.	P	234	8.8	A	4.20	0.33	0.18	.52	1.36	1.33	1.26	69	47	54.8	3.7	1.97	33.9
53	Cecil clay loam	Atlanta, Ga.	G	17,790	4.8	5.1	-----	-----	-----	-----	-----	-----	-----	61.2	48.3	33.7	18.2	1.60	7.0

See footnotes at end of table.

Table 1.4, Continued

Chemical and Physical Properties of the Soils at the NBS Test Sites[a]

Soil		Location	Internal drainage of test site[c]	Resistivity at 60°F	pH	Composition of water extract, mg-eq per 100 g of soil								Mean temperature[e]	Annual precipitation[e]	Moisture equivalent	Air-pore space	Apparent specific gravity	Volume shrinkage
No.[b]	Type					Total acidity[d]	Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4						
														°F	*Inches*	*Percent*	*Percent*		*Percent*
54	Fairmount silt loam	Cincinnati, Ohio	P	886	7.0	3.5	0.59	10.10	.59	.00	0.70	0.08	9.05	53.2	38.6	26.1	4.7	1.96	6.1
55	Hagerstown loam	Loch Raven, Md.	G	5,210	5.8	10.9								55.4	42.6	32.0	15.5	1.49	8.6
56	Lake Charles clay	El Vista, Tex.	VP	406	7.1	5.1	3.12	0.69	.47	.00	.80	1.59	3.04	69	49	28.7	5.0	2.03	30.1
57	Merced clay adobe	Tranquillity, Calif.	P	128	7.7	A	23.40	13.50	4.51	.00	.34	1.15	37.50	63	8	40.9	5.1	1.89	29.5
58	Muck	New Orleans, La.	VP	712	4.8	15.0	2.03	2.23	1.29	.00	.00	0.47	2.54	69.3	57.4	57.8	22.4	1.43	36.9
59	Carlisle muck	Kalamazoo, Mich.	VP	1,660	5.6	12.6	1.03	3.08	2.70	.00	.00	3.47	1.04	49	31	43.6			
60	Rifle peat	Plymouth, Ohio	P	218	2.6	297.4	2.91	10.95	2.86	.00	.00	0.00	56.70	49	37	43.4	33.2	1.28	9.1
61	Sharkey clay	New Orleans, La.	P	943	6.8	4.9	0.73	0.68	0.33	.00	.71	.10	0.91	69.3	57.4	30.8	2.3	1.78	16.4
62	Susquehanna clay	Meridian, Miss.	F	6,920	4.5	12.0								64.0	53.0	34.6	14.9	1.79	4.7
63	Tidal marsh	Charleston, S. C.	VP	84	6.9	14.6	33.60	6.85	4.0	.00	.00	12.70	36.60	66.0	45.2	46.7	19.5	1.47	18.8
64	Docas clay	Cholame, Calif.	F	62	7.5	A	28.10	2.29	0.76	0.00	0.89	28.80	0.26	58	16	41.1	4.7	1.88	27.7
65	Chino silt loam	Wilmington, Calif.	G	148	8.0	A	7.65	12.40	2.20	.00	1.30	6.05	16.90	62.4	15.2	26.4	15.8	1.41	5.7
66	Mohave fine gravelly loam	Phoenix, Ariz.	F	232	8.0	A	6.55	0.51	0.18	.00	0.73	2.77	2.97	69.7	7.8	16.5	20.1	1.79	2.7
67	Cinders	Milwaukee, Wis.	VP	455	7.6	A	0.77	3.03	.53	.00	.55	0.08	2.89	46.1	30.1	11.1			
68	Gila clay	Phoenix, Ariz.	F											69.7	7.8				
70	Merced silt loam	Buttonwillow, Calif.	F	278	9.4	A	8.38	0.38	.22	.02	1.87	1.12	5.57	65	6	24.7	6.1	1.69	0.2
71	Mahoning silt loam	West Austintown, Ohio	F	2,582	7.1	4	0.22	.37	.28		0.33	0.03	0.27						
72	Papakating silty clay loam	Deerfield, Ohio	VP	762	7.2	17	3.11	7.49	.95				11.58						
73	Wabash silty clay loam	East St. Louis, Ill.	VP	521	6.8	6	0.44	2.80	.68		1.75	.02	1.99						
74	Otero clay loam	Rocky Ford, Colo.	F	436	7.3	5	4.72	18.42	4.24		0.77	.38	26.22						
75	Unidentified silt loam	Albuquerque, N. Mex.	F	379	8.4	A	5.80	0.87	0.16		.56	.70	5.58						
76	Chino silt loam	Los Angeles, Calif.	G	2,650	9.2	A	1.54	.065		.16	1.23	.07	0.15						
77	Susquehanna clay	Louisville, Miss.	F	9,390	4.3	42	0.39	.14				40	.05						
78	Caddo fine sandy loam	Latex, Tex.	P	821	4.5	24	1.06	.18	.31			.82	.74						
101	Billings silt loam (low alkali)	Grand Junction, Colo.	F	261	7.3	A	5.21	19.24	1.43	.00	0.66	1.56	22.48	52.0	8.8	30.0			
102	Billings silt loam (mod. alkali)	Grand Junction, Colo.	F	103	7.3	A	22.63	16.56	3.85	.00	.56	4.67	36.82	52.0	8.8	20.4			
103	Billings silt loam (high alkali)	do	F	81	7.3	A	22.01	13.32	2.00	.00	.18	11.09	25.70	52.0	8.8	30.6			
104	Cecil clay	Charlotte, N. C.	G	8,500	4.6	11.0								60.2	46.1	34.1			
105	Cecil clay loam	Macon, Ga.	G	28,000	4.8	12.9								64.2	44.5	34.2			
106	do	Salisbury, N. C.	G	25,000	4.8	12.8								60	46	38.8			
107	Cecil fine sandy loam	Raleigh, N. C.	G	54,400	4.8	11.8								60.1	46.3	29.6			
108	Cecil gravelly loam	Atlanta, Ga.	G	44,400	4.9	11.2								61.2	48.3	34.3			
109	Fresno fine sandy loam (low alkali)	Fresno, Calif.	P	497	8.4	A	2.62	0.07	0.10	.31	.59	1.56	0.48	63	9	18.6			
110	Fresno fine sandy loam (mod. alkali)	do	P	531	10.2	A	3.53	.07	.12	1.49	1.07	0.79	.25	63	9	18.4			
111	Fresno fine sandy loam (high alkali)	Kernell, Calif.	P	51	7.3	A	41.55	16.21	.44	0.00	0.58	34.58	23.41	63	9	22.1			
112	Imperial clay (mod. alkali)	Niland, Calif.	P	149	7.4	A	22.18	14.09	1.29	.00	.36	10.94	25.98	71	2	34.6			
113	Imperial clay (high alkali)	do	F	102	7.4	A	9.56	0.84	.51	.00	.63	6.26	4.06	71	2	30.2			
114	Lake Charles clay	El Vista, Tex.	VP	320	7.1		2.65	.68	.26	.00	.77	1.84	0.93	69	49	35.8			
115	Memphis silt loam	Vicksburg, Miss.	G	3,450	6.9	4.7								65.6	51.9	25.7			
116	Merced clay	Los Banos, Calif.	F	320	9.2	A	9.30	.33	.18	4.60	2.10	1.17	1.57	63.4	8.1	39.7			
117	Merced clay loam adobe	Tranquillity, Calif.	P	106	8.5	A	36.19	14.66	.83	0.00	1.55	2.89	46.53	63	8	51.8			
118	Niland gravelly sand (low alkali)	Niland, Calif.	F	273	7.3	A	4.30	1.03	.64	.00	0.20	5.01	0.86	71	2	6.1			
119	Norfolk sandy loam	Macon, Ga.	G	10,800	4.7	9.7								64.2	44.5	24.1			
120	Norfolk sand	Pensacola, Fla.	G	34,400	5.7	1.3								67.7	57.9	4.4			
121	do	Tampa, Fla.	G	16,400	4.8	1.2								71.8	49.4	3.0			
122	Panoche clay loam	Mendota, Calif.	F	552	7.4	A	2.32	0.05	.26	.00	.70	0.07	1.40	63	6.4	30.0			
123	Susquehanna clay	Shreveport, La.	P	6.840	4.1	21.9								65.8	43.4	37.6			
124	do	Troup, Tex.	P	1,160	4.4	28.1								66.0	42.7	36.0			
125	Susquehanna fine sandy loam	Shreveport, La.	P	5,770	3.9	28.3								65.8	43.4	37.2			

[a] Measurements and determinations by I. A. Denison, R. B. Hobbs, and M. Romanoff. [b] Different numbers for soils that appear to be identical indicate either different sites in the same locality or that different classes of materials were buried at different times at the same site. [c] Internal drainage; G, good; F, fair; P, poor; VP, very poor. [d] A, alkaline reaction. [e] Data for mean temperature and annual precipitation furnished by United States Weather Bureau. Values with no figures to the right of the decimal point are for some nearby city.

Table 1.5

Soil Corrosion of Various Metals and Alloys for Different Resistivity Soils.[15]

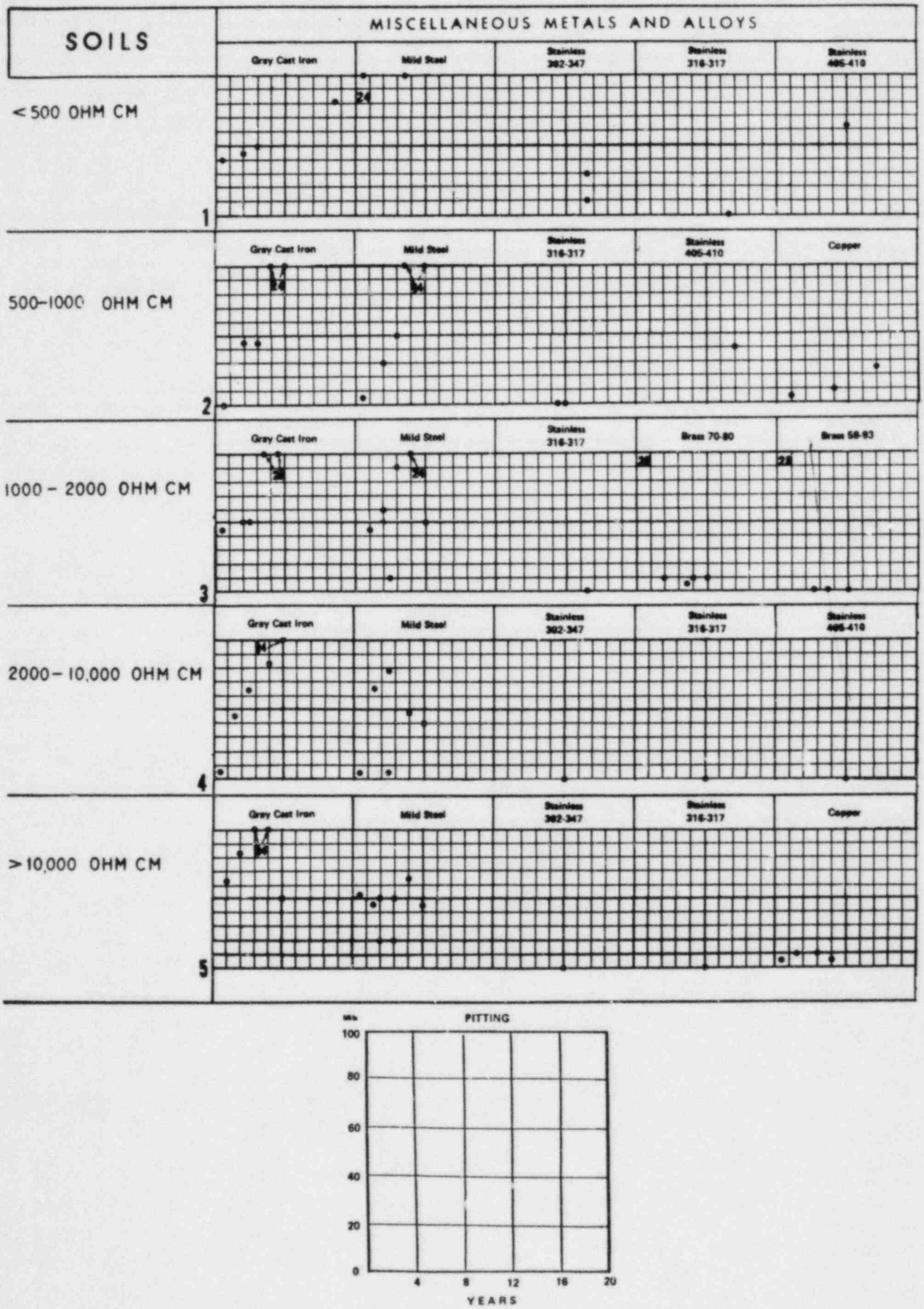
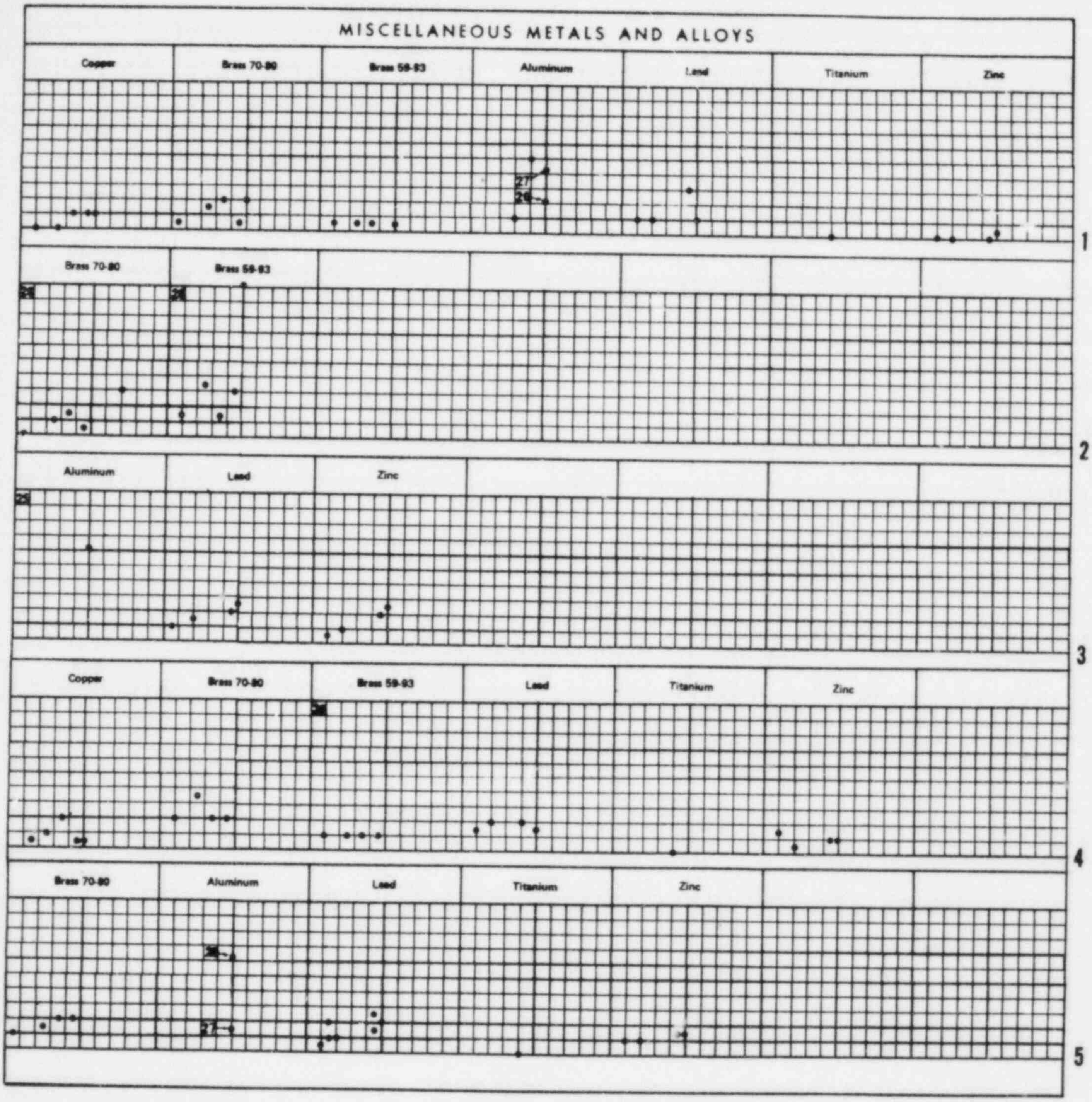


Table 1.5, Continued

Soil Corrosion of Various Metals and Alloys for Different Resistivity Soils.[15]



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 attack
16. Vapor
17. Aerated
18. Catalyzes
19. Static
20. Agitated
21. ~ 7 pH
22. < 7 pH
23. > 7 pH
24. >100 mpy
25. Perforation
26. 1100
27. 3003
28. May dealloy
29. 220 mils

1.1.7.1 Plain Iron and Steel

Plain iron and steel may be defined as iron and steel without alloying elements such as Cr, Ni or Mo. The NBS(12) conducted field tests on wrought iron, open-hearth iron, open-hearth steel, Bessemer steel, and carbon steel in different soils. It was evident that all the specimens in the same trench corroded similarly with respect to losses in weight and depths of the deepest pits. Thus, it was concluded that the corrosion rates of plain irons and steels do not depend on the composition or the surface finish, but on the kind of soils or soil conditions. Some of the results are shown in Figure 1.4, showing the degree of the differences of the corrosion rates in different soils. Results of additional corrosion studies are discussed in Section 1.1.11.

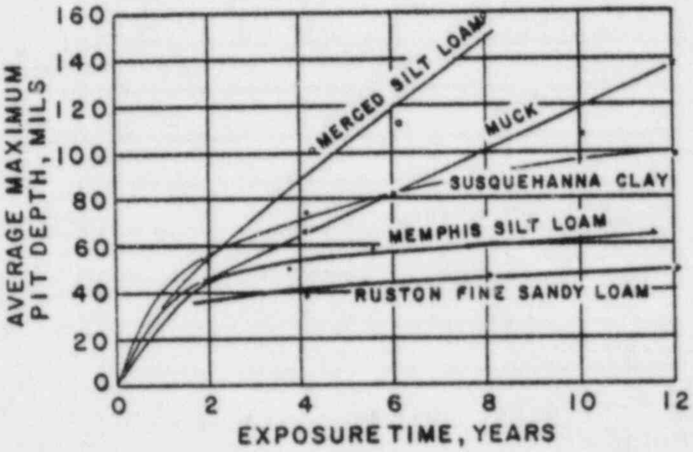


Figure 1.4 Pit depth vs time curves for wrought ferrous pipes in different soils.(12)

By plotting the logarithm of the average maximum pit depth of equivalent 3-in. specimens against the logarithm of the time, approximately linear relationships were obtained. The maximum pit depth may be expressed by an empirical equation,

$$P = k_{5.3} \left(\frac{t}{5.3}\right)^n$$

where P = depth of the deepest pit at the time t, and $k_{5.3}$ and n are constants. The constants $k_{5.3}$ and n for 47 different soils were calculated by Romanoff.(12)

1.1.7.2 Low Alloy Iron and Steel

Figure 1.5 shows some of the results obtained by the NBS underground test(12) of the low alloy irons and steels.

In comparison to the unalloyed open-hearth steel (A in Figure 1.5), low alloy steel with small amounts of Cr and Mo (E & H in Figure 1.5) showed significantly improved corrosion resistance.

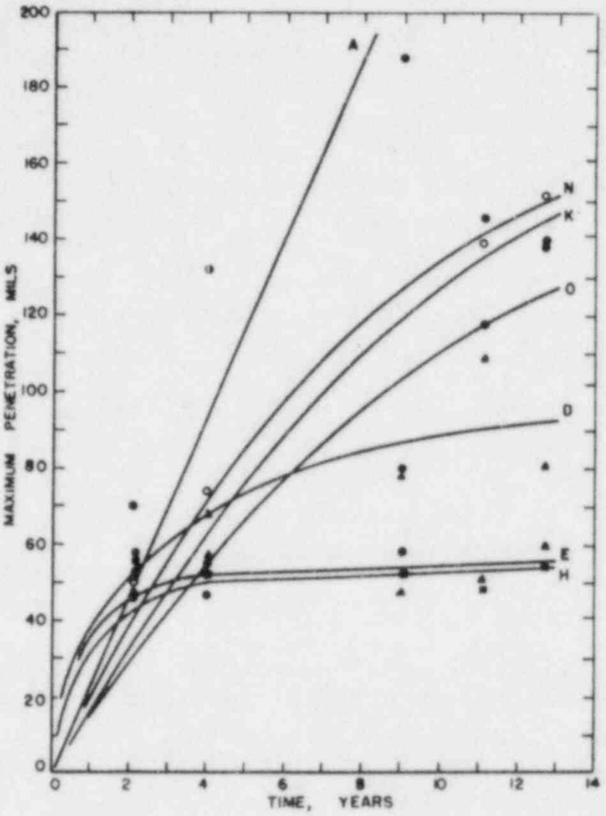


Figure 1.5 Pit-depth-time curves of copper-molybdenum open-hearth irons, chromium, and chromium molybdenum steels in cinders. A, open-hearth steel; N, open-hearth iron, 0.54 % Cu, 0.13 % Mo; K, 2% Cr-steel with Mo; D, 5.02% Cr-steel; E, 4.67% Cr-steel with Mo; H, 5.76% Cr-steel with Mo.(12)

Steels containing 1 and 5 percent of Cr, respectively, had pits of about the same depth. The addition of 0.43% Mo to the steel with 5% Cr (D, in Figure 1.5) further reduced pitting (H in Figure 1.5).

The relative corrodability of the low alloy irons and steels as measured by weight loss was independent of the aeration of the soils. Similarly, the 4-6% Cr steels were deeply pitted in all of the very poorly aerated soils, (except soil 67, Table 1.4), and the high rate of pitting continued through the exposure period.

1.1.7.3 Stainless Steels

Stainless steels may be defined as alloy steels containing at least 10% chromium, with or without other elements.

The NBS(12) tested some of the 300 and 400 series stainless steels in 15 different soils for 14 years. The compositions of the alloys and the test results are shown in Table 1.6.

Plain chromium steels, 410 and 430, showed severe pitting, while chromium-nickel steels, the 300 series, showed considerably better pitting resistance.

Adding chromium to plain carbon steel decreases the uniform corrosion gradually, but the addition of Cr beyond 6% increases the depth of pitting. In fact for some clays, steel containing 18% Cr may have deeper pits than plain steel.

Alloying with sufficient nickel or nickel plus molybdenum apparently neutralized the tendency of high concentrations of Cr to accelerate pitting.

Austenitic stainless steels are known to be susceptible to pitting where oxygen is in short supply. However, the field test results in Docas clay, poorly aerated and poorly drained soil containing 2% sodium chloride, showed that the 300 series stainless steels are very resistant to pitting while the 400 series stainless steels and low carbon steel showed very deep pitting. Type 316 SS, as shown in Table 1.7, showed negligible weight loss and no pitting.

A recent NBS study(16) on the corrosion behavior of selected stainless steels was conducted at six different test sites. The properties of soils at these test sites are shown in Table 1.8. AISI 200, 300, and 400 series were tested, but only the 300 series will be discussed in this report because the 200 and the 400 series stainless steels showed poor corrosion resistances, in comparison to the 300 series, confirming the results of the earlier NBS study.(12)

For this later NBS test, sensitized materials as well as the annealed materials were tested. Sensitizing means heating stainless steel at the temperature range of 480 to 810°C to make the stainless steel susceptible to intergranular corrosion.

<u>Annealed Materials</u> - In clay and tidal marsh (Site C and G), Types 301 and 304 SS were susceptible to pitting and tunneling corrosion, while Type 316 was unaffected by corrosion. In a typical coastal sand that is constantly damp and is occasionaly flooded with seawater, many of the annealed 300 series samples including Type 316 were perforated.

<u>Sensitized Materials</u> - In clay (Site C), all 300 series were susceptible to pitting corrosion with Type 316 being the least susceptible. In tidal marsh, poorly-drained marsh soils that are found along the Atlantic and Gulf coasts, Type 301 and 304 showed severe non-uniform attack, while the corrosion of Type 316 was negligible. In coastal sand, sensitized 300 series including Type 316 showed much higher weight loss rates than annealed materials, and all specimens were perforated. Table 1.9 shows some of the results.

(Continued Page 22)

Table 1.6

Loss in Weight and Depth of Pits of High-Chromium and Chromium-Nickel Steels Exposed for 14 Years[a]

M. Shallow metal attack, roughening of surfaces, but no definite pitting.
P. Definite pitting, but no pits greater than 6 mils.
+. One or more specimens contained holes because of corrosion.

AISI type No.	410		430		430		304		304		302		309		316			
Number of specimens	5[a]		5[b]		2		2		2		5[c]		5[c]		2[d]		2[d]	
Composition:																		
C, %	0.065		0.070		0.12		0.08		0.05		0.093		0.144		0.07		0.07	
Mn, %	.38		.36		.42		.44		.46		.36		1.80		1.24		1.99	
Cu, %			.02								.02		0.02				1.07	
Cr, %	11.95		17.08		17.72		17.20		17.52		18.69		22.68		17.78		19.27	
Ni, %	0.48		0.09		0.29		8.95		8.85		9.18		12.94		10.96		22.12	
Mo, %															2.63		3.52	
Soil[e]	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration
	oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
51							0.03	29 +							0.009	M	0.004	0
53							.0009	0							.02	0	.03	0
55	0.0002	M	0.0001	0							0.0005	0	0.0003	0	.004	0	.001	0
56							.20	32 +							.005	P	.0004	0
58					0.85	52	.002	0	0.0008	11					.0008	0	.0005	0
59	.0002	M	.001	M			.0007	0			.002	P	.001	P	.002	0	.001	0
60	5.4	37 +	.17	16 +			.0006	0			.003	M	.001	M	.006	0	.0007	0
61							.0004	P							.0004	0	0	0
62					.03	6	.0004	M	.003	6					.0002	0	.0001	0
63					.33	13	.06	P	.12	13					.001	0	.006	0
64	5.7	63 +	1.4	63 +	.34	48	.003	P	.04	7	.002	0	.0007	0	.002	0	.003	0
65	.46	62 +	.74	61 +			.01	16 +			0	M	.00004	0	.0004	0	0	0
66	3.2	62 +	2.3	62 +			.0009	P			0	M	0	M	0	0	0	0
67					5.19	73	.0008	12	.002	8					.01	M	.009	0
70															.0001	0	.0002	0

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[a] Annealed at 1,400°F, pickled, lightly cold-rolled.
[b] Annealed at 1,600°F, pickled.
[c] Heated to 1,850°F, air quenched, pickled.
[d] Specimens "CM" and "DT" were exposed to the soils for 13 years. The remaining specimens were exposed 14 years.
[e] See Table 1.4 for names and location of soils.

Table 1.7

Results of Exposure of High-Alloy Steels to a Poorly Aerated Soil Containing Sodium Chloride (Docas clay, soil 64)(12)

M, Shallow metal attack, roughening at surface, but no definite pitting.
+, One or more specimens contained holes because of corrosion. The thickness of the specimen has been used as the maximum pit in this case.
D, Destroyed by corrosion.

AISI type No.	410	430	430	304	304	302	309	316	....	Low-carbon steel
Composition (percent):										
C	0.065	0.070	0.12	0.08	0.05	0.093	0.144	0.07	0.07	....
Mn	.38	.36	.42	.44	.46	.36	1.80	1.24	1.99	....
Cu	....	.02	....	....	....	.02	.02	....	1.07	....
Cr	11.95	17.08	17.72	17.20	17.52	18.69	22.68	17.78	19.27	....
Ni	.48	.09	.29	8.95	8.85	9.18	12.94	10.96	22.12	....
Mo	....	....	....	....	....	....	....	2.63	3.52	....
	Loss in weight (oz/ft²)									
Period of exposure (yr):										
2	0.67	0.53	0.50	0.01	0.01	0.002	0.003	0.006	0.002	12.8
5	1.0	.28	.30	.002	.01	.002	.002	....	....	25.3
7	1.7	.44	(a)	.003	.02	.002	.005	.004	.004	35.6
9	3.2	1.2	(a)	.08	.06	.002	.006	.007	.002	D
14	5.1	1.4	.34	.003	.04	.002	.0007	.002	.003	D
	Maximum penetration (mils)									
2	63 +	63 +	(a)	17	8	8	5	M	O	130
5	63 +	54 +	10	<6	0	4	<6	....	....	154 +
7	63 +	63 +	21	8	0	M	<6	M	0	154 +
9	63 +	63 +	96	14 +	36	<6	<6	0	0	154 +
14	63 +	63 +	48	<6	7	0	0	0	0	154 +

[a] Data are not used because of corrosion caused by asphalt on the ends of the specimens.

Table 1.8

Properties of Soils at Test Sites(16)

Site Iden	Soil	Location	Internal Drainage Test Site	Resistivity[a] (ohm-cm)	pH	Composition of Water Extract (Parts per Million)								
						TDS[b]	Ca	Mg	Na + K as Na	CO_3	HCO_3	SO_4	Cl	NO_3
A	Sagemoor sandy loam	Toppenish, WA	Good	400	8.8	7,800	108	23	1,960	0.0	5,002	216	330	6
B	Hagerstown loam	Loch Raven, MD	Good	12,600-34,770	5.3	c	-	-	-	-	-	-	-	-
C	Clay	Cape May, NJ	Poor	400- 1,150	4.3	14,640	540	754	2,242	0.0	0.0	6,768	3,529	118
D	Lakewood sand	Wildwood, NJ	Good	13,800-57,500	5.7	c	-	-	-	-	-	-	-	-
E	Coastal sand	Wildwood, NJ	Poor	1,320-49,500	7.1	11,020	302	329	3,230	0.0	55	1,133	5,765	31
G	Tidal marsh	Patuxent, MD	Poor	400-15,500	6.0	11,580	140	165	2,392	0.0	0.0	1,709	3,259	37
						(Milligram equivalents per 100 grams of soil)								
A	-	-	-	-	-	-	0.54	0.19	8.50	0.0	8.20	0.45	0.93	0.01
B	-	-	-	-	-	c	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	2.70	6.18	9.51	0.0	0.0	14.0	9.94	0.19
D	-	-	-	-	-	c	-	-	-	-	-	-	-	-
E	-	-	-	-	-	-	1.51	2.70	13.9	0.0	0.09	2.36	16.2	0.05
C	-	-	-	-	-	-	0.70	1.35	10.2	0.0	0.0	3.56	9.18	0.06

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[a] Resistivity determinations made at the test site by Wenner's 4-pin method (5) except for Site A where Shepard's cane (6) was used.

[b] TDS, total dissolved soilds - residue dried at 105°C.

[c] Analysis not made for soils at Sites B and D because of the very low concentration of soluble salts in these soils.

Table 1.9

Average Weight Loss (mg/dm^2) and Pit Depth (mils) for Stainless Steel Sheet and Tube Specimens Buried in Sagemoor Sandy Loam (Site A) for up to Four Years

System[c]	Material	Treatment[d]	Exposure, Time, Days	Average[a] Weight Loss		Pit Depth, mils[b]	
				mg	mg/dm^2	Maximum	Average of 5 Deepest[e]
Exposed in 1970							
50	Type 201	--	413	--	--	--	--
			791	4	<1	--	--
			1442	--	--	--	--
51	Type 202	--	413	--	--	--	--
			791	--	--	IP	--
			1442	--	--	--	--
52	Type 301	--	413	--	--	--	--
			791	--	--	<5	--
			1442	--	--	--	--
53	Type 301	S	413	68	6	IP	--
			791	201	15	<5	--
			1442	1247	98	<5	--
54	Type 301	XBW	413	2	<1	--	--
			791	2	<1	<5	--
			1442	--	--	--	--
55	Type 304	--	413	--	--	--	--
			791	2	<1	--	--
			1442	--	--	--	--
56	Type 304	S	413	285	21	--	--
			791	255	21	<5	--
			1442	618	49	--	--
57	Type 304	HW	413	1	<1	--	--
			791	--	--	--	--
			1442	--	--	18	--
58	Type 316	--	413	3	<1	--	--
			791	--	--	--	--
			1442	--	--	--	--
59	Type 316	S	413	20	2	IP	--
			791	86	6	<5	--
			1442	384	12	7	--
60	Type 409	--	413	6	<1	29	--
			791	6	<1	<5	--
			1442	150	12	H	H
62	Type 409	HW	413	186	73	--	--
			791	101	40	IP	--
			1442	32	12	H	--
63	Type 409	HW	413	187	95	IP	--
			791	149	88	<5	--
			1442	75	37	H	H
64	Type 410	--	413	3510	281	48	--
			791	82	6	20	7
			1442	8843	705	H	H
65	Type 430		413	4	<1	--	--
			791	10	1	IP	--
			1442	66	6	22	--
66	Type 434		413	4	<1	--	--
			791	2	<1	IP	--
			1442	--	--	--	--
Exposed in 1971							
1	26 Cr-1 Mo	--	496	2	<1	IP	--
			860	--	--	--	--
			1147	--	--	--	--
2	18 Cr(Ti)	--	496	10	1	IP	--
			860	2	<1	--	--
			1147	1	<1	<5	--
3	18 Cr(Ti)	XBW	496	1	<1	<5	--
			860	4	<1	<5	--
			1147	4	<1	--	--

Table 1.9, Continued

Average Weight Loss (mg/dm^2) and Pit Depth (mils) for Stainless Steel Sheet and Tube Specimens Buried in Sagemoor Sandy Loam (Site A) for up to Four Years

System[c]	Material	Treatment[d]	Exposure, Time, Days	Average[a] Weight Loss mg	Average[a] Weight Loss mg/dm^2	Pit Depth, mils[b] Maximum	Pit Depth, mils[b] Average of 5 Deepest[e]
4	20 Cr-24 Ni-6.5 Mo	--	496	4	<1	IP	--
			860	1	<1	--	--
			1147	1	<1	--	--
5	20 Cr-24 Ni-6.5 Mo	S	496	1	<1	--	--
			860	--	--	--	--
			1147	--	--	--	--
6	18 Cr-2 Mo	--	496	3	<1	IP	--
			860	1	<1	--	--
			1147	--	--	--	--
8	18 Cr-8 Ni(N)	--	496	--	--	IP	--
			860	--	--	--	--
			1147	--	--	--	--
9	18 Cr-8 Ni(N)	XBW	496	20	2	IP	--
			860	--	--	--	--
			1147	2	<1	--	--
10	26 Cr-6.5 Ni	--	496	7	<1	<5	--
			860	--	--	<5	--
			1147	3	<1	--	--
14	Composite A[f]	--	496	81500	6412	N/A	
			860	116350	9154	N/A	
			1147	165175	12995	N/A	
15	Composite B[f]	HDZ	496	9075	714	N/A	
			860	21975	1729	N/A	
			1147	2775	2193	N/A	
16	Composite C[f]	--	496	83775	6591	N/A	
			860	112175	8825	N/A	
			1147	149075	11728	N/A	
17	26 Cr-1 Mo	HW	496	11	3	<5	--
			860	--	--	--	--
			1147	--	--	16	--
18	18 Cr(Ti)	HW	496	--	--	--	--
			860	--	--	--	--
			1147	4	2	--	--
19	20 Cr-24 Ni-6.5 Mo	HW	496	--	--	--	--
			860	--	--	--	--
			1147	--	--	--	--
Exposed in 1972							
7	18 Cr-2 Mo(Nb)		364	--	--	--	--
			651	4	<1	<5	--
11	18 Cr-2 Mo (Nb)	XBW	364	--	--	--	--
			651	13	1	--	--
12	18 Cr-2 Mo (Nb)	HW	364	--	--	--	--
			651	8	2	<5	--

---

[a] Average for four specimens.

[b] 1 mil = 0.025 mm. IP - incipient pitting; H - perforated; N/A - not applicable.

[c] Systems 12, 17, 18, 19, 57, 62, and 63 were tube specimens fabricated from sheet material, welded at the seams and then plugged and capped at each end to minimize internal corrosion. Specimens of all other systems were flat sheet material.

[d] All materials were in the annealed condition unless noted otherwise. Abbreviations used: S-sensitized; XBW-cross-bead weld; HW-heliarc weld; HFW-high frequency weld; HDZ-hot-dip zinc coated (galvanized, 4.5 oz/ft^2) after bonding. See footnote c.

[e] Average of five deepest pits on each of four individual specimens unless noted.

[f] All composites were metallurgically bonded. Composite A-carbon steel/type 430/carbon steel; Composite B-carbon steel/type 430/carbon steel; Composite C-carbon steel/type 304/carbon steel.

1.1.7.4. Aluminum

Unprotected aluminum alloys may be virtually unaffected under some conditions and severely corroded in certain other types of soils.

Sprowls and Carlisle(17) compared the corrosion behavior of aluminum alloys and alclad alloys in soil. Alclad alloys that consist of an aluminum alloy core covered on one or more surfaces with one or more layers of corrosion-resistant aluminum alloy showed superior performance in all soils tested. Figure 1.6 shows the pit depth-time curves for aluminum alloys and an alclad alloy in comparison to steel and copper.

It was concluded that certain soils may cause severe pitting of aluminum alloys and that it is very difficult to predict the performance of aluminum alloys on the basis of a chemical analysis or a resistivity measurement of the soil.

Campbell(18) tested 11 aluminum alloys in six different soils. In cinders, the corrosion of all specimens was too severe for any useful comparison between the alloys to be made. Corrosion was also severe in acidic peat. The cladding gave no protection in cinders, but in wet salt marsh, clay, and peat, it afforded protection for between 5 to 10 years. In addition, there was no decrease in the corrosion rate over the 10 year period.

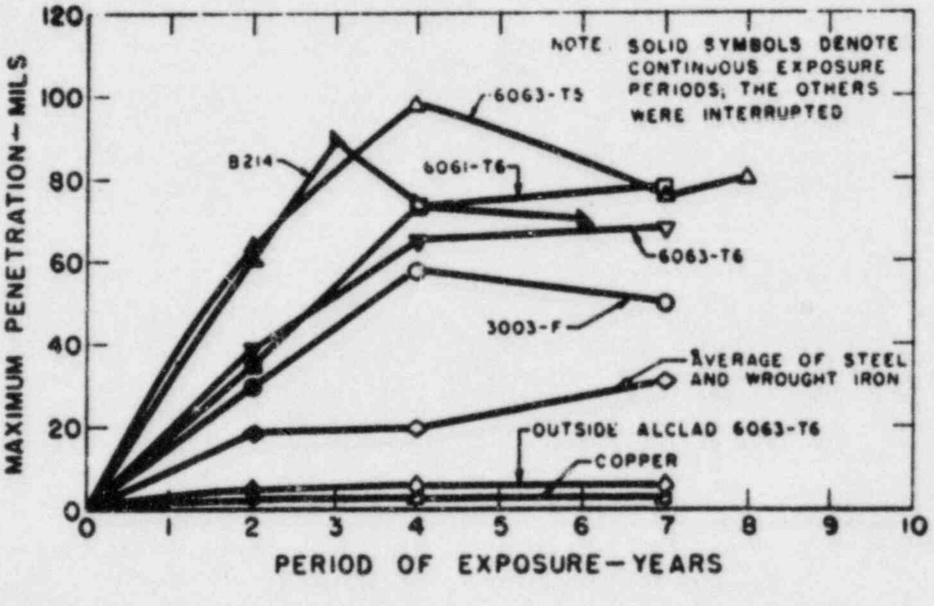

Figure 1.6 Pit depth-time curves for aluminum alloys and alclad in comparison to steel and copper.(17)

The NBS(12) exposed commercial aluminum, duralumin, and aluminum alloy in five different soils for 10 years. Among the specimens tested, alloyed aluminum showed the best performance. Unalloyed aluminum showed very good corrosion resistance in tidal marsh (soil 43 in Table 1.4) and Hanford very fine sandy loam (soil 13 in Table 1.4), but very poor performance in muck soil 29 in Table 1.4). Table 1.10 shows the underground corrosion test results on aluminum, duralumin, and Al-alloy of 0.16 cm thickness. Similar data for zinc and iron in the same soils are also shown for comparison.

1.1.7.5 Copper and Its Alloys

Copper and copper alloys were tested in 14 different soils for approximately 14 years by the NBS.(12) The results are shown in Table 1.11 in terms of weight loss and maximum pit depth.

As shown in this table, the corrosion rate in cinders (soil 67) was significantly higher than those in other soils. In soils having high concentrations of sulfides (soil 63), of organic and inorganic acidity (soils 58 and 60), and of chlorides (soil 64), the corrosion rates were slightly higher than those in other soils. The loss in weight and maximum pit depth of copper in four different groups of soils will be compared with those of zinc, lead, and steel in Section 1.1.7.7.

The results of the corrosion tests on copper-zinc (brass) and copper-nickel-zinc alloys show that in most soils the corrosion for the maximum exposure period was not appreciable. This type of data, however, does not show the extent of deterioration of these materials due to selective corrosion. Selective corrosion or selective leaching is the removal of one element from a solid alloy by corrosion processes. The selective leaching of zinc in Cu-Zn alloys (brass alloys) is called dezincification.

When dezincification occurs, there is little dimensional change. Thus, the corrosion rate expressed in terms of weight loss and maximum pit depth can be misinterpreted as good corrosion resistance, while the dezincified portion is weak, permeable and porous. The addition of zinc to copper lowers the corrosion resistance of copper.

1.1.7.6 Lead

Lead alloys have been used underground in the form of water service pipes and cable sheaths. Lead-coated ferrous metals are not used because any exposed iron or steel will suffer from accelerated galvanic corrosion caused by the cathodic nature of the lead.

Table 1.12 shows the field test results on four different lead alloys. From these results, the following conclusions can be made:

a. Soils deficient in oxygen (poor aeration) cause a high corrosion rate of lead. The corrosion behaviors of lead specimens exposed to two soils differing in aeration but similar in their chemical properties are illustrated in Figure 1.7. This shows that poor aeration causes high corrosion rates.

b. Organic soil is corrosive for lead because certain organic salts of lead (e.g., acetate) are water soluble and do not form protective corrosion products. Figure 1.8 shows the effect of organic acidity on the corrosion of lead.

(Continued Page 29)

Table 1.10

Loss in Weight and Maximum Pit Depth of Zinc and Aluminum Exposed in 1926(12)

Duration of exposure (years)		10.16		10.08		10.05		10.73		10.55	
		Soil 13 Hanford very fine sandy loam		Soil 29 Muck		Soil 42 Susquehanna clay		Soil 43 Tidal Marsh		Soil 45 Unidentified alkali soil	
Material	Symbol	Loss in weight oz/ft^2	Maximum pit depth mils	Loss in weight oz/ft^2	Maximum pit depth mils	Loss in weight oz/ft^2	Maximum pit depth mils	Loss in weight oz/ft^2	Maximum pit depth mils	Loss in weight oz/ft^2	Maximum pit depth mils
Sheet zinc	Z_1	3.52	40	4.66	39	0.85	17	2.48	36	D[a]	62+[b]
Cast zinc	Z_2	3.47	71	5.37	55	79	18	2.38	73	9.93	104
Sheet zinc	P	1.89	53	3.85	62+	1.06	20	4.85	40	D	62+
Aluminum	C_1	.086	21	D	62+	.35	62+	.18	<6	.49	46+
Al-Mn-alloy	C_2	.38	45+	.97[c]	62+	.20	14	.22	13	.33	20
Duralumin	C_3	D	D	D	D	1.39	62+	.15	<6	.56[c]	62+
Open-hearth iron	A	9.92	125+	5.86	62	5.61	70	D	125+	D	125+
Steel+0.2% Cu	S	D	62+	6.91	62+	5.40	59	D	62+	D	62+

[a] D = destroyed by corrosion.
[b] + = 1 or both specimens punctured because of corrosion.
[c] Data on 1 specimen only. The other specimen was destroyed by corrosion.

Table 1.11

Loss in Weight and Maximum Pit Depth of Copper and Copper-Silicon Buried in 1932(12)
(Average of two specimens)

Identification	Material	Average exposure	Test site number and soil type													
			51	53	55	56	58	59	60	61	62	63	64	65	66	67
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders
			LOSS IN WEIGHT (OUNCES PER SQUARE FOOT) [a]													
		Years														
A	Deoxidized copper	2.0	0.40	0.12	0.14	0.10	0.16	------	1.47	[b]0.06	0.16	1.13	1.41	1.71	0.28	3.98
		5.4	1.01	.15	.14	.51	1.56	0.12	3.82	.35	.26	2.45	2.22	[c]1.02	[c].75	9.33
		7.4	.40	.20	.15	.80	1.72	[c].11	1.10	.38	.38	4.25	3.00	[c]2.37	[c]1.32	4.89
		9.3	------	.22	.18	.78	2.10	.11	5.01	.35	.48	4.22	5.32	.24	[c].62	11.50
		14.3	[d].60	.24	.16	.89	2.39	[d].21	11.97	.66	.52	6.57	5.17	1.07	.54	13.77
C	Tough-pitch copper	2.0	.42	.12	[c].14	.12	.13	------	1.37	[b].09	.15	1.31	.67	.50	.11	3.15
		5.4	.91	.16	.19	.34	1.40	.13	4.68	.34	.26	2.99	.96	.47	.16	8.04
		7.4	.35	.23	.17	.60	1.66	[c].09	1.03	.37	.33	4.33	1.56	.55	.32	1.42
		9.3	------	.24	.20	.71	1.95	.12	7.26	.33	.36	4.46	2.80	.26	.45	9.84
		14.3	[d].46	.23	.16	.61	1.98	[d].19	[c]14.66	.58	.49	8.31	1.04	.47	.27	6.71
N	Copper-silicon alloy	2.0	.35	.19	.14	.16	.11	------	1.57	[b].14	.25	1.45	1.32	1.03	.22	5.37
		5.4	1.02	.24	.28	.32	1.36	.22	4.13	.42	.40	4.37	2.10	.53	[c].67	15.51
		7.4	.48	.38	.23	.40	1.70	[c].14	1.06	.38	.42	4.57	1.74	2.42	.55	1.99
		9.3	------	.30	.30	.62	1.97	[c].24	[c]3.96	.48	.57	6.96	4.87	.62	[c].51	22.51
		14.3	.53	.51	.38	.60	2.80	[d].26	10.65	.77	.54	8.30	4.59	.66	.53	9.46
[f]N_1	Copper-silicon alloy	2.0	------	------	------	.14	------	------	.79	[b].12	.15	1.98	1.48	1.23	.14	5.90
		5.4	------	.21	------	------	------	[c].26	------	.24	------	------	1.38	------	------	------
		7.4	------	.25	------	------	1.56	------	------	------	------	------	------	2.74	------	------
		9.3	------	------	------	------	------	------	1.82	------	------	------	------	------	.34	23.17
		14.3	------	------	.29	.55	------	.20	------	------	.44	6.84	------	------	------	------
E	Copper-silicon alloy	2.0	.51	.24	.29	.23	.19	------	1.61	[b].19	.33	1.16	.79	.48	.38	3.25
		5.4	1.04	.28	.29	.48	1.64	.28	3.76	.51	.61	1.93	1.26	.72	.51	5.63
		7.4	.97	.38	.24	.60	1.67	[c].23	1.03	.65	.52	3.53	1.44	1.17	1.22	1.47
		9.3	------	.37	.35	.76	2.11	.17	[c]3.22	.61	.69	[c]4.38	2.30	.96	[c]1.53	8.76
		14.3	[d]1.40	.45	.26	.70	2.73	[d].31	9.32	.87	.70	4.84	2.82	1.42	1.82	8.49
D	Copper-silicon alloy	2.0	.45	.18	.15	.10	.11	------	1.33	[b].13	.24	1.23	.67	1.10	.21	4.23
		5.4	1.07	.25	.20	.35	1.70	.10	3.32	.52	.42	2.64	1.14	[c].62	[c].53	20.95
		7.4	.41	.39	.28	.52	1.75	[c].18	.72	.61	.50	4.86	1.43	[c]1.28	.40	7.69
		9.3	------	.36	.28	.63	2.12	.15	4.46	.52	.60	5.32	2.88	.48	.55	13.47
		14.3	[d].55	.48	.24	.77	2.49	[d].21	9.74	.88	.66	5.16	2.81	1.24	.45	17.34

Table 1.11, Continued

Loss in Weight and Maximum Pit Depth of Copper and Copper-Silicon Buried in 1932(12) (Average of two specimens)

Identification	Material	Average exposure	Test site number and soil type													
			51	53	55	56	58	59	60	61	62	63	64	65	66	67
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders
			MAXIMUM PIT DEPTH (MILS)													
		Years														
A	Deoxidized copper	2.0	[g]M	<6	<6	M	M	------	7	[b]<6	<6	M	<6	<6	6	38
		5.4	<6	7	<6	<6	12	<6	28	[c].23	9	M	9	10	7	54
		7.4	<6	10	<6	<6	10	<6	8	8	14	8	<6	18	8	44
		9.3	------	<6	<6	<6	[c].14	<6	38	8	8	10	[c].16	<6	10	88
		14.3	[d]<6	8	<6	<6	19	[d]6	48	24	10	10	10	9	10	64
C	Tough-pitch copper	2.0	M	M	[c]<6	M	<6	------	<6	[b]<6	<6	<6	7	<6	<6	26
		5.4	<6	<6	6	<6	12	6	33	[c]15	6	<6	8	9	<6	56
		7.4	<6	11	7	8	14	6	9	16	6	7	14	20	<6	24
		9.3	------	6	8	<6	10	<6	40	8	8	6	[c]14	10	<6	51
		14.3	[d]<6	6	<6	<6	16	[d]6	46	20	10	14	14	12	<6	42
N	Copper-silicon alloy	2.0	M	<6	<6	<6	M	------	7	[b]<6	<6	<6	10	6	15	46
		5.4	<6	6	8	<6	7	<6	17	11	<6	<6	10	16	[c]18	80
		7.4	<6	<6	6	<6	9	<6	<6	11	6	6	12	20	14	31
		9.3	------	<6	<6	<6	12	M	10	10	<6	12	21	20	13	[h]145+
		14.3	[d]<6	6	7	<6	15	[d]<6	24	17	6	16	16	12	10	42
[f]N1	Copper-silicon alloy	2.0	------	------	------	<6	------	------	7	[b]<6	<6	<6	10	15	M	40
		5.4	------	<6	------	------	------	<6	------	<6	------	------	12	------	------	------
		7.4	------	9	------	------	16	------	------	------	------	------	------	24	------	------
		9.3	------	------	------	------	------	------	8	------	------	------	------	------	<6	90
		14.3	------	------	7	<6	------	11	------	------	8	11	------	------	------	------
E	Copper-silicon alloy	2.0	<6	12	13	12	11	------	24	[b]<6	14	16	20	23	12	38
		5.4	8	14	16	9	33	11	22	26	15	<6	19	21	16	49
		7.4	6	14	15	12	33	6	12	35	<6	14	12	33	15	33
		9.3	------	12	20	12	53	20	18	[c]37	22	10	34	22	22	102
		14.3	[d]15	20	20	12	54	[d]16	35	42	23	11	22	23	21	78
D	Copper-silicon alloy	2.0	M	<6	7	M	M	------	<6	[b]M	6	<6	19	<6	<6	34
		5.4	11	10	10	M	8	M	15	7	10	<6	11	11	[c]12	90
		7.4	<6	<6	10	7	12	<6	<6	6	12	13	12	14	16	28
		9.3	------	8	8	M	12	<6	21	<6	6	9	[c]16	11	9	80
		14.3	[d]<6	8	10	<6	16	[d]<6	28	13	10	10	24	13	10	74

[a] Each ounce per square foot corresponds to an average penetration of 0.0014 in.

[b] Exposed for 1.0 year only.

[c] Date for the individual specimens differed from the average by more than 50 percent.

[d] Data for 4 specimens.

[f] These specimens had welded joints - data for only 1 specimen.

[g] M, shallow metal attack, roughening of the surface, but no definite pitting.

[h] +, both specimens contained holes because of corrosion.

Table 1.12

Loss in Weight and Maximum Pit Depth of Lead Alloys Buried in 1937 and 1941[a],(12)

Identification	Material[b]	Average exposure	Test site number and soil type														
			51	53	55	56	58	59	60	61	62	63	64	65	66	67	70
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders	Merced silt loam
			LOSS IN WEIGHT (oz/ft^2)														
		Years															
O	Chemical lead	2.1	0.62	0.22	0.37	0.21	1.56	0.36	0.18	1.46	0.30	0.05	0.20	0.14	0.10	3.67	0.03
		4.0	......	.21	.20	.45	2.41	.81	.28	2.21	.93	.02	.19	.13	.10	12.21	.12
		9.0	3.06	.53	.37	2.02	2.49	1.76	.54	1.22	.67	.10	.46	.45	.34	11.21	.26
		11.2	......	.64	.41	3.49	2.82	2.06	.75	3.03	.94	.02	.60	.35	.18	3.06	.19
T	Tellurium lead	2.1	1.21	.25	.34	.38	1.68	.23	.15	1.21	.36	.06	.25	.17	.25	3.35	.09
		4.0	......	.31	.28	.82	2.80	1.08	.20	1.75	.64	[c].02	.18	.16	.12	13.22	.15
		9.0	3.82	.73	.54	2.30	2.60	2.09	.57	1.44	1.37	.13	.48	.59	.58	11.28	.32
		11.2	......	.67	.57	4.60	3.47	1.77	.84	3.40	1.00	.02	.88	.40	.36	3.42	.28
B	Antimonial lead	2.1	1.05	.25	.19	.31	1.45	.20	.10	.94	.27	.04	.12	.17	.06	3.14	.10
		4.0	......	.22	.15	.50	2.12	1.04	.22	1.75	1.03	.01	.19	.21	.12	4.21	.14
		9.0	3.09	.62	.30	1.65	2.24	1.97	.54	1.16	.77	[c].05	.45	.51	.28	12.27	.20
		11.2	......	.70	.35	4.54	3.02	1.09	.79	3.78	1.24	.01	.96	.35	.20	4.28	.16
M	Calcium lead	5.0	......	.43	.17	.52	.54	1.23	.74	.82	.69	.18	.50	.42	.24	1.18	.35
		7.2	......	[d].46	.27	4.98	.70	.82	[d].61	[d].63	[d].64	.20	.40	.38	.39	2.23	.18
		8.7	......	.64	.39	3.47	1.22	1.74	.79	1.48	.91	.14	.48	.40	.34	8.40	.19
		[d]10.9	......	.71	.46	5.20	2.09	1.85	.88	1.69	1.02	.22	.59	.53	.55	10.56	.26
			MAXIMUM PIT DEPTH (mils)														
O	Chemical lead	2.1	40	18	24	38	34	21	18	35	32	14	24	40	44	79	48
		4.0	......	12	26	37	28	15	15	39	29	18	16	24	34	104	14
		9.0	68	26	19	86	46	14	16	31	26	29	25	32	36	135	24
		11.2	......	18	31	100	52	20	33	70	34	12	25	15	24	85	24
T	Tellurium lead	2.1	54	12	26	30	55	8	29	33	19	10	21	22	23	71	16
		4.0	......	20	26	48	56	12	10	30	31	[c]12	11	16	41	94	27
		9.0	66	18	26	110	33	18	36	43	25	32	20	21	30	104	37
		11.2	......	16	30	107	53	21	23	73	40	8	17	20	23	61	16
B	Antimonial lead	2.1	56	10	26	39	50	9	6	31	12	<6	12	6	12	56	11
		4.0	......	10	18	52	58	7	<6	42	30	16	12	15	15	90	12
		9.0	63	14	15	74	66	20	20	62	26	[c]44	10	26	24	125	20
		11.2	......	9	16	104	51	12	28	89	14	6	19	7	16	46	9
M	Calcium lead	5.0	......	12	15	30	18	25	13	24	18	36	21	19	34	26	28
		7.2	......	[d]13	8	58	8	8	[d]8	[d]18	[d]10	8	10	12	18	15	10
		8.7	......	19	18	67	31	19	16	34	26	12	12	16	22	67	16
		[d]10.9	......	16	23	94	49	25	21	62	29	18	26	19	38	88	21

[a] Average loss in weight or depth of maximum pitting for 2 specimens except when indicated otherwise.

[b] See Table 52 of Reference 12.

[c] Date for 1 specimen only. The other specimen was missing.

[d] Data for 3 specimens.

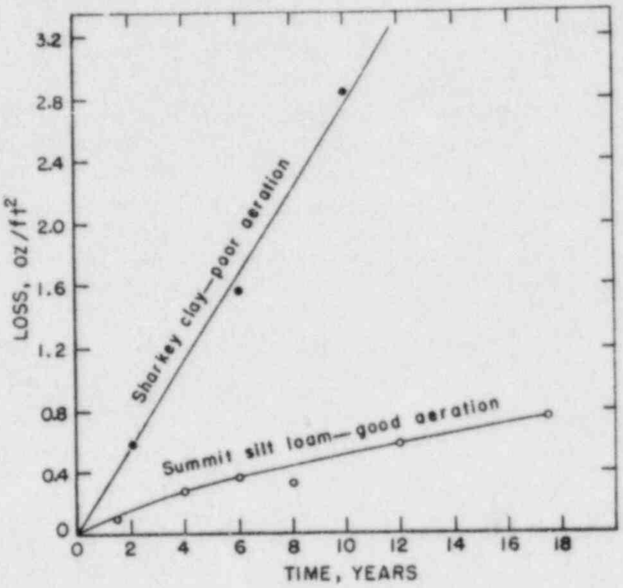

Figure 1.7 Effect of aeration on the corrosion of lead.(12)

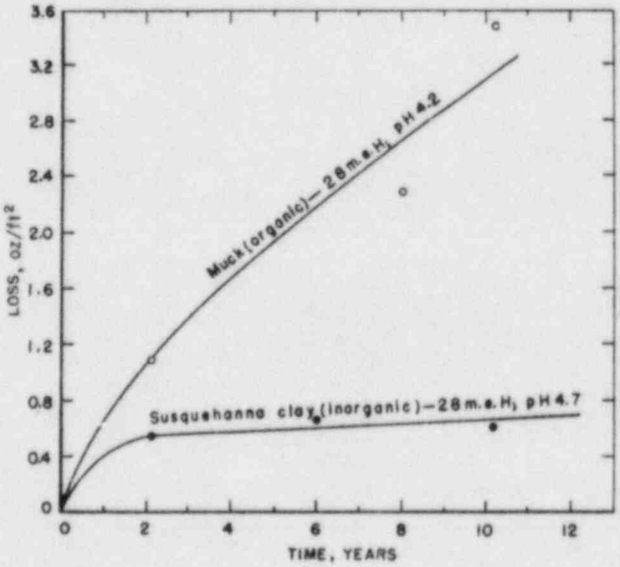

Figure 1.8 Effect of organic and inorganic acidity on the corrosion of lead.(12)

c. Sulfates and chlorides have a strongly inhibitive action on the corrosion of lead. In environments shown in Figure 1.9, high in soluble salts, ferrous metals and copper and its alloys corrode readily, while lead is highly resistant to corrosion. Figure 1.9 shows the inhibitive effect of sulfates and chlorides. If such ions as sulfates, chlorides, carbonate and silicates are not present in relatively high concentrations, lead will corrode at an appreciable rate.

From groundwater corrosion experiments of lead, similar results were obtained.(19)

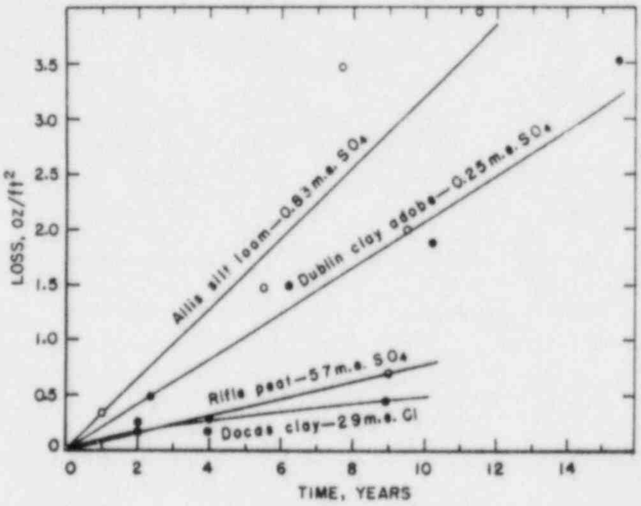

Figure 1.9 Effect of sulfates and chlorides in inhibiting the corrosion of lead; m.e.=meq=milliequivalent.(12)

1.1.7.7 Comparison of Corrosion of Copper, Zinc, Lead, and Steel

A comparison of the corrosion behavior of copper, zinc, lead, and steel was made by Romanoff.(12) The soils in which all four of these metals had been exposed were grouped into four environments as follows:

(1) Well aerated, acid soils low in soluble salts; soils 53, 55, and 62 in Table 1.4;

(2) Poorly aerated soils; soils 51, 56, 58, and 61;

(3) Alkali soils high in soluble salts, soils 64, 65, 66, and 70; and

(4) Soils high in sulfides; soils 59, 60, and 63.

The corrosion behavior of four metals in soils representative of each group is shown in Figure 1.10.

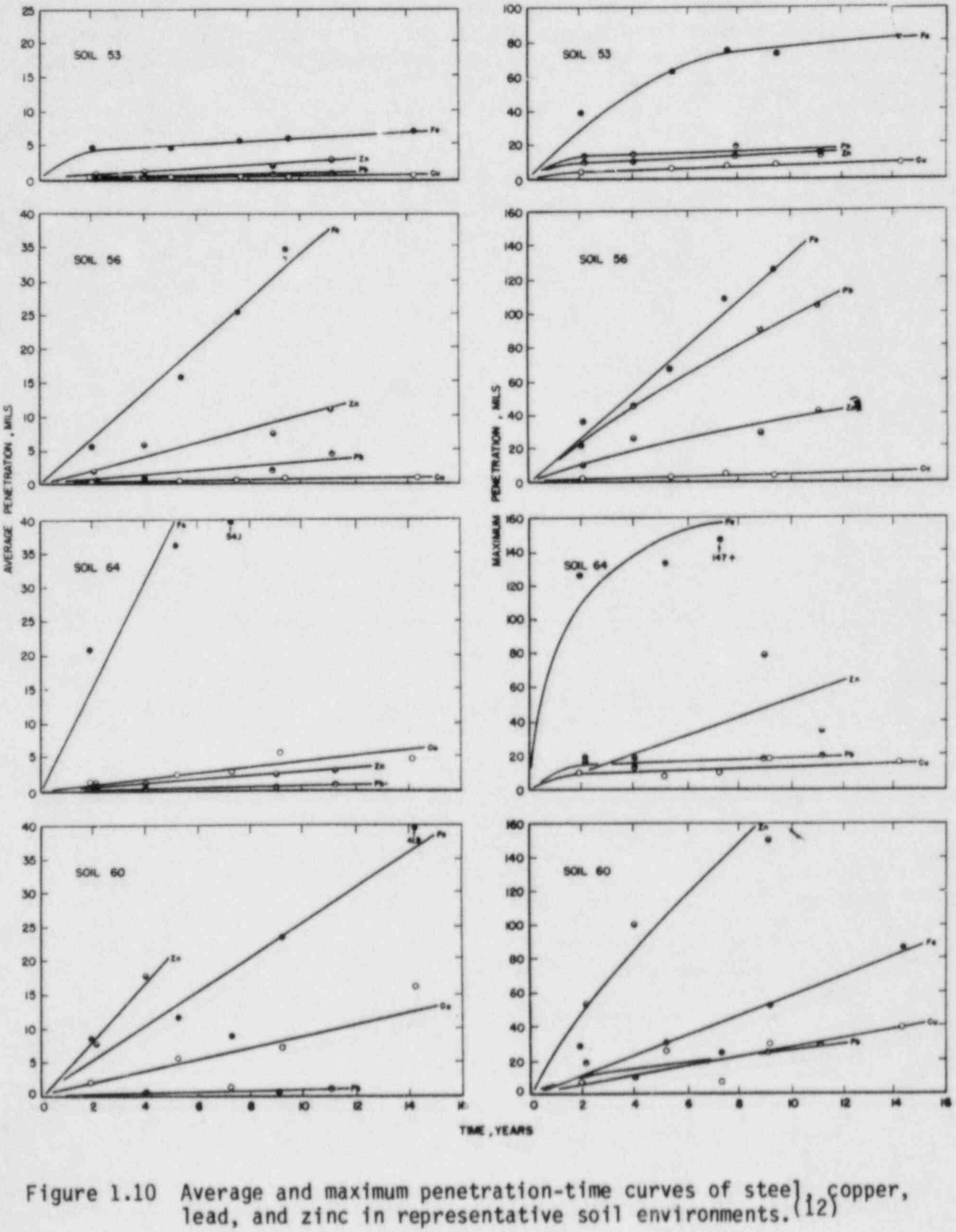

Figure 1.10 Average and maximum penetration-time curves of steel, copper, lead, and zinc in representative soil environments.(12)

It is evident from this illustration that copper is the most corrosion resistant metal in all soils except soils high in sulfates. As mentioned before, lead shows good corrosion resistance in soils with chlorides and sulfates.

In most of the environments, the ferrous metals corroded at considerably higher rates than any of the other metals.

1.1.7.8 Titanium

It was only after the end of World War II that industrial titanium uses began. This metal is known to have an excellent corrosion resistance.

The underground corrosion behavior of Ti was studied by the NBS(20) for 8 years, and the results are shown in Table 1.13. In this study, carbon steel specimens were buried together with Ti specimens for comparison. All the specimens were buried approximately three to four feet below the ground line.

As shown in Table 1.13, titanium specimens were unaffected by corrosion with respect to pitting or metal attack in any of the soil environments to which they were exposed.

Table 1.13

Average Weight Loss and Maximum Pit Depth of Titanium and Carbon Steel Exposed to Soils at Different Test Sites(20)

				Carbon Steel				Titanium	
			Exposure Time	Loss in Weight		Max. Pit Depth^b		Loss in Weight	Max. Pit Depth
Ident.	Soil Type	Location	(years)	(oz/sq ft)	(kg/m^b)	(mils)	(mm)	(oz/sq ft)	(mils)
A	Sagemoor Sandy Loam	Toppenish, WA	1.0	0.9	0.27	39	1.0	Nil	None
			2.0	2.5	.76	66	1.7	Nil	None
			4.0	3.0	.91	55	1.4	Nil	None
			8.0	4.4	1.34	71	1.8	Nil	None
B	Hagerstown Loam	Loch Raven, MD	1.0	0.9	0.27	18	0.5	Nil	None
			2.1	1.5	.46	20	0.5	Nil	None
			4.1	2.2	.67	53	1.3	Nil	None
			8.1	3.4	1.04	60	1.5	Nil	None
C	Clay	Cape May, NJ	1.0	1.0	0.30	12	0.3	Nil	None
			2.0	3.3	1.01	12	.3	Nil	None
			5.0	7.6	2.32	30	.8	Nil	None
			8.0	42.7	13.03	121+	3.1+	Nil	None
D	Lakewood Sand	Wildwood, NJ	1.0	1.4	0.43	19	0.5	Nil	None
			2.0	1.8	.55	33	.8	Nil	None
			4.0	2.6	.79	54	1.4	Nil	None
			8.0	4.0	1.22	45	1.1	Nil	None
E	Coastal Sand	Wildwood, NJ	1.0	0.3	0.09	13	0.3	Nil	None
			2.0	0.6	.18	9	.2	Nil	None
G	Tidal Marsh	Patuxent, MD	0.9	1.9	.58	12	.3	Nil	None
			1.8	2.0	.61	14	.4	Nil	None
			3.9	34.3	10.46	136+	3.4+	Nil	None
			7.8	40.0	12.20	128+	3.2+	Nil	None

[a] Average of four specimens.

[b] The plus indicates one or more specimens perforated by corrosion. Pipe wall thickness: carbon steel, 145 mils (3.7 mm).

1.1.7.9 Nickel and Nickel Alloys

Data on the behavior of nickel and nickel alloys in soil are sparse; in particular, it is uncertain whether microorganisms responsible for the accelerated corrosion of ferrous and other metals in certain anaerobic soils have any influence on nickel and its alloys.(21)

1.1.7.10 Composite Material for Pitting Corrosion Resistance

A new composite material known as Corrbloc* was developed by Armco Steel Corporation, and was reported by Bednar and Young.(22) The composite consists of a thin layer of stainless steel metallurgically bonded on each side to a heavy layer of carbon steel as shown in Figure 1.11. Built-in cathodic protection of the inner stainless core provided by the sacrificial galvanic corrosion of a steel layer increases the pitting corrosion resistance during underground exposures. Pitting corrosion will occur on the material's outer steel layer, but pit penetration is arrested when the stainless core is reached (Fig. 1.12). The carbon steel continues to corrode laterally, so pits increase in diameter rather than in depth, and the core is protected against pitting until a large area of stainless is exposed. At this point, the material still resists perforation as well as stainless steel alone.

Field tests on this composite material were conducted in acid mine water, fresh water marsh, and alkali soil. The specimens showed no corrosion perforations after 12 years exposure, whereas all carbon steel samples were nearly destroyed by corrosion.

The mechanical properties of this material are similar to plain carbon steel, and normal fabrication processes are employed. However, specific welding techniques must be used in order to maintain integrity at the welded areas.

Gerhold, et al.(16) of the NBS exposed three different composite systems to six different soils (described in Table 1.8) for four years. Some of the results are shown in Table 1.14. Composites A and B (System Nos. 14 and 15) were fabricated with Type 430 stainless steel as a core material while composite C (System No. 16) utilized Type 304 stainless steel. The total thickness was approximately 0.305 cm.

Composite B specimens were galvanized (4.5 to 5.0 oz/ft^2) by a hot-dipping method. Pitting corrosion of the carbon steel outer layers was observed on all specimens, but there was no apparent significant corrosion of the stainless steel core of these specimens. The hot-dipped zinc coating provided some protection to the underlying carbon steel and stainless steel core in all of the soils.

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*Trade name of Armco Steel Corporation, Middletown, Ohio.

(Continued Page 37)

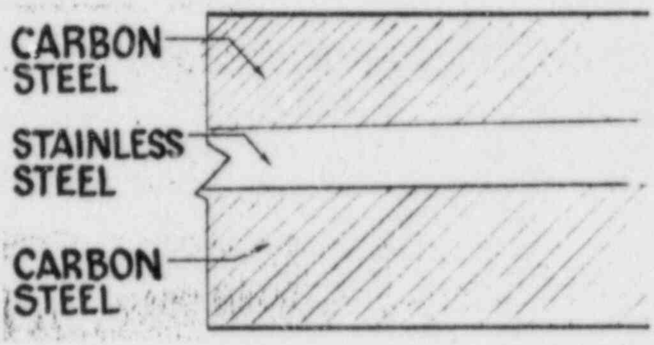

Figure 1.11 A cross-sectional view of the new composite.

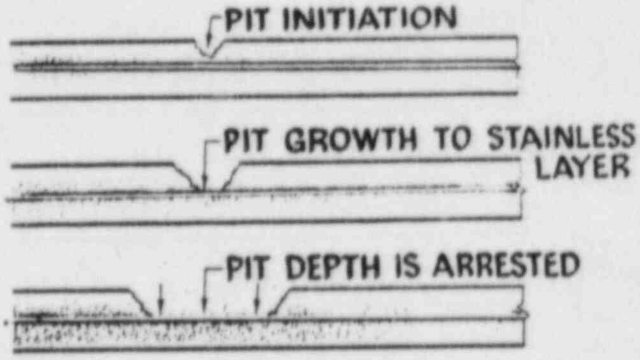

Figure 1.12 Pit growth in the new composite.

Table 1.14

Loss in Weight and Maximum Pit Depth of Galvanized[a] and Bare Steel Pipe and Zinc Plate Buried in 1937 (Average of 2 specimens)

Soil		Exposure	Galv[illegible]ed steel						Bare steel		Zinc	
			Condition of surface									
No.	Type		Coated with zinc and alloy layer	Coated with zinc	Coated with zinc-iron alloy	Bare steel exposed	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth
	INORGANIC OXIDIZING-ACID SOILS											
		Years	*Percent*	*Percent*	*Percent*	*Percent*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
53	Cecil clay loam	2.1	85 to 100	60 to 100	0 to 40	0	0.3	9	1.8	42	0.2	10
		4.0	100	20 to 40	60 to 80	0	1.4	6	2.9	98	.6	10
		8.9	100	20 to 40	60 to 80	0	.6	<6	3.4	74	1.1	13
		11.2	100	30	70	0	1.0	<6	3.4	78	1.6	16
		12.7	100	20	80	0	.6	<6	3.9	68	2.2	17
55	Hagerstown loam	1.9	100	60 to 100	0 to 40	0	.3	<6	1.8	33	.4	13
		3.9	100	20 to 40	60 to 80	0	1.2	8	2.6	50	.6	8
		9.0	95	20 to 40	55 to 75	<5	.7	6	4.1	92	.7	8
		11.0	100	70	30	0	1.0	<6	3.9	84	1.3	10
		12.6	100	70	30	0	.6	<6	3.4	73	1.2	9
62	Susquehanna clay	2.1	100	50 to 100	0 to 50	0	1.0	12	3.2	40	.6	9
		4.0	100	20 to 40	60 to 80	0	2.3	9	4.3	56	1.2	9
		8.9	100	0 to 20	80 to 100	0	.9	<6	5.3	68	1.3	12
		11.2	100	80	20	0	1.1	<6	6.0	72	1.3	11
		12.7	100	75	25	0	.8	<6	6.8	79	1.7	9
	INORGANIC OXIDIZING-ALKALINE SOILS											
65	Chino silt loam	2.1	100	20 to 40	60 to 80	0	1.1	<6	4.3	50	.5	30
		4.0	100	0 to 20	80 to 100	0	2.3	6	4.6	59	.8	36
		9.0	95	50 to 75	25 to 50	<5	1.6	<6	7.0	65	1.4	56
		11.2	95	0	95	<5	1.7	<6	6.2	84	1.1	40
		12.7	100	0	100	0	1.1	<6	7.2	98	1.8	56
66	Mohave fine gravelly loam	2.1	100	60 to 100	0 to 40	0	1.6	6	9.2	[d]145+	1.7	25
		4.0	100	20 to 40	60 to 80	0	3.3	8	12.3	145+	[b]2.6	28
		9.0	95	20 to 40	60 to 80	5	1.1	<6	8.1	78	.9	44
		11.2	95	0	95	5	2.7	<6	16.3	145+	4.4	56
		12.7	100	0	100	0	1.1	<6	[b]20.3	145+	5.5	34
	INORGANIC REDUCING-ACID SOILS											
61	Sharkey clay	2.1	100	60 to 100	0 to 40	0	.6	6	2.2	40	.5	12
		4.0	100	20 to 40	60 to 80	0	1.5	12	5.0	45	1.0	8
		8.9	95	75 to 95	5 to 20	<5	.7	<6	4.2	48	1.1	14
		11.2	95	0	95	<5	2.2	6	6.9	58	2.1	17
		12.7	100	0	100	0	1.1	6	7.5	64	2.0	14
51	Acadia clay	2.1	15	0	15	85	3.3	6	7.5	52	2.0	30
		[c]9.0	<5	0	<5	95	4.8	8	17.4	128+	4.8	28
	INORGANIC REDUCING-ALKALINE SOILS											
64	Docas clay	2.1	100	0 to 20	80 to 100	0	3.2	8	8.7	80	.7	16
		4.0	100	20 to 50	50 to 100	0	1.6	9	6.6	67	.6	18
		9.0	95	75 to 95	5 to 20	<5	1.6	10	4.7	80	1.4	79
		11.2	95	0	95	5	2.4	<6	12.4	118	1.6	35
		12.8	95	0	95	<5	1.6	<6	[b]17.2	122	2.0	[e]21
70	Merced silt loam	2.1	100	60 to 100	0 to 40	0	2.1	8	4.9	50	1.7	56
		4.0	100	0 to 20	80 to 100	0	4.5	12	[b]9.7	118+	[c]1.6	102+
		9.0	100	20 to 40	60 to 80	0	.1	6	13.4	122	3.6	84
		11.2	85	0	85	15	2.6	8	24.5	145+	D	150+
		12.8	90	0	90	10	1.3	8	21.3	145+	D	150+
56	Lake Charles clay	2.1	5 to 15	0	5 to 15	85 to 95	3.7	5	13.8	77	1.1	10
		4.0	5 to 15	0	5 to 15	85 to 95	3.9	7	16.0	104	3.4	26
		8.9	<5	0	<5	95	5.5	13	27.8	145+	4.5	29
		11.1	<5	0	<5	95	14.3	26	[f]D	145+	6.6	42
		12.7	<5	0	<5	95	13.8	66	D	145+	[b]9.0	[e]53

Table 1.14, Continued

Loss in Weight and Maximum Pit Depth of Galvanized[a] and Bare Steel Pipe and Zinc Plates Buried in 1937
(Average of 2 specimens)

Soil		Exposure	Galvanized steel						Bare steel		Zinc	
			Condition of surface				Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth
No.	Type		Coated with zinc and alloy layer	Coated with zinc	Coated with zinc-iron alloy	Bare steel exposed						
		ORGANIC REDUCING-ACID SOILS										
		Years	*Percent*	*Percent*	*Percent*	*Percent*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
59	Carlisle muck	2.1	30 to 50	0	0	50 to 70	1.2	8	1.5	12	0.7	66
		4.0	30 to 50	0	0	50 to 70	3.4	11	3.3	20	1.7	10
		9.1	50	0	20 to 50	50	3.0	8	7.5	101	4.6	22
		11.1	50	0	50	50	4.0	8	9.6	76	3.9	28
		12.7	40	0	40	60	3.4	<6.	9.6	72	4.6	18
63	Tidal marsh	2.1	100	50 to 100	0 to 50	0	1.2	<6	2.7	24	1.2	26
		4.0	100	50 to 100	0 to 50	0	2.1	10	9.2	38	[b]2.3	34
		8.9	95	0	95	5	2.0	8	10.7	80	[g]2.0	25
		11.2	75	0	75	25	2.9	8	12.2	94	3.8	30
		12.6	60	0	60	40	[b]4.8	[b]52	18.5	126	4.1	43
58	Muck	2.1	5 to 15	0	5 to 15	85 to 95	4.3	13	5.1	29	3.3	38
		4.0	0	0	0	100	5.4	[b]21	8.8	46	5.1	66
		9.1	0	0	0	100	9.0	64	17.3	98	7.4	58
		11.1	0	0	0	100	8.3	66	16.3	110	7.6	75
		12.7	0	0	0	100	10.7	76	17.6	124	7.5	50
60	Rifle peat	2.1	0	0	0	100	4.3	10	4.0	15	4.6	53
		4.0	0	0	0	100	7.2	12	8.1	[b]38	10.4	100
		9.1	0	0	0	100	19.8	83+	17.6	58	D	150+
		11.1	0	0	0	100	17.9	66	19.6	89	D	150+
		12.7	0	0	0	100	19.5	88	21.0	118	D	150+
		CINDERS										
67	Cinders	2.1	0	0	0	100	6.7	62	40.5	145+	[e]4.6	107+
		4.0	0	0	0	100	5.4	45	[e]37.0	145+	[e]12.2	118+
		9.0	<5	0	<5	95	5.6	21	31.7	145+	D	150+
		11.1	0	0	0	100	17.2	62	D	145+	12.0	78
		12.7	<5	0	<5	95	[b]11.9	[b]48	D	145+	D	150+

[a] Nominal weight of coating, 3.08 oz/ft^2.

[b] Data for the individual specimens differed from the average by more than 50 percent.

[c] The plus sign indicates that 1 or more specimens contained holes because of corrosion.

[e] Data for 1 specimen. The other specimens were destroyed by corrosion.

[f] D, both specimens destroyed by corrosion.

[g] Data for 1 specimen. The other specimen was missing.

1.1.7.11 Newer Corrosion Resistant Materials

Table 1.15 shows new alloys under development. Soil corrosion of these materials has not been studied. However, they all showed good resistance to pitting corrosion in salt water, and should be of interest for future underground use.

Table 1.15

Newer Corrosion Resistant Materials(23)

Material	Composition	Comments
18-18-2 (U.S. Steel)	Fe, 18 Cr, 18 Ni, 2 Si	Good stress corrosion resistance
JS 700 (Jessop)	Fe, 21 Cr, 25 Ni, 4.5 Mo, 3 Cb	Similar to material in NBS series
18-2 (Armco)	Fe, 18 Cr, 12 Mn, 1,6 Ni	
6X (Allegheny Ludlum)	Fe, 20 Cr, 24 Ni, 6.5 Mo, 1.5 Mn	Pit resistant in salt water
326 Stainless	Fe, 26 Cr, 6.5 Ni, 0.2 Ti	Austenitic-ferritic duplex alloy
216 Stainless	Fe, 20 Cr, 6 Ni, 2.5 Mo	Pit resistant in chlorides
Fiber reinforced plastics		
Vitreous materials		

1.1.8 Preventive Measures

Coatings have been used mainly for steel structures used in the construction of pipelines. Thus, existing data for coatings are mostly for steel.

1.1.8.1 Inorganic and Organic Coatings

A. Inorganic Coating

Portland cement coatings have given satisfactory protection for many years in some locations where corrosive conditions are severe. This will be discussed in details in a separate chapter.

Porcelain enamel coated steel specimens were tested by the NBS(12) for 14 years. After removal from the test sites, all specimens maintained their original gloss, indicating that the various soils had no deteriorating action on the coating. However, highly localized corrosion which was caused by the defects in the coatings, such as imperfect bonding of the coating to the specimen, was observed.

Table 1.16 shows the field test results for the vitreous enamel coated steel compared to bare steel.

Table 1.16

Condition of Steel Coated With Vitreous Enamel(12)
(Figures are the depths of the deepest pits, in mils)

No.	Soil Aeration	Exposure (years)	Condition of steel under the coating		Maximum pit depths of uncoated steel (Average of 2 specimens) (mils)
			Specimen 1	Specimen 2	
53	Good	2.0	U[a]	U	37
		5.4	U	U	50
		7.4	U	U	54
		9.3	U	U	59
		14.3	U	---	84
55	Good	2.0	U	U	41
		5.4	U	U	57
		7.4	M[b]	R[c]	57
		9.3	R	U	59
		14.3	U	15	65
62	Good	2.0	U	U	62
		5.4	U	U	66
		7.4	R	U	71
		9.3	U	U	87
		14.3	U	U	101
65	Good	2.0	U	U	40
		5.4	---	---	74
		7.4	U	M	83
		9.3	U	U	112
		14.3	U	U	86
64	Fair	2.0	U	U	130
		5.4	U	U	154+
		7.4	U	U	154+
		9.3	R	U	154+
		14.3	U	100	154+
66	Fair	2.0	U	U	66
		5.4	31	U	154+
		7.4	U	U	154+
		9.3	U	U	154+
		14.3	U	U	154+
58	Poor	2.0	---	---	18
		5.4	13	U	102
		7.4	41	52	110
		9.3	54	R	110
		14.3	U	U	154+
60	Poor	2.0	U	U	37
		5.4	U	U	24
		7.4	U	U	17
		9.3	U	U	27
		14.3	38	35	82

Table 1.16, Continued

Condition of Steel Coated With Vitreous Enamel(12)
(Figures are the depths of the deepest pits, in mils)

No.	Soil Aeration	Exposure (years)	Condition of steel under the coating		Maximum pit deptns of uncoated steel (Average of 2 specimens) (mils)
			Specimen 1	Specimen 2	
61	Poor	1.0	U	U	10
		5.4	U	U	54
		7.4	U	U	63
		9.3	U	U	96
		14.3	U	U	88
57	Poor	2.0	U	U	33
		5.4[d]	19	U	
			U	U	
			U	U	
			U	8	100
51	Very poor	2.0	28	U	82
		5.4	U	U	154+
		7.4	55	U	135+
		14.3[e]	U	U	146+
			U	U	
56	Very poor	2.0	U	U	20
		5.4	U	U	70
		7.4	U	U	125+
		9.3	U	M	154+
		14.3	U	U	135+
59	Very poor	5.4	U	U	20
		7.4	U	U	30
		9.3	U	U	40
		14.3[e]	U	U	34
			U	U	
63	Very poor	2.0	U	U	15
		5.4	U	U	36
		7.4	U	U	70
		9.3	U	U	54
		14.3	U	U	61
67	Very poor	2.0	U	U	154+
		5.4	U	U	119+
		7.4	U	U	127+
		9.3	U	43	154+
		14.3	U	30	154+

---

[a] Unaffected by corrosion.
[b] Metal attack-pipe surface roughened by corrosion.
[c] Metal rusted.
[d] Eight specimens removed at this period.
[e] Four specimens removed at this period.

B. Organic Coatings

Paint coatings used for atmospheric protection are not suitable to prevent soil corrosion. Organic coatings that are applied to steel are phenolic coatings, rubber and rubber-like coatings, and bituminous coatings.

Early NBS tests(12) of bituminous coatings started in 1912 indicated that these coatings were unsatisfactory. However, due to the materials and techniques developed since then, the majority of pipelines throughout the world today are coated with hot-applied coal tar or petroleum asphalt-base-filled pipeline enamels, into which reinforcing wraps, such as glass fiber are applied.

In 1930, the American Petroleum Institute (API) and the NBS(24) jointly conducted an extensive investigation to study the usefulness of bituminous coatings. Table 1.17 shows the results after 10 years. None of the coatings completely protected all the pipes to which it was applied. Among the coatings, mastic coating showed the best performance. Mastic is a coating that uses a graded aggregate with only enough bitumen to fill the voids between the solid particles, and has a structure resembling that of concrete.(25)

Table 1.17

Summary of Conditions of Line Pipe Under A.P.I. Coatings After Ten Years(24)

Coating		Total Feet Inspected	Unaffected	Rusted	Metal Attack	Pitted	Depth Deepest Pit	
Thickness, mils	Character		Per Cent	Per Cent	Per Cent	Per Cent	millimeters	mils
		1. Cold Applications						
21	Cutback coal tar	106	1.2	5.4	9.6	84.5	8.18	322[a]
65	Asphalt emulsion	178	0	0	1.7	98.3	8.18	322[a]
		2. Enamels						
60	Coal-tar-asphalt enamel	152	13.8	13.8	10.7	62.0	6.71	264
60	Coal-tar-asphalt enamel	183	7.2	8.2	29.6	55.0	4.95	195
58	Coal-tar enamel	151	0	0	2.0	98.0	5.87	231
80	Coal-tar enamel	137	19.8	3.8	6.4	70.1	8.18	322[a]
		3. Mastic						
519	Asphalt mastic	213	72.5	18.4	6.6	2.8	0.97	38
		4. Shielded Coatings						
29	Cutback asphalt	104	1.2	10.4	18.3	70.0	5.08	200
419	Asphalt emulsion	170	3.5	39.0	21.8	35.9	2.72	107
63	Coal-tar-asphalt enamel	202	29.3	17.0	25.3	27.8	8.18	322[a]
81	Coal-tar enamel	177	43.0	4.0	5.1	48.0	6.10	240
		5. Reinforced Coatings						
107	Grease	208	0	4.3	29.4	66.3	2.26	89
150	Asphalt	166	0	1.7	23.5	75.3	7.37	290
151	Asphalt	192	4.7	8.9	36.5	50.0	5.00	197
201	Asphalt	228	0.4	9.7	46.1	44.1	4.06	160
143	Asphalt enamel	208	20.2	9.2	20.2	50.5	5.00	197
171	Coal-tar-asphalt enamel	218	30.8	6.0	23.5	39.9	3.20	126
351	Coal-tar enamel	175	14.9	14.3	33.1	37.7	1.47	58
230	Asphalt	229	5.2	13.5	61.1	20.1	3.15	124
	Total	3,537	14.7	10.0	22.9	52.2	....	....

[a] Went through pipe.

The Interstate Commerce Commission and a committee of the API agreed upon the following extensions to the life of a pipeline due to the presence of a protective coating: Paint coatings, 1 year; bituminous coatings, single ply, 5 years; double ply, 7 years; cement coating, 20 years.(26) Although this is an old estimate (made in 1937), it gives some idea about the effectiveness of these coatings.

Shreir(27) reviewed the recent development in coatings as follows:

> The use of coatings applied in the form of tape is also increasing. Polyethylene and polyvinyl chloride films, either self-adhesive or else supporting films of butyl adhesive, petrolatum or butyl mastic are in use as materials applied 'cold' at ambient temperatures. Woven glass fiber or nylon bandage is also used to support films of filled asphalt or coal tar and these are softened by propane gas torches and applied to the steel surface hot, cooling to form a thick conforming adherent layer.
>
> Recently, sheets of high density polyethylene extruded on to the pipe surface over an adhesive have become available and the use of polyethylene or epoxy powders sintered on to the steel surface is becoming more frequent."
>
> Some use has been made, in the water industry, of loose envelopes of polyethylene sheeting, and with the increasing lengths of submarine pipeline requiring heavy concrete coatings for reducing buoyancy, the use of a heavily filled bituminous coating is projected.

1.1.8.2 Metallic Coating

The NBS(12) studied soil corrosion of zinc-coated (galvinized) steel, lead-coated steel, aluminum-coated steel, and tin-coated copper for about 10 years. Of these, zinc coating showed the best performance. Five different base metals (Bessemer steel, wrought iron, plain and copper-bearing steel, and open-hearth iron) were zinc coated by a hot-dip process. In most of the soils, zinc coatings of 2 oz/ft^2 or less were destroyed during the 10 year exposure period, and pitting of the underlying steel occurred.

However, the test showed that a 3 oz/ft^2 coating remained intact on at least half of the specimens, and in only one of the 47 soils was there any measurable development of pits in the steel. It was also learned that the base metal was not a factor in the corrosion rate.

Some base metals with 3 oz coatings were tested for 13 years in 10 different inorganic soils, and the results are shown in Figure. 1.13. A 3 oz/ft^2 zinc coating is not sufficient for protection of steel in highly reducing soils or in cinders, and additional protection is needed. Burns(28) demonstrated that long life for galvanized steel armor wires could be achieved by coating with asphalt and jute.

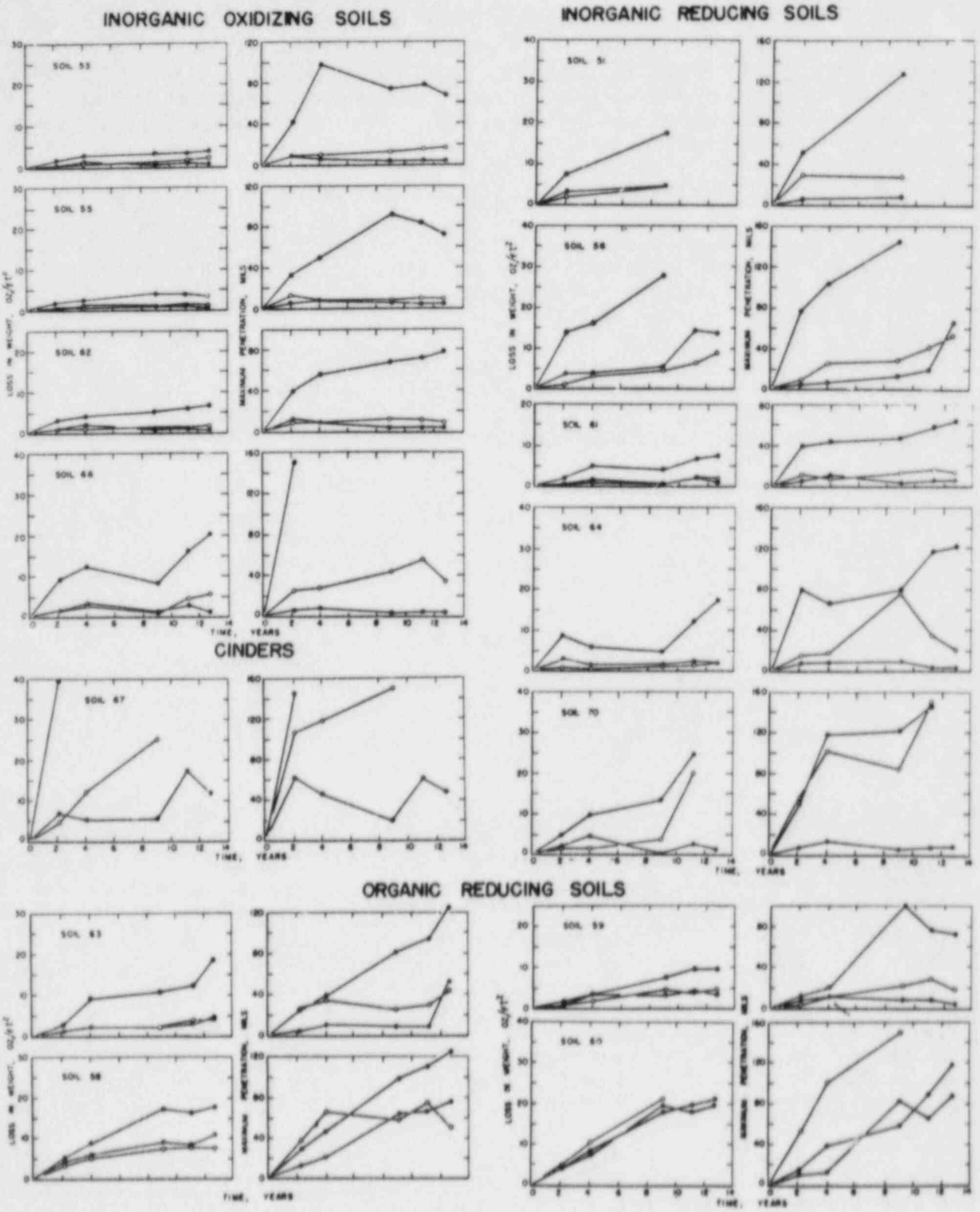

Figure 1.13 Weight loss and maximum penetration as a function of time for galvanized steel, bare steel, and zinc. ●, Bare steel; O, zinc; ◐ galvanized steel.(12)

1.1.8.3 Prevention of Corrosion by Altering the Trench Environment

Microbial corrosion can be prevented by using chalk ($CaCO_3$).(29,30) A "french drain" of small broken stone may be placed at the bottom of the trench underneath the canister to drain wet soils in which the canister is to be buried and to avoid contact between the bottom of the canister and the soil. In laying canister through a dense or wet soil, drainage may be facilitated by back-filling the trench with sand or gravel.

The trench should be prepared so that a protective container coating will not be injured by rocks or hard clods of soils. A sand base is preferable.(31)

The Dutch Corrosion Committee(32) examined a 9-year-old pipe laid in a bog, surrounded by sand containing 5.1% $CaCO_3$ and had a pH of 7.9. The pipe was intact except at a point where the sand was no longer in contact with the trench.(33)

1.1.9 Comparison of Cost

Branch(34) compared the relative cost of corrosion control for underground residential distribution (URD) equipment, and this is shown in Table 1.18. This comparison was made in 1973, and the current market price should be different. However, this table can be used to estimate the relative cost.

As shown in this table, titanium is the most expensive, and clad materials (composite materials) are cheaper than stainless steels.

Table 1.18

Cost of Corrosion Control (1973)[34]

		Estimate Cost Per Sq Ft ($)			
Example	Material	Base Material	Coating	Cathodic Protection	Total
A	Mild steel (.095)	.39	.50	.75	1.64
B	409 stainless (.095)	1.16	.50	.75	2.41
C	304 stainless (.095)	2.32	-	-	2.32
D	304 stainless (.065)	1.59	-	-	1.59
E	316 stainless (.065)	2.25	-	-	2.25
F	Outer sheathing of				
	316 stainless (.020)	.73			
	w/mild steel (.075)	.31	-	-	1.04
G	Outer sheathing of				
	alloy 20/825 (.010)	.78			
	w/mild steel (.085)	.35	-	-	1.13
H	Clad material steel/304/steel	1.15	.15	-	1.30
I	Clad material 304/steel/304	1.32	-	-	1.32
J	Inner liner of				
	304 stainless (.010)	.27			
	w/mild steel (.085)	.35	.15	-	.77
K	Silicon bronze (.095)	3.80	-	-	3.80
L	Titanium (.065)	6.17	-	-	6.17
M	Polyester FRP (.250)	1.19			
	Aluminum (.020)	.11	-	-	1.30

1.1.10 Canister Corrosion by Groundwater

According to Czyscinski and Weiss,(35) infiltrating groundwaters accumulate in some low-level trenches resulting in a "bath tub" situation where the waste is immersed in standing water. At the Maxey Flats, KY, and West Valley, NY, disposal sites, trench water pump-outs are a part of the routine site maintenence. In such environments, the corrosion behavior of the metal canister in the local groundwater becomes important. The local groundwater are also modified by waste-derived leach products, and subsequent bacterial processes which further modify the trench water composition as a function of time.

As noted previously, both pH and electrical resistivity are in some cases, indicators of a soil's corrosivity. Pertinent pH and resistivities for existing disposal trenches have been determined.(35) These properties were determined through the analysis of actual trench water and are believed to reflect the trench environment. At Maxey Flats, KY, the majority of trenches have pH values between 6.5 and 7.5. However, values as low as 2.4 and as high as 12 were also observed. Specific electrical resistivities ranged from 83 to 435 ohm/cm. At West Valley, NY, trench water pH values clustered in the neutral range, while resistivity varied from 70 to 294 ohm/cm. More limited data on Barnwell, SC, indicate pH values of 5.8 to 6.6 and resistivity values ranging from 714-4760 ohm/cm.

These observations and others(35) indicate that the chemistry of a particular diposal trench depends highly upon the waste which was diposed of in the trench.

Low trench water pH (highly acidic) in some cases has been attributed to disposal of urea-formaldehyde solidified waste, while high pH has been attributed to the presence of cement waste forms. The variation in trench water conductivity no doubt, is a result of the many and varied ionic compounds, such as sodium sulfate, and boric acid that have been disposed in these trenches.

Information and data for metallic corrosion in groundwater have been reviewed by Brookhaven National Laboratory.(36) One set of data reviewed(37), is shown in Table 1.19.

Casteel, et al.,(37) exposed 22 different alloys in the groundwater, whose composition is shown in Table 1.20. This was an accelerated experiment at temperatures higher than rcom temperature.

Since the weight changes are expressed in mg/cm^2, it is not easy to compare these values with the results from soil corrosion field tests. Also, pitting corrosion was not studied. However, the relative corrosion resistance can be seen. While carbon steel specimens were destroyed, AISI 316, AISI 304, Ti, and Inconel 625 showed good corrosion resistance.

Estimation of container corrosion lifetime for this set of varied conditions, if it were possible, would have been a very substantial task. We

Table 1.19

Corrosion of Candidate Container Materials in Groundwater as a Function of Temperature and Time (Expressed in mg/cm^2)(37)

Alloy	Temperature and Time		
	49°C 4 Months	49°C 9 Months	98°C 4 Months
AISI 304	0	-0.10	+0.12
	0	-0.04	+0.10
AISI 304L	0	-0.04	+0.08
	-0.02	-0.04	+0.22
AISI 316	0	-0.08	+0.70
	0	-0.08	+0.10
AISI 316L	0	-0.08	+0.10
	0	-0.02	+0.08
AISI 430	0	+0.08	+0.10
	-0.02	-0.06	+0.08
1803 T	0	-0.08	+0.10
	0	-0.04	+0.10
Inconel 600	-0.02	-0.18	+0.02
	0	-0.14	+0.06
Incoloy 800	-0.08	-0.30	+0.04
	+0.02	-0.08	+0.06
Ni-200	-0.02	-0.16	+0.04
	-0.08	-0.18	+0.08
1803 Mot	+0.14	+0.22	+1.0
	+0.76	-0.02	+0.08
Carbon steel	destroyed	destroyed	not exposed
	destroyed	destroyed	not exposed
Chromised steel	-6.46	-7.64	+0.08
	-5.28	-6.18	+0.04
Hastelloy C	+0.02	-0.12	+1.08
	-0.04	-0.12	+0.20
Hastelloy B	-0.08	-0.28	+0.20
	-0.02	-0.18	+0.16
Inconel 625	-0.06	-0.16	+0.32
	-0.02	-0.12	+0.20
URB904L	-0.04	-0.12	+0.20
	-0.02	-0.08	+0.24
AISI 304L	-0.02	-0.08	+0.20
	0	-0.08	+0.28
IMI 260	-0.02	-0.08	+0.28
	-0.10	-0.14	+0.44
Ti	-0.02	-0.14	+0.24
	0	-0.02	+0.24
Ti-Al-Sn 52	-0.04	-0.04	+0.20
	-0.02	-0.14	+0.61
Ti-Al-V 6-4	-0.04	-0.10	+1.76
	-0.04	-0.10	+2.12
AISI 304L	-0.04	-0.14	+0.02
	-0.01	-0.06	+0.30

0 = weight change less than ±0.005 mg/cm^2.

have therefore, estimated container lifetime for soil groups which are similar to those at the existing disposal site.

Given the uncertainty in predicting the effect of trench pH, resistivity, and chemical constitutents on the rate of container corrosion, it is recommended that waste disposed of by the "high integrity container" option be segregated from other wastes which would significantly alter soil chemistry.

Table 1.20

Groundwater Used in Corrosion Tests(37)
(pH = 7.35)

Component	Concentration[a]
SiO_2	8.05 ppm
Na	63.4 ppm
K	7.4 ppm
Mg	3.57 ppm
Ca	21.3 ppm
Pb	< 1 ppb
Fluorides	817 ppb
Phosphates	53 ppb
Free CO_2	6 ppm
Carbonates	188 ppm
Organic Species	3.7 ppm
Chlorides	35.5 ppm
Sulphates	< 0.5 ppb
Nitrates	5.95 ppb
Fe	189 ppb
Cu	<10 ppb
Sn	<10 ppb

[a] ppm = mg/L; ppb = μg/L

1.1.11 Recommended Canister Materials for Major Commercial Low-Level Sites

Figure 1.14 shows the major nuclear waste storage/disposal sites. Of the low-level sites, only three sites, Hanford, Beatty, and Barnwell, are in operation at the present time.*

As mentioned earlier, soils in the same soil series are similar in important characteristics and arrangement in the soil profile. Thus, if we know the soil type (or soil series) of a site, it is possible to make an approximate estimate of the corrosion behavior of a metal in that site, utilizing the field test corrosion data in the same soil type.

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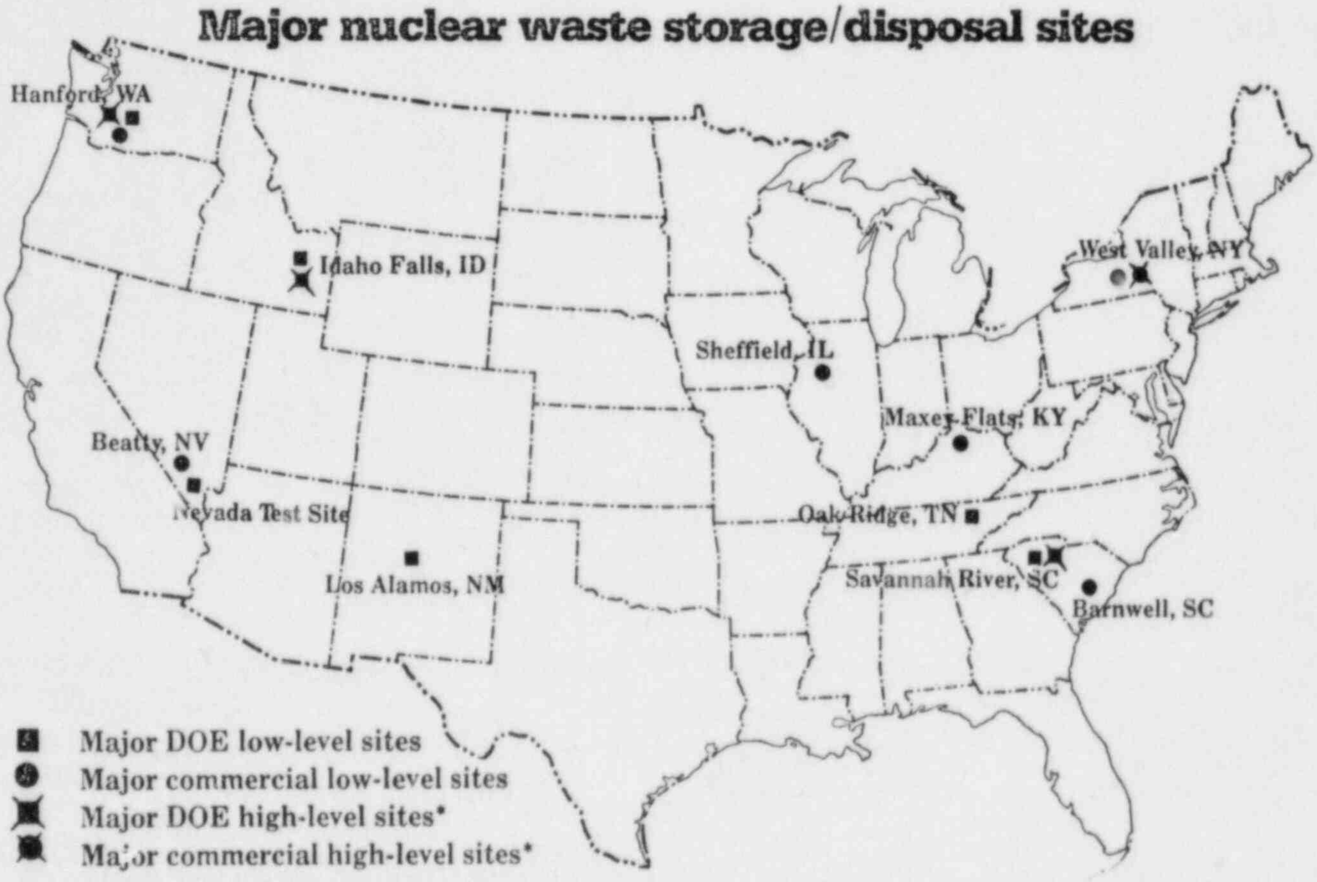
*At press time, only Hanford and Barnwell are in operation.

The soil type of Barnwell, South Carolina was reported to be Fuquay-loamy sand, and the soil of Beatty, Nevada has not been given a soil type classification.(39) The soil type of Hanford, Washington was not available. Fuquay-loamy sand was not included in 125 soil types tested by the NBS.(12)

Thus the next best thing to do is use the the corrosion data from the same soil group. By overlapping the two maps, Figure 1.1 and Figure 1.14, the soil groups of the three sites were chosen.



*Spent fuel is currently being stored on reactor sites and at the reprocessing centers in Morris, IL and West Valley, NY.

Figure 1.14 Major nuclear waste storage/disposal sites.(38)

The corrosion data from Tables 1.6, 1.9, 1.13, 1.14, 1.21, 1.22, and 1.23 were used for an approximate estimate of the maximum pit depth for different metals after 100 years in soils similar to those of the three commercial low level sites in operation. Existing data were linearly extrapolated to 100 years.

(Continued Page 54)

Table 1.21

Loss in Weight and Maximum Penetration of Wrought Black Ferrous Pipe Buried in 1922[a,b] (Average of 2 specimens)

Soil		Duration of exposure	Loss in weight (oz/ft²)								Maximum penetration (mils)							
			1½-in. pipe				3-in. pipe				1½-in. pipe				3-in. pipe			
No.[c]	Type		Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu
	Material....	....	a	b	e	y	B	K	M	Y	a	b	e	y	B	K	M	Y
		Years																
40 (61)..	Sharkey clay..............	2.0	2.1	2.1	2.1	2.0	2.3	2.5	2.2	2.8	46	28	38	31	28	41	32	42
		4.1	4.0	4.3	3.9	3.7	4.2	4.3	4.6	4.2	61	52	43	35	41	46	44	46
		6.0	5.4	5.5	5.0	5.3	6.1	6.6	6.1	5.6	61	69	70	60	65	88	74	84
		8.0	6.4	6.5	6.5	5.5	7.0	7.1	8.2	7.7	86	101	64	74	70	99	96	92
		10.0	6.9	7.2	7.3	6.0	8.1	7.2	9.3	7.5	75	62	67	62	65	72	64	86
		12.0	6.9	7.9	7.2	6.7	8.6	8.6	7.0	8.3	139	68	69	82	69	91	78	75
41......	Summit silt loam............	1.5	0.8	0.4	0.5	1.0	0.6	0.6	0.4	0.4	19	39	33	40	44	30	42	32
		4.0	2.7	3.6	3.0	3.0	2.7	2.9	2.4	2.5	34	36	40	45	47	38	43	46
		6.0	4.6	4.7	4.5	4.2	3.2	3.6	4.1	3.9	53	50	48	63	55	52	67	52
		7.9	4.8	5.4	5.0	4.7	4.2	4.2	4.6	4.4	61	65	55	60	58	58	62	56
		12.0	6.0	6.2	6.3	5.3	6.5	6.3	6.0	6.0	101	94	79	91	86	72	85	80
		17.4	5.9	7.4	6.9	7.0	5.5	5.5	7.0	7.0	122	94	92	101	86	67	101	78
42 (62)..	Susquehanna clay...........	2.0	3.0	3.6	3.3	3.1	2.9	2.4	2.9	1.9	53	58	59	50	54	62	78	55
		4.1	4.5	7.3	5.7	5.9	4.8	3.4	5.1	3.4	64	74	73	76	79	85	82	74
		6.0	7.0	8.0	7.7	7.3	5.7	6.9	6.2	6.6	77	92	84	74	78	86	95	81
		8.0	5.9	7.7	8.2	9.3	6.4	6.8	6.7	5.6	76	89	113 +	111 +	80	93	88	90
		10.1	11.5	10.6	12.1	12.5	8.8	11.1	9.3	9.2	84	84	104	92	96	129	103	104
		12.0	16.6	17.1	12.5	17.4	8.9	11.2	11.0	13.4	94	89	111	86	88	125	92	116
43(63)..	Tidal marsh......	1.3	1.4	1.7	1.9	2.8	2.0	2.2	2.3	2.4	18	36	24	28	44	45	66	47
		4.1	3.6	7.2	4.6	4.8	4.7	5.2	6.9	6.4	39	44	35	46	101	79	83	59
		6.2	5.8	8.0	9.7	7.4	7.2	6.2	7.7	8.3	88	82	67	76	104	132	119	53
		8.0	9.1	15.3	10.3	11.4	10.1	10.8	9.0	14.4	84 +	102 +	76	70	116	136	78	90
		9.9	11.6	11.4	10.5	17.0	10.4	11.2	9.8	12.0	94	76	70	73	136	100	116	155
		12.0	15.5	16.6	19.5	17.6	14.1	12.7	13.1	16.3	90	80	100	105	138	78	74	72

Table 1.21, Continued

Loss in Weight and Maximum Penetration of Wrought Black Ferrous Pipe Buried in 1922[a,b]

Soil			Loss in weight (oz/ft²)								Maximum penetration (mils)							
			1½-in. pipe				3-in. pipe				1½-in. pipe				3-in. pipe			
No.[c]	Type	Duration of exposure	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu
	Material		a	b	e	y	B	K	M	Y	a	b	e	y	B	K	M	Y
44	Wabash silt loam	1.1	0.3	0.6	0.4	0.5	0.4	0.3	0.4	0.4	38	36	28	32	26	39	32	38
		3.6	1.4	1.8	2.0	1.8	1.4	1.4	1.2	1.3	78	43	54	55	46	44	44	50
		5.7	2.3	2.2	2.3	2.4	2.1	2.2	2.0	2.0	70	52	51	66	56	72	60	68
		7.6	1.7	2.3	2.2	2.0	1.9	2.1	2.0	2.1	72	49	62	50	56	50	62	88
		11.6	2.9	4.1	4.7	3.5	3.4	2.8	3.4	3.2	87	56	63	69	65	58	82	74
45	Unidentified alkali soil	1.2	1.2	1.4	1.4	1.3	1.1	1.0	1.7	1.4	<10	20	15	13	<10	17	30	28
		3.8	3.6	3.0	2.9	3.3	2.9	3.2	2.8	3.3	36	28	24	24	32	36	31	49
		5.8	2.9	3.2	2.3	3.1	3.3	3.1	3.2	3.0	45	43	40	34	47	36	48	52
		7.7	3.5	[d]5.6	4.2	3.8	4.1	3.9	3.8	4.2	50	[d]46	60	45	56	60	60	66
		9.8	13.7	11.9	11.9	12.1	12.5	13.1	12.3	13.5	143	114	138	117	118	138	128	158
		11.7	9.7	9.0	9.7	9.3	10.6	11.2	9.3	11.2	82	78	84	82	85	112	98	124
46	Unidentified sandy loam	1.5	0.8	1.3	1.2	0.9	1.0	1.1	1.2	1.2	57	54	55	54	50	40	56	79
		4.0	2.7	3.2	2.9	2.6	2.4	2.6	2.7	3.2	80	64	79	82	66	58	106	110
		5.1	2.9	2.8	3.1	3.0	2.8	3.0	2.6	3.2	68	65	66	54	68	46	96	96
		8.0	5.6	6.2	5.2	5.7	5.7	5.9	5.8	6.7	60	80	108 +	118 +	69	68	136	134
		10.2	4.0	4.7	4.8	4.1	4.4	3.6	4.3	3.9	74	95	68	83	82	66	84	80
		12.0	4.0	5.1	4.5	4.4	4.7	4.3	4.8	4.8	48	62	64	104	77	62	114	80
47	Unidentified silt loam	1.5	[d]0.5	0.5	0.5	0.4	0.4	0.6	0.5	0.4	[d]<10	<10	<10	<10	<10	<10	<10	<10
		4.1	1.3	1.9	1.7	1.3	1.3	1.3	1.6	2.0	<20	<20	<20	<20	<20	<20	<20	<20
		6.1	1.2	1.5	1.6	1.2	1.9	1.6	2.2	1.5	<20	<20	<20	<20	<20	<20	<20	<20
		8.0	2.2	2.1	1.7	1.8	2.1	2.1	2.0	1.6	<20	<20	<20	<20	<20	<20	<20	<20
		12.1	2.3	3.9	3.0	2.8	3.2	3.0	2.8	3.1	16	46	26	31	34	24	27	26
		17.4	3.8	6.4	7.9	8.4	6.1	6.5	5.4	5.1	42	53	37	57	51	40	48	46

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[a] See Table 10 of Reference 12 for composition of materials. [b] See Table 6 of Reference 12 for properties of soils. [c] The soil number in parentheses is the number assigned to the same soil in a later series of tests. See Table 15 of Reference 12. [d] Data for 1 specimen only. [e] The plus sign indicates that 1 or both specimens contained holes because of corrosion. [f] Site 43 is not identical with site 63 geographically, but the soil environment, tidal marsh, is the same.

Table 1.22

Loss in Weight and Maximum Penetration of 3-inch Wrought Black Ferrous Pipe Buried in 1928 (Average of two specimens)

Soil		Duration of exposure	Loss in weight			Maximum penetration		
No.	Type		Open-hearth iron	Wrought iron	Bessemer steel	Open-hearth iron	Wrought iron	Bessemer steel
	Material....	....	A	B	M	A	B	M
		Years	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*
52	Lake Charles clay loam	2.0	3.1	3.4	2.7	66	62	40
		5.4	14.7	14.6	13.5	116	123	118
		7.5	16.0	19.0	16.9	116	176	163
54	Fairmount silt loam	1.9	1.0	1.0	0.7	14	16	6
		5.2	1.5	1.3	1.2	14	21	11
		7.3	3.4	2.5	3.5	54	36	40
68	Gila clay	1.7	3.2	3.6	2.9	42	50	37
		5.4	3.7	4.3	3.7	43	43	38
		7.2	4.8	4.9	4.4	48	48	45
101	Billings silt loam (low alkali)	1.9	3.9	5.2	3.9	70	66	60
		4.1	7.5	8.8	7.2	116	94	94
		9.3	10.5	9.4	9.1	131	95	86
102	Billings silt loam (moderate alkali)	1.9	3.9	5.1	4.3	42	37	26
		4.1	9.4	10.2	9.3	102	80	72
		9.3	18.3	16.1	17.6	124	93	95
103	Billings silt loam (high alkali)	1.9	3.7	5.0	3.6	63	48	37
		4.1	11.2	10.4	10.1	88	86	66
		9.3	18.8	21.3	17.8	190	136	192
104	Cecil clay	1.9	2.9	3.0	2.5	71	70	88
		4.1	4.8	4.3	3.7	84	86	93
		11.7	7.1	7.2	7.6	88	94	114
105	Cecil clay loam	2.0	3.2	3.6	3.4	50	45	58
		4.0	3.6	3.8	4.2	48	48	46
		11.7	4.8	3.7	4.9	58	51	54
106	do	1.9	2.6	2.5	2.0	62	46	48
		4.1	3.4	4.0	3.6	64	64	56
		11.7	7.3	8.6	9.0	93	70	75
107	Cecil fine sandy loam	1.9	2.0	2.3	2.4	57	66	64
		4.1	2.9	3.2	3.1	73	72	66
		11.7	5.4	5.5	5.6	97	90	129
108	Cecil gravelly loam	1.9	2.8	3.3	3.4	67	38	53
		4.0	3.1	3.6	3.4	86	50	62
		11.7	4.7	4.5	5.9	85	70	95
109	Fresno fine sandy loam (low alkali)	1.9	4.7	5.9	5.2	70	70	74
		4.0	7.9	7.6	6.3	74	82	63
		9.2	11.6	11.8	11.3	121	109	108
110	Fresno fine sandy loam (moderate alkali)	1.9	3.9	4.5	4.1	74	60	42
		4.0	7.6	7.1	7.4	84	85	73
		9.2	18.6	15.8	20.2	155	126	155
111	Fresno fine sandy loam (high alkali)	1.6	4.4	4.5	5.2	54	48	38
		3.7	8.7	7.8	8.7	104	78	80
		8.9	17.6	13.8	19.4	162+	165	119
112	Imperial clay (moderate alkali)	1.9	7.1	7.3	7.3	76	58	68
		4.0	14.5	13.6	14.0	188+	128	132
		5.9	19.8	16.9	18.8	250+	177+	232+
113	Imperial clay (high alkali)	1.9	8.2	8.1	8.2	92	54	54
		4.0	19.0	16.0	18.5	216+	157+	216+
		5.9	25.8	21.8	23.6	224+	178+	231+
114	Lake Charles clay	0.9	1.5	1.3	1.3	32	15	14
		3.0	4.8	6.0	5.0	99	72	67
		10.5	14.3	14.6	14.1	159	90	106
115	Memphis silt loam	2.0	1.8	1.9	1.7	32	34	32
		4.1	2.4	2.8	2.7	75	64	64
		11.7	3.3	3.5	3.9	89	48	64
116	Merced clay	1.9	6.1	6.6	5.8	46	51	36
		4.0	13.0	11.8	11.5	96	97	90
		9.3	21.6	19.1	19.4	121	173	88
117	Merced clay loam adobe	1.9	7.6	7.9	8.0	118	92	86
		4.0	9.6	9.9	9.4	135	112	101
		9.3	21.0	19.8	20.5	185	127	141
118	Niland gravelly sand (low alkali)	1.9	5.4	5.0	5.5	108	72	60
		4.0	12.2	10.9	13.1	151+	124	122+
		5.9	16.0	15.4	14.9	240+	153	158
119	Norfolk sandy loam	2.0	0.7	0.6	0.5	<10	<10	<10
		4.0	3.9	4.3	4.6	86	52	68
		11.7	8.2	8.7	8.9	98	67	77

Table 1.23

Corrosion of Copper-Rich Alloys Buried in 1926

(For the condition, the letters indicate the worse of 2 specimens. The figures are rates of maximum pit depth, in mils per year.)

M, Shallow metal attack, roughening of the surface but no definite pitting.
P, Definite pitting, no pits greater than 6 mils.
U, Unaffected by corrosion.
S, severe uniform corrosion, impossible to measure penetration because of even destruction of surface.
D, selective corrosion such as dezincification over large areas.
d, selective corrosion in spots.
Z, destroyed by dezincification.

Soil	Duration of test	Average rate of loss in weight (oz/ft²)/yr						Condition of surface and pit depth (mils)				
		Copper pipe		Brass		Cu-Zn-Ni rod,	Cu-Al rod,	Copper pipe		Brass pipe,	Cu-Zn-Ni rod,	Cu-Al rod,
		M	P	Pipe, B	Ell, Me	A	N	M	P	B	A	N
	Years											
1	8.1	0.060	0.063	0.097	0.185	0.157	0.057	1.5	P	M, D	P, d	M, D
2	13.5	.023	.016	.065	.090	.101	.019	P	P	P, D	P, D	M
3	8.0	.027	.029	.074	.109	.156	.063	P	P	1.2, d	1.2, d	D
4	7.9	.019	.019	.144		.176	.070	1.3	M	P, D	1.3, d	D
5	13.4	.030	.032	.059	.317	.118	.045	0.6	P	P, D	0.5, D	P
6	13.3	.011	.0093	.017	.025	.056	.0023	P	P	P, d	P, D	P
7	13.4	.036	.026	.188		.155	.032	P	P	S, D	0.07	P
8	8.0	.024	.019	.018	.319	.136	.026	1.5	1.3	M, d	1.5, d	1.9, d
9	13.4	.030	.036	.174	.092	.165	.011	P	P	0.5, D	0.9, D	P
10	13.2	.076	.095	.235		.207	.037	0.8	0.5	0.6, D	0.8, D	P
12	8.0	.312	.278	.222		.199	.090	1.5	S	P, D	M, d	P, d
13	8.0	.023	.031	.101	.024	.012	.028	P	P	M, D	M, d	M, d
14	8.0	.040	.025	.044	.089	.096	.017	P	0.9	P, d	1.9, d	M, d
15	8.0	.013	.016	.030		.045	.026	M	M	D	d	d
16	8.0	.057	.058	.170	.166	.234	.093	3.3	1.9	1.3, D	0.9, d	d
17	8.0	.037	.040	.059	.257	.108	.049	M	M	M, d	P, d	D
18	8.0	.0076	.0077	.021	.070	.044	.013	U	M	M, d	1.3, d	U
19	8.0	.039	.040	.122	.067	.165	.027	1.1	P	P, D	1.3, d	M, d
20	8.1	.042	.039	.044	.193	.138	.044	1.5	1.2	P, d	P, d	D
22	8.0	.068	.070	.195	.283	.277	.075	1.9	1.0	1.1, D	P, d	M, D
23	8.0	.118	.135	.752	1.85	.288	.169	1.9	1.3	Z	U	D
24	13.2	.019	.018	.025		.030	.018	P	P	P, d	P, D	P
25	8.0	.012	.011	.051	.142	.126	.043	P	U	P, D	P, d	D
26	13.4	.013	.012	.072	.058	.118	.034	P	P	P, D	P, D	P
27	13.6	.012	.012	.046	.080	.063	.023	P	P	P, D	P, D	P

Table 1.23, Continued

Corrosion of Copper-Rich Alloys Buried in 1926

(For the condition, the letters indicate the worse of 2 specimens. The figures are rates of maximum pit depth, in mils per year.)

M, Shallow metal attack, roughening of the surface but no definite pitting.
P, Definite pitting, no pits greater than 6 mils.
U, Unaffected by corrosion.
S, severe uniform corrosion, impossible to measure penetration because of even destruction of surface.
D, selective corrosion such as dezincification over large areas.
d, selective corrosion in spots.
Z, destroyed by dezincification.

Soil	Duration of test	Average rate of loss in weight (oz/ft²)/yr						Condition of surface and pit depth (mils)				
		Copper pipe		Brass		Cu-Zn-Ni rod,	Cu-Al rod,	Copper pipe		Brass pipe,	Cu-Zn-Ni rod,	Cu-Al rod,
		M	P	Pipe, B	Ell, Me	A	N	M	P	B	A	N
28	8.0	.084	.079	.080	....	.163	.017	P	P	M, D	P, d	M, D
29	8.0	.123	.116	.275	....	.257	.082	P	P	P, D	1.9, d	M, d
30	13.4	.0078	.0097	.014	.048	.032	.0071	P	P	P, D	P, D	P
31	13.7	.0083	.0086	.019	.026	.022	.026	P	P	P, d	P, D	M
32	7.9	.049	.018	.089	.152	.129	.016	U	M	1.0, D	1.3, d	d
33	8.0	.137	.117	.175	.218	.208	.040	0.9	1.0	P, D	1.3, d	M, d
34	8.0	.016	.022	.057	.080	.177	.021	M	P	M, D	P, d	d
35	8.0	.017	.016	.020	.422	.063	.039	M	P	D	1.0, d	D
36	13.6	.019	.019	.049	.039	.087	.014	P	P	0.7, D	0.7, D	P
37	8.0	.169	.162	.152	.274	.175	.060	1.8	1.3	P, D	P, d	M, d
38	8.0	.025	.043	.028	.037	.034	.019	M	P	M, d	P, d	U
40	8.0	.125	.168	.349	.330	.385	.092	2.3	4.1	1.8, D	1.9, d	d
41	13.4	.027	.030	.083	....	.126	.035	P	P	P, D	0.5, D	P
42	8.0	.047	.049	.095	.089	.154	.057	P	1.1	P, D	1.9, d	P, D
43	8.0	.635	.555	.026	.022	.007	.022	S	S	M, d	U	2.3
44	8.0	.079	.061	.175	....	.248	.026	P	P	1.3, D	2.4, d	P, d
45	8.0	.033	.030	.016	.214	.081	.030	1.0	1.0	d	1.0, d	D
47	13.4	.032	.035	.037	.30	.101	.056	1.2	0.8	P, D	P, D	P

Usually the corrosion rate slows down as time increases. For an example, the corrosion rate of plain steel showed a logarithmic behavior (see Section 1.1.7.1). As shown in Figure 1.10, the maximum pit penetration rates for lead, copper, and zinc also decrease with time. Thus it is believed that the real corrosion rate of these metals should be considerably lower than these estimated values. Maximum pit penetration rate after the initiation of pits has not been studied as extensively for stainless steel because in some cases there is no observable pitting after 14 years. When data was available for pitting rate, linear extrapolation was used for stainless steel.

1.1.11.1 Beatty, Nevada

The soil at this site belongs to the gray desert soils, (group VIII). Among the NBS test sites, soil 66 of Phoenix, AZ, soil 47 of Salt Lake City, UT, and soil 68 of Phoenix, AZ are in soil group VIII. Estimated maximum pit depths for different metals after 100 years in service in this soil group are shown in Table 1.24.

Table 1.24

Estimated Maximum Pit Depths for Different Metals in Soil Group VIII After 100 Years in Service[a]

Materials	Soil 47 Salt Lake City, UT	Soil 66 Phoenix, AZ	Soil 68 Phoenix, AZ
Plain steel	0.8 cm (0.3")	45 cm (17.5")[b]	1.7 cm (0.7")
Copper			
Deoxidized copper		0.2 cm (70 mils)	
Tough-pitch copper		<0.1 cm (42 mils)	
Copper-silicon alloys		0.4 cm (150 mils)	
Stainless steel			
AISI 304		<0.1 cm (43 mils)	
Galvanized steel		<0.5 cm (175 mils)	

[a] Linearly extrapolated using available pitting rates. AISI 316 SS showed no pitting in 14 years.

[b] There was a hole in a 0.145 in. plate in 2 years.

Canister materials recommended:

Composite material:	Steel-AISI 304 or 316 SS - steel with heavy (>3 oz/ft^2) hot-dipped zinc coating.
Stainless steel:	AISI 304 - with built-in cathodic protection. AISI 316 - with built-in cathodic protection.
Copper:	With protective coatings.
Titanium:	Commercially pure.

The thickness of a canister should be determined using the corrosion data available.

1.1.11.2 Barnwell, South Carolina

The soil of this site belongs to group III, red and yellow soils. Among the NBS test sites, soil 63 of Charleston, South Carolina, and soil 104 of Charlotte, North Carolina, are in soil group III.

The estimated maximum pit depths for different metals after 100 years in service in soil group III are shown in Table 1.25.

Table 1.25

Estimated Maximum Pit Depths for Different Metals in Soil Group III After 100 Years in Service.[a]

Soils Materials	Soil 63 Tidal Marsh, Charleston, SC	Soil 104 Cecil Clay, Charlotte, NC
Plain steel	2.3 cm (0.9 in.)	2.5 cm (1")
Galvanized steel	steel was attacked 52 mils/12.6 yrs	
Copper		
Deoxidized	0.2 cm (70 mils)	
Tough-pitch	0.25 cm (100 mils)	
Copper-silicon alloy	0.3 cm (120 mils)	
Stainless steel		
AISI 304[b]	0.25 cm (90 mils)	

[a] Linearly extrapolated using available pitting rates. AISI 316 SS and titanium showed no pitting in 14 years.

[b] Sensitized AISI 304 showed severe non-uniform attack.

Canister materials recommended:

Stainless steel: AISI 316 - with built-in cathodic protection.

Copper: Deoxidized copper

Titanium: Commercially pure.

The thickness of the canister should be determined using the corrosion data available.

1.1.11.3 Hanford, Washington

For the Hanford, Washington site, the corrosion data from Seattle, Washington, soil 6 of the NBS test,(12) were used. This soil type was

Everett gravelly sandy loam, and internal drainage of the test site was good (see Table 1.4). The estimated maximum pit depths for different metals after 100 years in this soil are shown in Table 1.26. It should be noted that this soil is in the portion of the State that is characterized as wet. The burial site is in a dry portion.

Field tests were conducted in Sagemoor sandy loam at the Yakima Indian Reservation near Toppenish, Washington (site A, NBS test)(16) on 304, sensitized 304, and 316 stainless steels. This soil is a well-drained alkaline soil (pH of 8.8) with a resistivity of 400 ohm-cm and is typical of that found in vast areas of eastern Washington and Oregon. The soil is consistent in composition to a depth of at least 2.13 m (7 feet).(16) It should be noted that estimates for maximum pit depths in buried stainless steels after 100 years were not made for this soil because no pitting was observed in the specimens after 4 years and no linear extrapolation of pitting rate is possible.

Table 1.26

Estimated Maximum Pit Depths for Different Metals in Soil Similar to That of Hanford Site After 100 Years Service[a]

Materials	Soil 6 Seattle, WA
Stainless steel	
316 sensitized	0.5 cm (180 mils)
Copper	<0.1 cm (45 mils)[b]

[a] Linearly extrapolated using the existing data.

[b] After 13.3 years, copper specimen showed definite pitting, but no pits were greater then 6 mils.

Canister materials recommended:

Same as those for Beatty, NV site.

1.1.12 Final Comments

- Corrosion can be greatly reduced by alteration of the soil and an advanced trench design which provides for good drainage of water.
- Multilayer concepts might be necessary. For instance, a corrosion resistant metal can be used as an outer layer, while using a metal that has a low permeability for tritium as an inner layer.
- For some soils, composite materials may be useful.

1.2 Corrosion of Metals in Concrete

Literature consulted on steel corrosion in concrete is predominantly based on engineering data focusing on structural stability in high chloride environments. These discussions deal with reinforcing (high carbon) steel and cement mortar liner pipes. Experimental data dealing with other probable candidate container metals, such as aluminum, titanium, and copper were not available. Concrete in contact with water produces hydroxide dissolution and hydration of free lime. The alkaline environment formed in this process should not pose a threat to the steel container.(40)

Corrosion of steel in contact with concrete is dependent on (a) availability of oxygen, and (b) disruption of the protective oxide film at the surface interface. Under normal conditions the high pH associated with the hydration of Portland cement will have no adverse effects on the oxide film. Variation in concrete composition may have an effect on steel corrosion in the presence of chlorides.(41) Calcium chloride is often used as an accelerator and may be present in the mix. Flaws, such as hairline cracks, which permit electrolytes and passage of oxygen, will lead to the formation of galvanic cells. If the process is continued, the results would lead to a break in the concrete due to the expansive pressure generated by the corroding steel.

The electrochemical behavior of steel in contact with moist Portland cement was evaluated using steel rods in a saturated lime solution (pH approximately 12.5). The experimental results indicated a threshold concentration of chloride ions above which pitting corrosion of mild steel is initiated. The threshold, assuming the presence of free oxygen, is approximately 0.02 M or 700 ppm chloride ion. These boundary conditions between pitting and inhibition are shown in Figure 1.15. The critical polarization potential plotted as a function of Cl^- concentration is shown in Figure 1.16. The results reported by Hausmann, Leckie, and Uhlig illustrate the corrosion resistance of steel in contact with concrete in the absence of high concentrations of environmental chlorides.(42,43)

Corrosion of steel in concrete may be prevalent with the formation of electrochemical cells due to poor quality application of concrete. The adverse effects of corrosion resulting from electrochemical cells may be suppressed through the use of protective coatings such as zinc, nickel, or an asphalt-epoxy.(44)

The risk of attack of steel in contact with Portland cement decreases as the thickness of the concrete increases along with the ratio of cement to aggregate. The use of lime water for mixing concrete shows that the presence of 2-7% calcium chloride does not give rise to steel corrosion; 2% calcium chloride in concrete fashioned with plain water has produced instances of localized corrosion.(27) Shreir has summarized the main points involved in the corrosion of steel in concrete as follows:

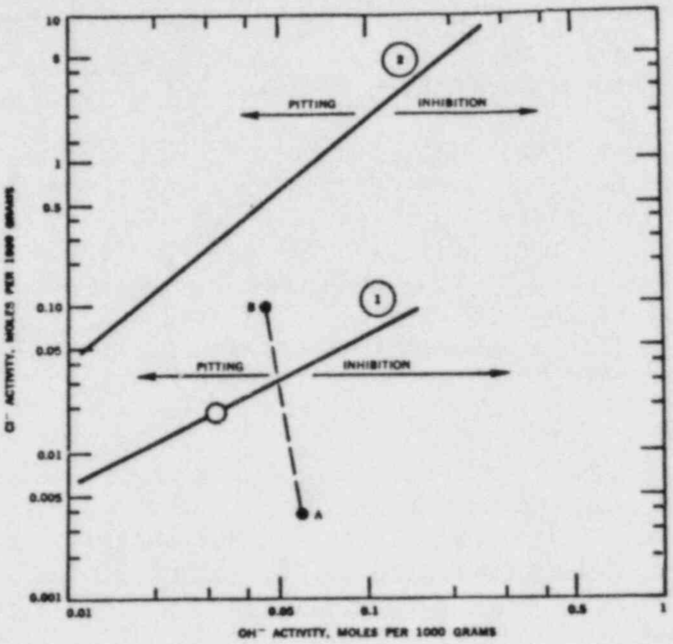

Figure 1.15 Boundaries between pitting and inhibition in alkaline aqueous solution containing chlorides. Curve (1) is steel with air bubbles trapped against the surface; the encircled point represents a saturated lime solution. Curve (2) is for 18-8 stainless steel in deaerated solution. Point A: pitting corrosion will not occur; cathodic protection not required. Point B: pitting corrosion likely; cathodic protection required (after Hausmann, 1968).

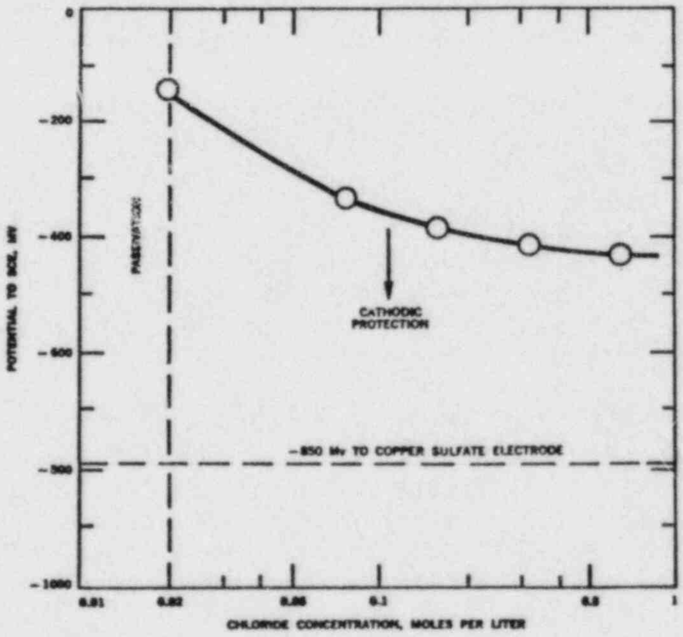

Figure 1.16 Critical polarization potential for cathodic protection of steel in saturated lime solutions containing sodium chloride.

(a) Given a good contact between steel and concrete of low permeability, corrosion is negligible; however, actual rates were not quoted;

(b) Concrete should be sufficiently plastic to allow an application of a continuous film around the steel structure;

(c) High compressive strength is desirable in the prevention of spalling of the concrete due to the formation of steel corrosion products;

(d) The benefit of applying protective paints on steel is short-lived. Bitumen paints may result in a lack of bond between steel and concrete.(27)

The primary considerations, as reflected in the literature, in determining corrosion rates of steel in concrete are governed by engineering concerns especially in the area of marine (high chloride) environments. Under such conditions, corrosion rates, deemed "severe" for reinforcing steel in concrete, have been determined in the range of 0.015 to 0.025 cm per year.(45)

The passivating action of concrete on steel is dependent in part on the durability of the former to act as a barrier. Flaws, such as cracks, and concrete permeability will result in the presence of corrosion cells and allow the concrete to act as an electrolyte. Corrosion of the steel would result in the formation of an iron-oxide film which could occupy a volume of approximately 2.2 times that of the original non-corroded steel. The expansion would result in the flaking or cracking of the concrete coat.(46) Under conditions in which the concrete is capable of preventing moisture and air from reaching the steel, protection to the steel is permanent. The protective film generated by the application of concrete acts as an anodic inhibitor and obstructs oxygen diffusion to the metal surface.(47)

The galvanic process at the steel-concrete interface may be summarized as follows:

Phase 1. Passivity due to the alkalinity of cement at pH >10;

Phase 2. Presence of anodic and cathodic regions at the interface -

- (a) Anodic: iron into solution; pH lowered; formation of oxide at metal surface;
- (b) Cathodic: concentration of alkali metal ions; pH raised.

Phase 3. (a) Anodic zones: equilibrium is maintained due to the protective cement coating and increased ohmic resistance; or, if flaws are present in the coating, or if conditions are extremely corrosive, ferric iron compounds are formed leading to the destruction of the protective coating.

(b) Cathodic zones: state of alkalinity is maintained without adverse effects on the coating; or, increase alkalinity due to the presence of high sodium or in potassium content would lead to a breakdown of the cement.(48)

A key factor in the corrosion process of steel in concrete is the permeability of the concrete. Corrosion is attributed to the formation of differential oxygen cells in the pore space containing water and dissolved solids. Attempts should be made to attain a relatively impermeable concrete through low water-to-cement ratio.(49) Wagner cites evidence of cement-mortar linings on pipes as having successfully protected against corrosion in highly aggressive water at high flow rates and mildly acidic pH (5-6). Failures of the protective coating were mainly attributed to localized deformation resulting from tension and compression arising as a function of the engineering constraints which are not likely to develop in waste emplacement environments.(50)

In summary, the effectiveness of concrete as an inhibitor to the corrosion of high carbon steel is dependent on the proper formulation and application of the protective coat. Care in handling procedures would assure that the concrete barrier remained undamaged during emplacement at the site of final deposition.

Based on existing data, an evaluation of the extension of container lifetime afforded by cement overpacking cannot be made at the present time. Concrete-container interactions involving candidate metals such as stainless steel or titanium, have not been evaluated and as a result one cannot adequately characterize the integrity and behavior of a "high integrity" container. Standardized corrosion tests are required to resolve some of the basic questions involved in the use of a metal-concrete container design. ASTM has adopted standard procedures for corrosion testing, such as ASTM G45 (potentiostatic and potentiodynamic anodic polarization measurements) and ASTM G46 (examination and evaluation of pitting corrosion), which may be modified to include concrete or other protective coatings. Corrosion testing of composite container/overpack materials should be conducted under laboratory and in situ conditions in order to adequately characterize the performance of the container following burial.

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2. GAS PRESSURE GENERATED THROUGH RADIOLYSIS AND BIODEGRADATION

2.1 Industrial Generation of Tritiated Waste

Of the companies replying to NRC's I&E Bulletin No. 79-19(1) to which BNL has had access, three generated essentially all the tritiated waste - New England Nuclear Corporation, Timex Corporation, and Self-Powered Lighting, Ltd. At that time (fall of 1979), Timex and Self Powered Lighting produced several kilocuries each, while New England Nuclear produced approximately 150 kilocuries and thus was far and away the largest generator (Table 2.1). If the total industrial tritiated waste stream indeed amounts to 200 kCi, we do not have the names of the other generator(s), but New England Nuclear (NEN) would still be the largest generator in the U.S. The situation since 1979 has changed somewhat. According to telephone conversations with responsible officials of the companies, NEN is now the only one producing tritiated waste in significant amounts, and its generation rate is essentially unchanged, e.g., 140 kCi for 1980.

Table 2.1

Significant ^{3}H Waste Identified from I&E Bulletin No. 79-19 and Personal Contact

Generator	Production Rate (kCi/yr) 1979	Production Rate (kCi/yr) Current
New England Nuclear	160	140
Timex (Waterbury)	4	<<1
Self-Powered Lighting (Elmsford)	4	<<1

Therefore, NEN's waste stream is the only one that requires consideration. Approximately 99% of their high-activity waste is in the form of tritium gas and is thus not a problem from the point of view of gas generation. Consequently, the only waste of concern for gas generation is that connected with handling the organic compounds which NEN tritium labels.* For CY 1980, the low-level organic residues were disposed of in organic solvents at the average rate of roughly 190 to 284 liters per week, which amounted to about five drums per week. The curie level of this waste is nominally 1.5 kCi (the remaining 1% of the total 150 kCi), which means that the average drum contains 6 Ci (based on a total generation of 250 drums for 1980). This waste organic solution is mixed with 1-2 times its weight of adsorbent clay

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*This information on waste streams was considered to be accurate when this report was written. A complete characterization and analysis of NEN waste can be found in NUREG/CR-3018 (1983). There is a high-activity organic residue waste stream (5-10 Ci/mL) that is not considered in this report. This high-activity organic waste stream generates enough gas to break the glass bulb package.

(Speedi-Dri),* placed in a sealed stainless steel container and packed in a 210-L drum also containing Speedi-Dri. The potential gas generation in each drum would result from the 6 Ci of tritium contained in some 50 kg of organic solvent and a much smaller amount of miscellaneous tritiated organic compounds.

2.2 Calculation of Tritium and Organic Content Limits for Waste Packages

BNL has been asked to provide information on the internal pressures which tritium waste containers (210-L drums) with a 6.35 mm (0.25 in.) metal overpack could be expected to withstand. The metal overpacks chosen for comparison are stainless steel and copper. As a consequence of biodegradation and beta radiolysis, the potential exists for the generation of significant gas pressures within these metal overpacks. It is the purpose of the calculations detailed below to provide estimates of the amounts of tritium contaminated waste which could be permitted for the following container pressures: (1) 152 kPa (7.4 psig), (2) 450 kPa (50 psig), and (3) the overpack pressure limits.

The information needed in the calculations for the radiolytic gas generation was obtained largely from published experimental data from the Mound Facility (MF) and Savannah River Laboratory (SRL). Information about waste packaging and contents was obtained by private communication with appropriate personnel at NEN. Although detailed information about the dimensions, volume, etc., for the waste package components and the level of contamination per drum were provided by NEN, some conservative assumptions were still required. However, justification has been provided for these assumptions and pressures were calculated for credible scenarios.

2.2.1 Gas Generation Due to Tritium Beta-Radiolysis

2.2.1.1 Tritium Gas/Tritiated Concrete Waste Packages

As discussed in Section 2.1, the major tritium waste stream from industry is tritium gas, mainly as HT. It is normally disposed of by filling a glass vessel with the appropriate quantity of tritium (to meet transportation and disposal requirements) and then encapsulating the glass vessels using a "can-in-a-can" containment scheme. A typical waste package for tritium gas, including primary, secondary, and tertiary containers, is given in Figure 2.1. The concrete used to encapsulate the secondary container is generally made with tritiated waste water so that the activity content of the concrete is nominally 2 Ci.** Under normal handling and transportation conditions, the glass vessels will remain intact. However, in the event of a breach scenario, tritium gas could diffuse through the primary and secondary containers and exchange with the water in the concrete. The water would then undergo radiolysis, yielding mainly hydrogen gas. The amounts of tritium needed to generate the pressures given above will be estimated for this situation.

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*Speedi-Dri is a trade name of the Engelhard Minerals and Chemical Corp., Edison, NJ.

**K. Bennett, New England Nuclear Corp., private communication to G. Bida, BNL, April 3, 1981.

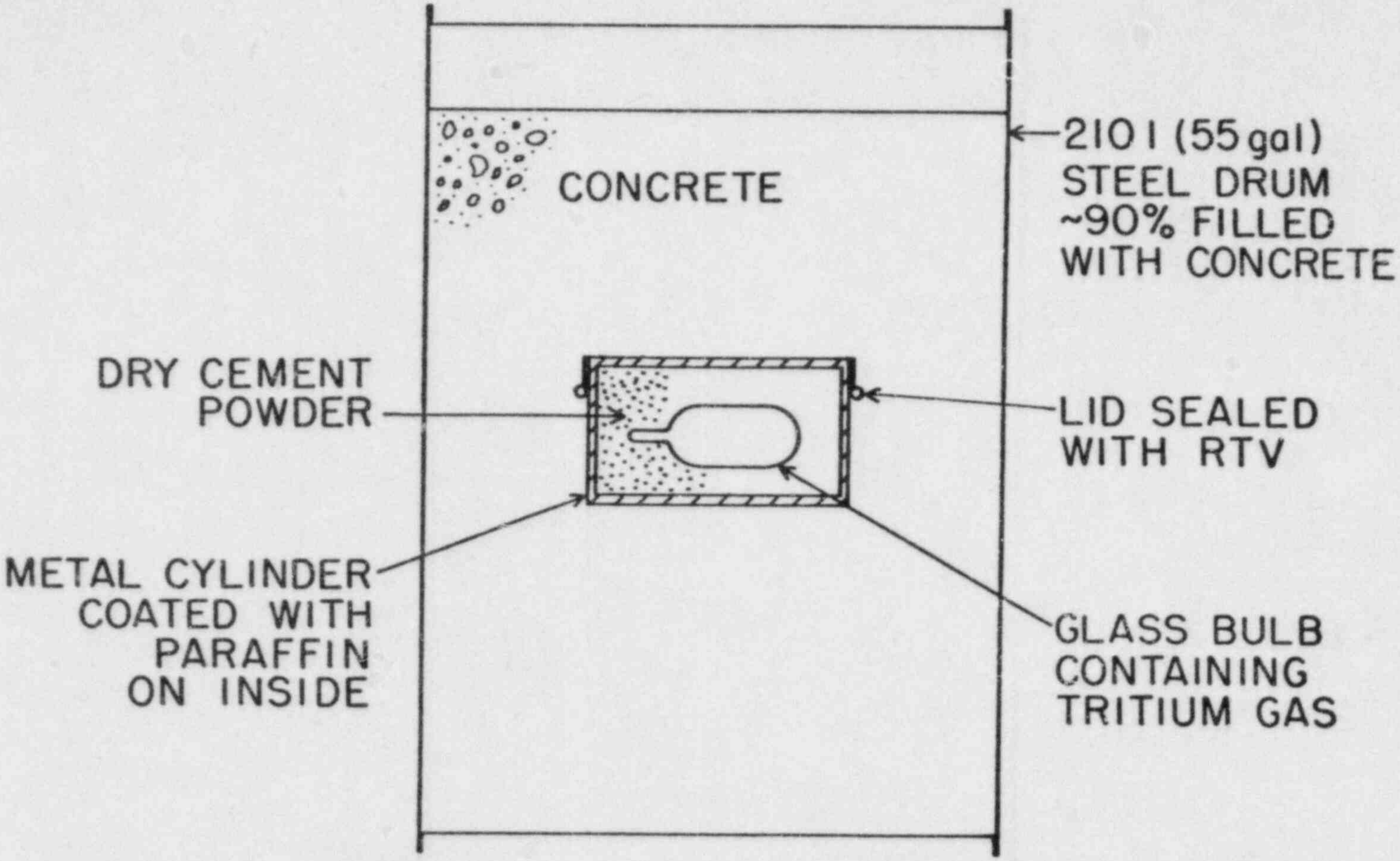

Figure 2.1 Schematic diagram of typical waste package for industrially-generated waste tritium gas.

(1) The glass vessels containing the tritium are assumed to have broken and released their contents but the secondary and tertiary containers remain intact. Another scenario would be a highly permeable glass container such that diffusion out of this vessel is rapid. Permeabilities of tritium through various materials are given in another section of this report.

(2) Diffusion of tritium through the cement mix, paraffin, etc. is rapid and the secondary containers are highly permeable to tritium so that the gas is in contact with the concrete soon after breach. Some materials have rather low permeabilities for tritium which makes this assumption concerning rapid diffusion rather conservative.

(3) It is assumed that the water-hydrogen exchange reaction heavily favors formation of HTO, i.e., the exchange of tritium for hydrogen is rapid and complete. In actuality, for the reaction

$$HT + H_2O \rightleftharpoons HTO + H_2 \ ,$$

the equilibrium constant is about 6 (25°C).[2] This reaction will only proceed in the presence of a catalyst or under radiolytic conditions. If a significant amount of the β^- energy were absorbed by the concrete matrix, the reaction may occur, albeit slowly.

(4) Based on information received from NEN and assuming a 1.27 cm (0.5 in.) clearance between the outer wall of the 210-L drum and the inner wall of the metal overpack, a void volume of 70 L has been estimated for containment of the radiolytically generated gases. The following additional assumptions were made in order to calculate the void volume (refer to Figure 2.1):

(a) The dry cement mix is assumed to be 50% void space.

(b) The 210-L drum is filled to 90% of its volume with concrete.

(c) The concrete is assumed to be 10% porous. A recent experimental determination of the porosity of Portland Type-I concrete has found it to be 15%.(3)

The last piece of information needed to calculate the amount of tritium required to generate the pressures of interest is the G value for the tritium beta radiolysis of water in concrete. Yields of radiation-induced reactions are expressed as G values, where G is the number of molecules changed (formed or destroyed) per 100 eV of energy absorbed. Bibler and Orebaugh(4) have reported results for the Co-60 gamma radiolysis of a cement-plaster mixture. The studies found the rate of gas generation (G value) to be independent of dose rate over the range 8.9×10^4 to 2.6×10^7 rad/hr. In addition, hydrogen was produced and oxygen was consumed, and as the radiation dose increased the rate of hydrogen pressurization decreased until a steady-state pressure was attained. From the $G(H_2)$ values for gamma and alpha radiolysis of water in concrete and the linear energy transfer (LET) values for Co-60 gamma, H-3 beta, and Cm-244 alpha radiation, the $G(H_2)$ for beta radiolysis of water in concrete was estimated to be between 0.1 and 0.3.(4) Bibler has concluded that the effects of tritium beta radiolysis can be closely simulated by Co-60 gamma radiolysis(5) because of the similar results for the steady-state hydrogen pressure obtained in the cases of Co-60 gamma radiolysis and H-3 beta radiolysis of water sorbed onto vermiculite.(4,5) This assumed similarity included the steady-state H_2 pressure behavior. From this, Bibler and Orebaugh predicted a final hydrogen pressure < 69 kPa for a 102-L drum containing 10^5 Ci of tritium solidified in 76 L of concrete.(4)

Results from Mound Facility have been reported for radiolytic gas generation from tritiated water fixed in cement-plaster and used in the preparation of Portland Type-I concrete and polymer-impregnated concrete. In the case of the non-polymer impregnated concrete, which most closely resembles the assumed scenario, the sample dose rate was 2.4×10^4 rad/hr, hydrogen was the only gas produced, but, in contrast to the SRL results, a steady-state hydrogen pressure was not observed.(6,7) For tritiated water fixation on cement-plaster, the addition of 0.21 to 0.24 MPa of hydrogen overpressure had no effect on the rate of gas generation.(7) After 900 days irradiation (which corresponds to about 5×10^8 rad total dose), the rate of gas generation for the tritiated concrete showed only a slight decrease but certainly no attainment of a steady-state pressure.(7) For the SRL experiments, equilibrium pressures were dose rate dependent and were attained after total doses of about 10^{10} rad.(4) It may be that such doses are required for steady-state pressurization in the case of the Mound experiments. Since important differences exist between the experimental systems and results from MF and SRL, we have chosen to use the data from MF since their experiments actually involved tritium beta radiolysis of water in concrete. In addition, this is the more conservative choice since it does not involve a hydrogen back reaction which may limit pressure buildup. From the data reported in Reference 7, we estimate a $G(H_2)$ of 0.13. This is in good agreement with the value predicted by Bibler and Orebaugh.(4)

Included in the pressure limits, for which we are estimating the allowable tritiated waste per container, are those that pertain to the 210-L drum metal overpack. These limits were estimated from tabulated data listed in reference 8. In the manufacture of metal overpacks, two types of joints may be encountered: circumferential and longitudinal. For the case of stainless steel, tubing of the appropriate diameter is available, thus, only circumferential joints will result from welding of the end caps. Should the overpacks be fabricated from rolled sheet steel, a longitudinal joint is required in addition to the circumferential joints. For circumferential joints, the design pressure is given by:

$$P = \frac{2SEt}{R-0.4t} \tag{2.1}$$

where

P = the design pressure limit, psi (the design pressure is one-fourth the bursting pressure),

S = maximum allowable stress, psi,

E = joint efficiency (0.8 is considered a reasonable and conservative value),

t = minimum required thickness, in inches.

R = inside radius of the shell, in inches.

For longitudinal joints, the design pressure is given by:

$$P = \frac{SEt}{R+0.6t} \tag{2.2}$$

For convenience, British units will be used for calculation of the pressure limits.

For a given set of container dimensions, the design pressures for various metals are directly proportional to the value for the maximum allowable stresses. This value is about 1.5×10^4 psi for carbon and low alloy steels. Aluminum has values of S ranging from 0.3×10^4 to 2×10^4 psi, depending on alloy and temper. Taking $S = 0.3 \times 10^4$ psi, t = 0.25 in., and R = 15 in., the design pressures for aluminum would be 40 and 80 psi for longitudinal and circumferential joints, respectively. A stress of 0.3×10^4 psi would most certainly be the minimum tolerable limit. However, alloys with higher stress values are available and presumably at not much higher cost. For copper alloys, S values range from 0.6×10^4 to 2×10^4 psi depending on alloy, heat treatment, etc. Finally, S values for non-alloyed titanium of different grades and heat treatments range from 0.9×10^4 to 1.5×10^4 psi. The design pressures calculated for a variety of metal cylinders of different outside diameters and thicknesses are listed in Table 2.2 below. In each case, the minimum value of S was used in the calculations. Note that P is inversely proportional to R.

Table 2.2

Minimum Design Pressure for Various Metals and Dimensions
(Burst Pressures are a Factor of Four Higher)

		Dimensions (in.)		Design Pressure P (psi)	
Metal	S (10^4 psi)	O.D. (2R)	Wall Thickness(t)	Longitudinal Joint	Circumferential Joint
Carbon Steel ($\sim$stainless steel)	1.5	30	0.25	200	400
		30	0.125	100	200
		20	0.25	300	600
		20	0.125	150	300
		16	0.25	375	750
Copper	0.6	30	0.25	80	160
		20	0.25	120	240
		16	0.25	150	300
Aluminum	0.3	30	0.25	40	80
	0.3	20	0.25	60	120
Titanium	0.9	30	0.25	120	240
		20	0.25	180	360

All the pressure values apply to cylinders with "dished" end caps, roughly hemispherical in shape. Depending on the exact shape, the wall thickness of the caps might have to be increased slightly for a given pressure. (Note that the additional volume due to the dished ends was not taken into account in the void volume calculation. This extra volume would decrease the pressures calculated). Most 210-L drums have outer dimensions of 61.0 cm (24 in) diameter x 88.9 cm (35 in) height. Since the exact dimensions and manner of fabricating the overpacks are not known, we have chosen the design pressure for the two base case metals corresponding to dimensions of 0.25 in. thick x 30 in. O.D. for an overpack having longitudinal joints, i.e., 200 psi for carbon steel and 80 psi for copper. If the overpacks are made with a smaller O.D. and/or from tubing rather than rolled sheets, then the design pressures will be higher and, correspondingly, will be able to contain a larger quantity of tritiated waste.

Based on the information provided and the assumptions discussed above, the tritium contaminated contents per drum can be estimated for the given pressure limits. The final pressure of hydrogen generated from radiolysis of water in concrete, and accounting for tritium decay, is given by:$^{(4)}$

$$P(H_2, \text{ in psi}) = \frac{RT}{NV} \cdot \frac{G(H_2)}{100} \cdot \frac{Ci_{t_o} \cdot I}{\lambda} \qquad (2.3)$$

where

R = gas constant, 1.20 psi liter/mole °K

T = temperature, °K, (298)

N = Avogadro's number, 6.02×10^{23} molecules/mole,

V = estimated void volume in the metal overpack, 70 L

$G(H_2)$ = 0.13 molecules of gas changed per 100 eV beta radiation absorbed

Ci_{t_0} = initial curies of tritium present,

I = 1.8×10^{19} ev/Ci · day

λ = ^3H decay constant, 1.5×10^{-4} day^{-1}.

Substituting the appropriate values into Eq. (2.3) and solving for Ci_{t_0}, Eq. (2.3) becomes

$$Ci_{t_0} = (7.5 \times 10^2 \text{ Ci/psia}) \cdot P(H_2) \tag{2.4}$$

From the equation, the initial quantities of tritium gas that could be permitted for the base case metal overpacks and pressure limits of interest have been estimated and are summarized in Table 2.3. An initial pressure of 101 kPa (1 atm) in the overpacks was assumed. Mound Facility estimated a

Table 2.3

Maximum Allowable Tritium Contents for Various Pressure Limits[a]

Pressure, kPa (psig)	^3H content, C_i
152 (7.4)	5.6×10^3
450 (50)	3.8×10^4
1484 (200)[b]	1.5×10^5
656 (80)[c]	6.0×10^4

[a] The allowable ^3H content has been calculated for the pressures expressed in psig, although Eq. (2.3) requires the pressure be expressed in psia. This is necessary in order to account for the initial 1 atmosphere of pressure assumed to be present in the overpacks.

[b] Carbon steel overpack.

[c] Copper overpack.

final hydrogen pressure of 690 kPa (99 psia) in void volume of 35 L for 2.5 x 10^4 Ci of tritiated water fixed on cement-plaster.(9) Present regulations* do not allow shipment of more than 1000 Ci of tritium gas from industrial waste generators such as NEN. As can be seen from Table 2.3, the amount of hydrogen generated from beta radiolysis of water containing 1000 Ci of ^3H for our assumed conditions would be negligible. At this point, some of the assumptions made for the purpose of this calculation should be recalled. It is quite unlikely that any of the pressures listed in Table 2.3 would be attained under actual breach conditions.

Several methods of reducing $G(H_2)$ have been investigated for the alpha radiolysis of water in concrete.(10) Some of the additives accomplish this reduction by reacting with the hydrogen precursors. This being the case, it is anticipated that these additives should be as effective in reducing $G(H_2)$ for the beta radiolysis of water. The only method of reducing $G(H_2)$ that appears applicable to the present tritium gas disposal practice is the addition of nitrite ions to the water used to make the concrete. For alpha radiolysis experiments, this addition resulted in a decrease of $G(H_2)$ by a factor of 10 to 20.(10) We are not aware of any experiments that deal with the reduction of gas generation from ^3H beta radiolysis of water. Whether the addition of nitrite ions to tritiated waste would reduce hydrogen production awaits experimental verification.

2.2.1.2 Tritiated Organic Waste Fixed on Sorbent

The other important industrially generated tritium contaminated waste stream consists of tritium labeled compounds dissolved in a variety of organic solvents. These solvents are then sorbed onto Speedi-Dri, an attapulgus clay material which is essentially hydrated magnesium aluminum silicate. According to information we received from NEN, tritiated organic waste is packaged for disposal in a somewhat different manner than for tritium gas. Normally, a 115-L (30-gal) steel drum is filled with Speedi-Dri. Then, the contents of 18 3.8-L (1-gal) containers of tritiated waste organic solvents are poured onto the sorbent. These containers are usually not full, and the volume of liquid disposed of per 115-L drum is in the range of 45 to 57 liters. These RTV-sealed 115-L drums are then placed into a 210-L (55-gal) drum and packed with dry Speedi-Dri and mechanically sealed. As is the case with water (in concrete), the organics can and do undergo ^3H beta radiolysis to yield a number of products. Because these organics undergo self-radiolysis, gases will be produced and an assumed accident or breach scenario is unnecessary. The major gaseous product for organics is hydrogen. In this section, we estimate the maximum permissible quantities of organics that would be allowed in a container based on the same pressure limits as for section 2.2.1.1.

In estimating the void volume for container pressurization, the same metal overpack dimensions were assumed. The only difference between this case

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*K. Bennert, New England Nuclear Corp., private communication to G. Bida, April 3, 1981.

and that of tritium gas, as far as the void volume is concerned, is the assumed porosity of the Speedi-Dri sorbent versus that of Portland concrete. The bulk density of Speedi-Dri is reported to be about 0.5 g/cm^3, while the crystal density is 2.5 g/cm^3.* In addition, a maximum of about 57 L of solvent is contained in the 115-L primary drum. Based on these data and assumptions, we estimate a total waste package void volume of 139 L for the case of organics sorbed onto Speedi-Dri.

The tritiated organic waste stream reported by NEN is composed of some nine or ten fairly common solvents, with ethanol and methanol comprising roughly 50% (by volume) of the total. The complex nature and composition of this waste permits only a guess as to the magnitude of G(H_2). For simple aliphatic alcohols under gamma radiolytic conditions, G(H_2) values are relatively large (about 4 to 5) and depend strongly on the purity of the material. For example, the yield of hydrogen from liquid methanol can be depressed by as much as 10 percent by the presence of certain substances at concentrations of only 2 μM.(11) This was also observed in the gamma radiolysis of octane.(6) It has been found that the yield of hydrogen is nearly independent of LET over the range 0.03 to 30 ev/Å.(12) This has also been observed for the radiolysis of n-octane and pump oil.(4) Since the bulk of the organic solvent waste from NEN is ethanol and methanol, and other solvents are present at $\leq$ 8% (v/v), we have assumed that the entire tritiated organic waste is methanol for which a G(H_2) value of 5.4 has been reported.(12) This is conservatively high for the purpose of this calculation since the G(H_2) values for the other organic solvents in the waste are generally $<$ 5,(11) and any impurities in the solvent will tend to depress the hydrogen yield. Finally, for the gamma radiolysis of n-octane and vacuum pump oil, the value of G(H_2) was found to depend on the mass fraction of organic sorbed onto the vermiculite, i.e., the greater the fraction of organic, the larger the value of G(H_2).(4) The reason for this is that the energy absorbed by the vermiculite is not transferred to the organic material to produce H_2. Similar behavior is expected for the ^{3}H beta radiolysis of absorbed organics. In summary, we have made the following conservative assumptions regarding the composition and radiation chemistry of the tritiated organic waste stream:

(1) The waste stream is tritium contaminated methanol.

(2) G(H_2) = 5.4 for ^{3}H beta radiolysis.

(3) G(H_2) is independent of dose, dose rate, and impurities, but depends on the mass fraction of sorbed organic.

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*D. Gregg, Engelhard Minerals and Chemicals Corporation, private communication to G. Bida, BNL, April 7, 1981.

The final pressure of hydrogen that will be generated from the beta radiolysis of organics sorbed onto Speedi-Dri is given by:(4)

$$P(H_2) = \frac{RT}{NV} \cdot \frac{G(H_2)X}{100} \cdot \frac{Ci_{t_0} \cdot I}{\lambda} \qquad (2.5)$$

where

X = mass fraction of organic material present (X = 0.44 for 57 L of methanol sorbed on 115 L (30 gal) of Speedi-Dri), and all other quantities are as previously defined for eq. (2.3). Substituting the appropriate values into eq. 2.5 and rearranging,

$$Ci_{t_0} = (81\ Ci/psia) \cdot P(H_2) \qquad (2.6)$$

From this equation, the initial quantities of tritium contamination for a given mass fraction of 0.44 that could be permitted for the base case metal overpacks and pressure limits of interest have been estimated and are listed in Table 2.4. An initial pressure of 101 kPa in the overpacks was assumed. Current regulations governing the disposal of tritiated organic waste allow only 20 Ci of activity per 210-L drum. No significant gas generation is expected for this level of contamination. We would like to note, however, that due to the variability in composition of the organic waste stream, we cannot be absolutely certain of the limiting values listed in Table 2.4. Any questions along these lines can only be answered by conducting experiments with actual waste samples.

Table 2.4

Maximum Allowable Tritium Contamination in Adsorbed Organics (Mass Fraction = 0.44) for Various Pressure Limits[a]

Pressure, kPa (psig)	^3H content, Ci
152 (7.4)	6.0×10^2
450 (50)	4.1×10^3
1484 (200)[b]	1.6×10^4
656 (80)[c]	6.5×10^3

[a] Accounts for initial 1 atmosphere in the overpack (see footnote a, Table 2.3).

[b] Carbon steel overpacks.

[c] Copper overpacks.

As far as reducing the concentration of hydrogen precursors is concerned, the situation for organics appears to be more complicated than for water. In the condensed phase, radicals are formed very close together, either in the spurs or in the particles' tracks. These radicals will react very rapidly with one another and cannot easily be intercepted except with impractically high concentrations of scavengers. Furthermore, there is evidence that not all hydrogen precursors are scavenged.(6,13) Therefore, because of the existence of spurs, some of the hydrogen precursors are not readily scavenged. and there will always be a certain radical yield that leads to H_2 formation. There is evidence from the gamma radiolysis of n-propanol having nitrous oxide scavenger that the reduction in $G(H_2)$ approaches a limiting value (about 2 at 25°C).(12) Due to the varied composition of the tritiated organic waste stream, some scavengers will probably be solubility limited and, thus, ineffective. However, $G(H_2)$ values will already have been lowered due to the rather likely presence of impurities in the waste. At this point, we can only speculate that addition of a radical scavenger, such as bromine, may be effective in reducing the hydrogen yield further.

2.2.2 Gas Generation Due to Microbial Degradation

Of the two major tritium waste streams we have identified, only the organic waste has the potential of undergoing any significant biodegradation. Microorganisms, which are ubiquitous in nature, have long been recognized for their ability to degrade organic molecules.(14) Some of the products that can result from microbial degradation are gases, the amounts of which are important to this assessment of metal overpacks for tritium waste containers.

The degradation of complex natural and synthetic materials can be accomplished by the actions of heterotrophic and lithotrophic microbes. In the degradation of organic matrix wastes, gases can be produced by bacterial decomposition via the metabolic processes of aerobic or anaerobic respiration, fermentation, denitrification, etc. The production, consumption, and transformation of gases by microorganisms have been studied and extensively reviewed.(15,16) Carbon dioxide is the major gas expected as a result of aerobic bacterial decomposition of organic matrix waste. Under anaerobic conditions, hydrogen is the next most important primary gas produced. Assuming the appropriate conditions exist, hydrogen can then be used by several groups of microorganisms to produce several gases which include methane, hydrogen sulfide, and ammonia. From the degradation of complex organic compounds, several volatile compounds may result.(17)

Several reports and papers have been published that deal with gas generation from the microbial degradation of transuranic contaminated organic waste under anticipated conditions of long-term geologic isolation(18) and from microbial transformations of organic wastes in shallow land, low-level radioactive waste disposal sites.(19,20,21) The bacteria and fungi in these wastes responsible for the biodegradation were derived mainly from humans who worked with and disposed of the contaminated materials, from the air, and from laboratory animals. However, the major source of the microorganisms appear to be derived from the waste disposal environment, i.e., soil. The situation that we are addressing for the case of tritiated organic waste fixed on a sorbent is not exactly the same as that for the cases reported in the literature. For the tritiated waste, the material will be sorbed on an appropriate material and then placed in high integrity containers. It is intended that these containers withstand the effects of corrosion, gas pressurization, and tritium permeation during a period of 100 to 200 years. The container will thus be an effective barrier against intrusion of soil microorganisms in a shallow land burial site. However, this type of waste containerization does not preclude the potential for gas production from biodegradation. In fact, in discussing this problem with some of the personnel involved in the research reported in references 18 through 21, the concensus is that microbial degradation will take place in these containers and potentially significant quantities of gas may be generated. There is support for such a claim in the literature. In experiments involving the biodegradation of transuranic contaminated waste, measured degradation rates were nearly identical for two separate experiments where a microbial soil inoculum was utilized in one case and not in the other.(18) The credibility of microbial degradation of tritiated organic waste is further supported by the fact that the Speedi-Dri sorbent is a natural clay material and will quite likely contain a large distribution of aerobic and anaerobic microorganisms.

On the other hand, one might be tempted to assume that significant quantities of microbes would not be able to flourish under the "hostile" chemical and radiation environment of the organic waste. There is, however, ample information in the literature to sufficiently dispel such a belief. We will only cite a couple of examples to make our point. In experiments conducted to demonstrate the biogenesis of tritiated methane from low-level radioactive waste,(21) the levels of tritium used in the experiments (0.07 mCi/mL) had no effect on methanogenesis. This is just slightly less than the average tritium contamination level reported for the organic waste stream from NEN. Thermophilic microorganisms are known to survive and grow at higher temperatures (55 to 60°C). However, some bacteria have been found to grow profusely at temperatures of 93 to 95°C.(17) Ionizing radiation and organic compounds can act as mutagens to produce strains of bacteria that would otherwise not survive under these conditions.(18,20,22)

With the likelihood of biodegradation of tritiated organic wastes established for the particular disposal situation that concerns this report, the next questions would be (1) at what rate(s) will the gas(es) be generated, and (2) how much gas (pressure) can be expected to be produced? Unfortunately, these questions do not lend themselves to simple analysis because of a dearth of information generated for waste disposal conditions similar to those under consideration. The best one can do is assume a "worst-case" situation in which the entire organic contents of a typical waste container undergo biodegradation to produce gaseous products only. The rates of gas production and amounts generated will depend on the type and quantity of microbes present which in turn depend on the waste composition and environmental conditions such as pH, temperature, moisture, etc. Because of the variability in these parameters, the rates of gas generation may vary widely on a per drum basis. These problems have been encountered elsewhere.(18)

It should be obvious at this point that any estimate or prediction of the extent and consequences of microbial degradation of tritiated organic waste typically generated by industry is simply speculation. However, for calculational purposes only, we have assumed a scenario in which the entire organic contents of an average drum of waste is aerobically transformed into carbon dioxide over the course of 100 to 200 years of containment. As discussed above, strict anaerobic conditions will yield gases other than carbon dioxide. The production of these gases depends upon when, and if, conditions become anaerobic, and their identity depends upon the nature of the microorganisms present and the nutrients available to them. This information is, of course, unavailable.

As mentioned previously, the average volume of organic waste disposed per 210-L drum is 57 liters. Based on the distribution of organic compounds in the waste, we have estimated a total carbon content of 22 kg per drum. From this, 1.8×10^3 moles of CO_2 can be produced. For a void volume of 139 L, calculated in section 2.2.1.2, and assuming ideal gas behavior, a pressure of 3.2×10^4 kPa (4.6×10^3 psia, 25°C) will result from complete oxidation. An initial pressure of 101 kPa in the overpacks was assumed. As a comparison, the rate of CO_2 generation from the degradation of asphalt intentionally inoculated with soil microorganisms was found to be approximately 5 moles of CO_2/yr/210-L drum (25°C).(18) Assuming a 50% void volume in the drum, a pressure of 1.4×10^4 kPa will be generated in 120 yr at that generation rate. This is obviously in excess of the design pressure limits for the base case metal overpacks. The maximum carbon content per drum that could be permitted for the base case metal overpacks and pressure limits of interest have been estimated for the biodegradation scenario and are given in Table 2.5.

Table 2.5

Maximum Allowable Carbon Content per Drum for Various Pressure Limits.[a]

Pressure, kPa (psig)	Carbon Content, g
152 (7.4)	34.1
450 (50)	232
1484 (200)[b]	929
656 (80)[c]	372

[a] Accounts for initial 1 atmosphere in the overpack (see footnote a, Table 2.3).

[b] Carbon steel overpacks.

[c] Copper overpacks.

Only two possible methods for reducing the chances for significant microbial degradation come to mind: sterilization of the Speedi-Dri before use, or addition of a biocide to the organic waste. However, sterilization is precluded by the fact that the Speedi-Dri will require subsequent handling in a contaminated environment and furthermore, the waste organics will possibly contain significant quantities of microbes. The second alternative may also have limited effectiveness. Given the length of time being considered for containment, it is felt that even the biocides will undergo a certain amount of degradation.* It might still be worthwhile to investigate the effectiveness of some biocides against the growth of bacteria isolated from the adsorbent material. In conclusion, until experimental evidence proves otherwise, it must be assumed that microbial degradation of the tritiated organic waste has the potential to produce quantities of gas that will yield pressures far in excess of the metal overpack limits.

2.3 Summary and Conclusions

We have established that New England Nuclear Corporation is the major tritiated waste generator in the U.S. Of the approximately 160 kCi of tritium disposed of by NEN in 1979, 99% of the waste was tritium gas. (This percentage was found to be inaccurate after completion of this report. See NUREG/CR-3018, 1983). The remainder was tritium contaminated organic solvents sorbed onto Speedi-Dri. Although the organic solvent waste stream is the only one that can realistically lead to gas generation from beta radiolysis and biodegradation mechanisms, we have assumed a scenario for which gas generation may take place for the tritium gas waste package. In this section, estimates were given for the maximum allowable tritium waste that could be permitted for various pressure limits of a typical waste container having a 6.35 mm metal overpack. The pressure limits used in the calculations were: (1) 152 kPa (7.4 psig), (2) 450 kPa (50 psig), and (3) the metal overpack pressure limits. These estimates required that we make several conservative assumptions. The results of these calculations and the conclusions drawn from them are summarized below.

- For the base case metal overpacks, copper and stainless steel, we estimated design pressure limits of 656 kPa (80 psig) and 1484 kPa (200 psig), respectively.

- Based on a somewhat unrealistic breach scenario and rather conservative assumptions regarding tritium diffusion and exchange, for the case of gas generation due to beta radiolysis, the maximum allowable tritium gas content (in curies) per overpacked container was found to be in the range 5.6×10^3 to 1.5×10^5 for the pressure limits given above.

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*A. J. Francis, Brookhaven National Laboratory, personal communication to G. Bida, BNL, April 10, 1981.

- For the present regulations governing disposal of tritium gas ($\leq$1000 Ci/container), we conclude that none of the pressure limits considered in this section are likely to be attained.

- It is possible that the addition of nitrite ion (NO_2^-) to the water used to make the concrete employed in tritium gas disposal will help to further reduce the potential for gas generation from this waste stream.

- For the tritium contaminated organic waste stream, the calculations assumed the waste to be 100% methanol since this is one of the major constituents of that waste stream and will yield conservatively high estimates of the amount of gas that can be generated per unit volume or organic waste. Assuming a mass fraction of 0.44 (organic sorbed onto Speedi-Dri), the maximum allowable tritium contamination (in curies) in adsorbed organics per metal overpacked container estimated for the case of gas generation due to beta radiolysis was found to be in the range of 6.0×10^2 to 1.6×10^4 for the overpack pressure limits given above.

- Since current regulations governing the disposal of tritium contaminated organic waste do not allow more than 20 Ci of activity per 210-L drum, no significant radiolytic gas generation is expected for this level of contamination.

- Because of evidence indicating that not all hydrogen precursors are scavengable in liquid phase organics, we can only speculate that addition of known free radical scavenged will be effective in reducing the hydrogen yield from radiolysis.

- It is quite likely that the tritium contaminated organic waste will evolve gas(es) from biodegradation over the course of 100 to 200 years of containment. However, due to a lack of experimental data, the rate of gas production and the amount generated are unknown.

- For calculational purposes, a worst-case scenario was assumed in which the total carbon content (22 kg) of a typical container of tritium contaminated organic waste was aerobically transformed into carbon dioxide. The estimated pressure was 3.2×10^4 kPa (4.6×10^3 psia), well in excess of the design pressure limits for the base case metal overpacks.

- For the case of gas generation from microbial degradation, the maximum allowable carbon content per metal overpacked container was found to be in the range of 34 to 929 g for the pressure limits of interest.

- How realistic these estimates are for microbial degradation will require identification of appropriate microorganisms in the Speedi-Dri adsorbent and determination of their gas generation potential and the factors that affect the rates and quantities of gas produced.

2.4 References

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3. DIFFUSION OF HYDROGEN THROUGH MATERIALS

Assuring that tritium will not escape from the waste-disposal package by diffusion through the container wall is one of the easier tasks involved in tritium disposal. The problem of hydrogen containment at ordinary temperatures was solved long ago; witness the familiar laboratory cylinder (4130 steel) which stores hydrogen at 2000 psi with an annual loss of 0.8%.(1) Tritium's diffusion behavior has been shown to be essentially the same as that of normal hydrogen. Also, much practical experience in tritium containment has been accumulated at Mound Facility, Savannah River Laboratory, Oak Ridge National Laboratory, and elsewhere. Shipping containers for gaseous tritium, which meet rigorous safety requirements, have been developed, and these are in routine use. These are discussed in Section 4.

It is desirable, however, to back up the observations based on practical experience with a review of more fundamental research on the interaction of hydrogen with candidate materials of construction. Such interaction can take the form of chemical reaction to form a metallic hydride; solution and subsequent permeations; and hydrogen embrittlement at high pressures. An associated problem of helium embrittlement over long periods of storage may occur when solubilized tritium decays to helium within the metallic lattice. However, most of the results obtained with hydrogen will apply to tritium, subject to the application of a small correction factor. In order to specify this factor more precisely, articles on hydrogen isotope effects in metals are included in the review; and, of course, papers directly concerned with tritium itself in metals.

The literature on these topics is enormous. Fortunately, much of it can be eliminated at once from further consideration, since no metal capable of forming hydride by direct reaction with hydrogen can be considered as a container material. This eliminates the alkali and the alkaline earth metals (except magnesium), scandium, yttrium, and the rare earths, titanium, zirconium, hafnium, thorium, vanadium, niobium, tantalum, and palladium. The remaining metals of possible utility as container materials are copper, silver, gold, zinc, cadmium, aluminum, tin, lead, chromium, molybdenum, tungsten, manganese, iron, cobalt, nickel, and magnesium. Of these, there are comprehensive hydrogen permeability data on iron, nickel, and aluminum. Somewhat less complete information is available on several of the others. Permeability data have been excerpted from a selected group of the most recent publications. A container that will be essentially impermeable to tritium under the expected conditions will not be optimal for resistance to environmental attack, except by coincidence; in general, one must expect that a composite container will be required. Other factors such as material strength, ease of fabrication, compatibility with adjacent environments and response to irradiation-induced rate increases(2) can mitigate against the use of low permeability metals. Tungsten, unless in a very pure form, is too brittle to fabricate even though it is highly impermeable to hydrogen. Titanium, a highly corrosion resistant metal, cannot be used because of hydride formation.

A brief introduction to the conventional method of presenting permeability data is in order at this point. At a given temperature, the amount of gas, f_g, passing through a membrane per unit time depends on the area, A, the thickness, t, the high-side pressure, p_1, the low-side pressure, p_2, and of course, on the nature of the gas and the material of the membrane. For most combinations of diatomic gases and membrane material, the relation(3) is given approximately by:

$$f_g = \frac{A}{t} (p_1^{\frac{1}{2}} - p_2^{\frac{1}{2}})P \tag{3.1}$$

The permeability, P, is a characteristic of the particular system. It is customarily given in such units as $cc(STP) \cdot cm^{-2} \cdot s^{-1} \cdot cm \cdot (atm)^{-1/2}$. Here the second "cm" refers to the thickness of the membrane. In general, the amount of gas is proportional to the area of the membrane, to the elapsed time, and to the square root of the pressure. (Atomic diffusion produces the square root pressure dependence; molecular diffusion, as in polymerics and oxide films displays a linear dependence). The amount of gas is inversely proportional to the thickness of the membrane.

The mechanism of permeation in metals is considered to involve adsorption, dissociation, atomic solution (as H or H^+), migration through it by diffusion under the driving force of a concentration gradient, recombination, desorption, and passage into the gas phase on the low-pressure side. Permeability is dependent upon temperature, the nature of the material, boundary conditions (chemisorption or dissociation), and thickness (for thicknesses greater than 1 mm).(4) The square-root pressure dependence of permeability results from the similar dependence of gas solubility, according to Sievert's law, expressed as $C(conc) = k \cdot p^{1/2}$. It can be shown that the permeability is equal to the product of solubility times diffusivity (from Fick's first diffusion law). Permeability can thus be either measured directly or obtained from independent measurements of solubility and diffusivity. For this review, the direct measurements have appeared adequate and we have not undertaken the much more extensive tasks of compiling P values from solubilities and diffusivities.

A major factor increasing the permeability is the increase in solubility with increasing temperature. Diffusivity changes little with temperature in comparison with solubility. The temperature dependence of permeability is of the Arrhenius form

$$P = a \cdot e^{-E/RT} \tag{3.2}$$

at least in the higher temperature region where most measurements have been made. At lower temperatures, permeabilities tend to be lower than extrapolation by this formula would predict, due to different rate-controlling mechanisms having different activation energies. At low temperatures, solubility is the rate-controlling factor; at high temperatures, diffusion is rate-controlling.

3.1 Tabulation of Permeability Data on Materials

Permeabilities are reported in the literature in a variety of units. In order to facilitate comparisons, published values nave been converted where necessary to a common unit, namely $cc(STP) \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot atm^{-1/2}$. For metals, entries with inserted dashes represent alloys; entries with inserted slashes represent laminates. Wherever reliable data on temperature dependence were available, permeabilities were calculated for the temperatures 25°C, 100°C, and 200°C. (See Table 3.1). Metals with permeabilities greater than 10^{-8} at 298°K were not included. Discrepancies in permeabilities that were attributed to experimental difficulties were not included. It should be noted that the permeabilities of binary alloys fall within the permeabilities of the pure components.

It is sometimes the case that a multiplex metal structure is used to form a barrier to gas. When such materials are placed in a series to form a laminate, then the combined permeability coefficient, P_L, may be calculated from the coefficients of its constituent layers, assuming that the values of area, time, and pressure are the same for all constituent layers,(5)

$$\frac{1}{P_L} = \frac{1}{L} \sum_{i=1}^{i=n} \frac{x_i}{P_i} \tag{3.3}$$

where

P_L = permeability of the laminate

P_i = permeability of the ith layer

x_i = thickness of the ith layer

L = thickness of the laminate

This equation is limited to permeability coefficients which are independent of pressure. For a two layer laminate, the rearranged equation becomes

$$P_L = \frac{LP_1P_2}{P_2x_1+P_1x_2} \tag{3.4}$$

Even though fifty-fold reductions in permeability have been reported(6) at high temperature (600°C), laminates generally provide small decreases in permeation when compared to equal thicknesses of the separate layers, especially at room temperature. For specific design purposes,(7) a laminate can be chosen, but it should have been proven successful in terms of bond formation, mechanical integrity, and thermal shock resistance, because of the potential problem of delamination.

Table 3.1

Permeability of Metals to Hydrogen and Its Isotopes[a,b]

Isotope	Material	298°K	373°K	473°K	Reference
H	Tungsten	4.2×10^{-25}	1.9×10^{-20}	1.5×10^{-16}	3
D	Gold	10^{-21}	---	10^{-13}	41
D	Aluminum Alloys	6.9×10^{-19}	1.4×10^{-15}	5.4×10^{-11}	20
H	Molybdenum	4.3×10^{-18}	6.4×10^{-15}	3.0×10^{-12}	3
H	316SS/Cu/316SS[c]	4.5×10^{-18}	1.3×10^{-14}	1.1×10^{-11}	42
T	21Cr-6Ni-9Mn SS[d]	4.7×10^{-18}	1.9×10^{-14}	2.1×10^{-11}	27
H	Pt-Ir (75/25)	4.8×10^{-17}	3.1×10^{-14}	7.1×10^{-12}	19
T	316 SS	2×10^{-16}	8.3×10^{-15}	1.5×10^{-13}	22
H	310 SS[e]	2.4×10^{-16}	2.4×10^{-14}	1.1×10^{-12}	28
T	Aluminum	3×10^{-16}	10^{-12}	10^{-8}	24
H	Copper	6.0×10^{-16}	8.8×10^{-13}	4.0×10^{-10}	42
H	Copper	---	---	4.2×10^{-11}	43
D	Molybdenum	6.5×10^{-16}	2.4×10^{-13}	3.4×10^{-11}	44
T	Incoloy 800	1.1×10^{-15}	7.1×10^{-13}	2.5×10^{-10}	45
H	Copper	1.7×10^{-15}	9.0×10^{-13}	1.75×10^{-10}	44
T	Incoloy 800	3.8×10^{-15}	---	9.2×10^{-10}	17
T	Tungsten Alloy (1.5 Fe, 3.5 Ni)	4.0×10^{-15}	6.4×10^{-13}	4.5×10^{-11}	17
D	21Cr-6Ni-9Mn-SS[f]	---	---	8×10^{-11}	10
H	110 SS	---	1.2×10^{-12} [g]	---	46
H	EN58E SS	---	1.7×10^{-12} [g]	---	46
H	Kovar Alloy (Fe,Co,Ni)	5.8×10^{-15}	1.9×10^{-12}	2.5×10^{-10}	47
T	21Cr-6Ni-9Mn SS[e]	2.7×10^{-14}	5.7×10^{-12}	5.1×10^{-10}	10
T	316 SS	2.9×10^{-14}	7.2×10^{-12}	7.4×10^{-10}	17
T	Incoloy 800	3.9×10^{-14}	9.2×10^{-12}	9.2×10^{-10}	48
T	Sanicro 31	5.9×10^{-14}	1.2×10^{-11}	1.0×10^{-9}	17
T	Hastelloy N	6.8×10^{-14}	1.4×10^{-11}	1.3×10^{-9}	17
D	21Cr-6Ni-9Mn SS	6.8×10^{-14}	1.4×10^{-11}	1.3×10^{-9}	49
D	309 SS	1.0×10^{-13}	1.6×10^{-11}	1.1×10^{-9}	49
H	304 SS	1.4×10^{-13}	5.0×10^{-11}	6.8×10^{-9}	42
D	304L, 316L SS	1.5×10^{-13}	1.7×10^{-11}	9.1×10^{-10}	19
H	347 SS	---	2.4×10^{-11}	8.3×10^{-10}	43
H	321 SS	2.4×10^{-13}	3.0×10^{-11}	1.7×10^{-9}	21
H	Ceramvar Alloy	4.1×10^{-13}	4.8×10^{-11}	2.6×10^{-9}	44
H	Ceramvar Alloy	4.3×10^{-13}	4.9×10^{-11}	2.7×10^{-9}	47
T	305 SS[h]	4.4×10^{-13}	4.4×10^{-11}	2×10^{-9}	50
H	Incoloy 903	8.3×10^{-13}	8.7×10^{-11}	4.4×10^{-9}	47

Table 3.1, Continued

Permeability of Metals to Hydrogen and Its Isotopes[a,b]

Isotope	Material	298°K	373°K	473°K	Reference
H	316 SS	1.1×10^{-12}	2.3×10^{-10}	1.9×10^{-8}	42
H	Inconel	---	---	4.7×10^{-9}	43
H	Inconel 718	1.3×10^{-12}	1.2×10^{-10}	5.6×10^{-9}	47
D	Inconel 718	---	1.5×10^{-9} [i]	---	19
D	Hastelloy N	1.4×10^{-12}	1.0×10^{-10}	3.7×10^{-9}	19
H	Cobalt-Based Alloy	1.5×10^{-12}	9.5×10^{-11}	3.1×10^{-9}	19
T	Croloy[j]	2.2×10^{-12}	5.3×10^{-11}	7.7×10^{-10}	51
T	406 SS	5.3×10^{-12}	---	1.09×10^{-8}	17
H	316 SS	5.5×10^{-12}	9.5×10^{-10}	7.2×10^{-8}	52
T	Nickel	7.0×10^{-12}	4.5×10^{-10}	1.7×10^{-8}	17
T	Nickel	7.3×10^{-12}	---	2.8×10^{-8}	53
H	321 SS	1×10^{-11}	1.3×10^{-9}	7.4×10^{-8}	52
T	Martensite	2×10^{-11}	5.8×10^{-10}	1.0×10^{-8}	19
T	Croloy	2.3×10^{-11}	---	2.6×10^{-8}	17
H	Inconel 625	2.3×10^{-11}	3.1×10^{-9}	1.8×10^{-7}	52
H	Inconel 718	4.0×10^{-11}	3.9×10^{-9}	1.8×10^{-7}	52
T	Iron	2.7×10^{-10}	6.7×10^{-9}	1.0×10^{-7}	54
T	Croloy	3.3×10^{-10}	8.0×10^{-9}	1.2×10^{-7}	51
D	4130 Carbon Steel	3.7×10^{-10}	7.9×10^{-9}	1.03×10^{-7}	25
H	T-1 Steel	7.3×10^{-10}	1.8×10^{-8}	2.6×10^{-7}	25
T	Iron/Marz Grade	7.3×10^{-10}	1.8×10^{-8}	2.6×10^{-7}	25
D	Low-Alloy Steel	$1\text{-}5 \times 10^{-9}$	5×10^{-8}	5×10^{-7}	19
T	Ferrite-Perlite	10^{-8}	---	---	19

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[a] P is in units $cc(STP) \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot atm^{-1/2}$.

[b] Estimating the inside surface area of 55 gallon drum to be 2.0×10^4 cm^2, multiply P values by 10^9 to convert to units of $L(STP) \cdot 0.25$ inch/20,000 cm^2/year/atmosphere.

[c] SS refers to stainless steel.

[d] Steel was chemically cleaned.

[e] Steel was coated with 200 Å palladium coating.

[f] Specimen was electropolished.

[g] P value was measured at 353°K.

[h] Data represents averaging of available permeabilities for 304, 304L, 316, and 347 SS. (P at 298°K was corrected for a grain boundary contribution).

[i] P value was measured at 423°K.

[j] Specimen was steam-oxidized.

In non-metallic solids, interstitial solution of hydrogen is assumed, although substitutional replacement may be anticipated in cases such as polymerics (see Tables 3.2, 3.3, and 3.4). Hydrogen solution in polymers and glasses is normally molecular. For tritium specifically,(8) the possibility exists that isotopic exchange of tritium with the hydrogen in the polymer could eventually degrade the polymer by breaking the bonds where replacement tritium decayed. (Some elastomers are corroded by protium.) The permeabilities of polymerics are well above those of metals, e.g., stainless steels. The permeability of borosilicate glass is on the order of some stainless steels. Even so, non-metallics may be chosen to be a part of the waste package on the basis of internal corrosion factors, e.g., chemical resistance, and/or water permeability. These are discussed in Section 4.

3.2 Effect of Surface Treatment on Permeability

To reduce permeability, one has to mainly alter the amount of hydrogen dissolved in the metal. In metals, hydrogen enters in a dissociated form, rather than in molecular form. It is uncertain whether the form is atomic or ionic (H^+). The permeation of hydrogen in steel does not obey Sievert's law (dependence on $p^{1/2}$) below 400°C.(4,9) This is thought to be due to presence of naturally-occurring oxide layers. It appears that entry of the hydrogen into the steel is the controlling factor. Therefore, surface treatments of metals in view of permeation reduction are important. Additional mechanisms by which permeation is suppressed involve inhibition of molecular dissociation and increases in the energy of activation for entry.

Gill(10) judged the tritium-barrier properties of ten containers by correlating amounts of HT present after one year in initially 99.7% tritium gas in contact with the surface evaluated. Results indicated that: (1) the mechanical treatment of a chosen material is important; (for example, permeability in cold-worked 304L SS is about 30 times greater than in annealed form);(11) (2) the surface area of a prospective vessel must be minimized (e.g., by polishing); (3) the permeation of hydrogen through a metal can be decreased by altering surface oxide films with nitric acid passivation, wet hydrogen firing, oxygen bombardment or electropolishing.

The most exchanged tritium (HT) was found in two commercially-available containers: one, an untreated 304 SS, had greater than 11.0[HT] mole %; the other, an aluminum with a chemical conversion coating, had a 5.0[HT] mole % content. Vessels containing HT in the range 0.7 to 1.2 [HT] mole % included cadmium-plated, electrocleaned 304 SS; borosilicate glass; and electropolished, oxygen discharge-treated 304 SS. In order of decreasing HT content (from 0.1 to 0.3 mole %), the following containers provided least interaction of tritium gas with the surface: dry-polished, wet hydrogen fired 304 SS > dry-polished, gold-ion-plated 304 SS = burnished aluminium > electropolished 304 SS > dry-polished 304 SS.

3.3 Permeation Resistant Coatings

There exists a considerable amount of data on the effect of surface coatings on the hydrogen permeability of metals, although much of it was obtained

Table 3.2
Permeability of Plastic Films to Hydrogen and Its Isotopes[a,b]

Isotope	Material	298°K	Comments	Reference
H	poly(ethylene terephthalate)	4.4×10^{-9}	high resistance	55
H	"Mylar" polyester	4.5×10^{-9}	to radiation	56
H		4.6×10^{-9}	5×10^8 rad maximum	57
D		4.1×10^{-9}		56
H	poly(tetrafluoroethylene)	6.1×10^{-8}	low resistance	56
D	"Teflon"	9.8×10^{-8}	to radiation	56
D		1.3×10^{-7}	1×10^6 rad maximum	58
T		1.0×10^{-7}		56
H	polyimide	1.1×10^{-8}	----	57
H	"Kapton"	1.3×10^{-8}		56
D		1.3×10^{-8}		56
T		1.9×10^{-8}		56
H	poly(vinylidene chloride)	3.1×10^{-7}	----	59
H	"Diofan"	3.6×10^{-8}		56
D		2.3×10^{-8}		56
H	vinylidene chloride- vinyl chloride copolymer "Saran"	4.2×10^{-9}	----	57
H	poly(vinyl chloride)	4.6×10^{-10}	high resistance	57
H	(plasticized and	6.8×10^{-9}	to radiation	57
H	unplasticized) "Geon"	1.5×10^{-8}	1×10^8 rad maximum	60
H		3.3×10^{-8}		61
T		1.2×10^{-7}		62
H	vinyl chloride- vinyl acetate copolymer "Vinyon"	7.6×10^{-8}	----	63
H	polyamide "Nylon 6"	5.0×10^{-9}	----	57
H	polyamide "Nylon 11"	1.5×10^{-8}	----	57
H	polyethylene	8.9×10^{-8}	high resistance	57
H	low and medium density	7.4×10^{-7}	to radiation	62
T	branched	8.7×10^{-8}	1×10^8 rad maximum	63

Table 3.2, Continued

Permeability of Plastic Films to Hydrogen and Its Isotopes[a,b]

Isotope	Material	298°K	Comments	Reference
H	cellulose acetate	8.4×10^{-8}	----	63
H		3.8×10^{-8}	----	57
H	regenerated cellulose-cellophane	1×10^{-10}	----	57
H	FEP fluoroplastic	1×10^{-7}	low resistance to radiation	57
H	poly(trifluorochloroethylene)	1.5×10^{-8}	resistance to radiation 1×10^{7} rad maximum	57
H	polyvinyl fluoride	2.6×10^{-9}	low resistance to radiation	57
H	polycarbonate "Lexan"	7.3×10^{-8}	resistance to radiation 1×10^{8} rad maximum	57
H	polystyrene	6.9×10^{-7}	high resistance to radiation 5×10^{9} rad maximum	63
H	polysulfone	8.2×10^{-8}	----	57
H	polypropylene	9.1×10^{-11}	biaxially oriented	57
		7.8×10^{-8}	resistance to radiation 10^{7} to 10^{9} rad	57

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[a] P value is in $cc(STP) \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot atm^{-1}$.

[b] Names in quotation marks are registered trademarks illustrative of polymer type. No endorsement is implied or intended.

Table 3.3

Permeability of Elastomeric Films to Hydrogen and Its Isotopes[a,b]

Isotope	Tradename	P at 298°K	Reference
H	polyisoprene	3.5×10^{-7}	56
H	natural rubber	3.9×10^{-7}	64
D		3.0×10^{-7}	56
T		2.6×10^{-7}	56
D	butadiene-acrylonitrile	5.6×10^{-8}	56
D	copolymer	9.8×10^{-7}	56
T	"Buna N"	4.4×10^{-8}	56
H	styrene-butadiene copolymer "Buna S"	3.2×10^{-7}	61
H	isoprene-isobutylene copolymer butyl rubber	5.9×10^{-8}	61
H	polychloroprene "Neoprene"	1.0×10^{-7}	61
T	filled	3.9×10^{-9}	62
H	silicone rubber	4.9×10^{-6}	63

[a] P value is in $\mathrm{cc(STP) \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot atm^{-1}}$.

[b] Names in quotation marks are registered trademarks illustrative of polymer type. No endorsement is implied or intended.

Table 3.4

Permeability of Glasses to Deuterium[a]

Material	P at 298°K	P at 373°K	P at 473°K	Reference
Borosilicate	10^{-13}	10^{-12}	10^{-11}	65
Fused quartz	3.7×10^{-13}	3.7×10^{-12}	10^{-10}	66

[a] P value is in $\mathrm{cc(STP) \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot atm^{-1}}$.

under conditions quite unlike those that will be encountered in tritium waste disposal.

Oxides have been proposed as permeation barriers,(12) but their properties depend critically on the substrate, conditions of growth, and utilization environment.(13) Anomalous permeation behavior is often observed, e.g., a nonlinear permeability decrease with increasing thickness (often attributed to cracks induced by thermal stresses) or increasing permeability as a function of time due to oxide reduction. Thick oxides generally exhibit energies of activation similar to substrates, while thin oxides have higher activation energies for permeation.

The mechanism by which the presence of an oxide film on metal, either naturally-occurring or enhanced, affects permeability has been studied.(14) It is believed that hydrogen molecules are prevented from dissociating at the surface, and thus cannot dissolve as atoms. Permeation, therefore, involves molecular hydrogen permeation through defects in the material. Roehrig and Blumensaat(15) followed a model analagous to Kirchhoff's laws for electric current in describing the permeation flux through the oxide film and afterwards the metal, i.e., the connection of a linear and non-linear permeation resistance in series.

Stickney(3) summarized work done up to 1972. Some of the salient points were the following. Hydrogen permeation through type 430 stainless steel was reduced about 100-fold at 650°C by "calorizing" the surface, i.e., treating it with aluminum. A calorized coating is said to consist mainly of an aluminum-iron intermetallic compound with a surface film of aluminium oxide. Calorizing type 347 stainless steel had about the same effect on permeability as with type 430. The measurement in that case was made at 860°C. Thermacore(4) reportedly reduced tritium permeation by five to six orders of magnitude on 2 mm thick stainless steel (processed in-situ at 500°C). However, this layer is easily damaged and needs maintenance at high temperature to remain useful. A nickel-aluminide coating on 304 SS, processed at temperatures in excess of 800°C has been detailed by McGuire.(16)

Glass coatings of various types have been applied to stainless steels, with subsequent permeability reductions of up to 200 fold. McGuire(16) has recommended a phosphate glass external coating on austenitic SS operated in excess of 550°C in fission and fusion reactors. Liquid phosphoric acid, applied to exterior surfaces, is fired in place at 350°C (e.g., by the heat of the reactor). Exposed to air, this surface becomes glassy. Again, susceptibility to damage is high.

Several stainless steel tests including 347, 304, 316, and 410, were oxidized by exposure to a mixture of hydrogen and steam at 1000°C. The treatment reduced their permeability by about two orders of magnitude. Type 321 steel did not respond the same way, its permeability not being influenced significantly by the treatment.

Another summary, which includes more recent results, was given in a paper by Bell and Redman(17) in 1979. This is shown in Table 3.5. It is to be

Table 3.5

The Effects of Oxidation to Form Oxide Layers and to Reduce Hydrogen Permeation Rates[a]

Alloy	Temp. °C	Oxidant	Time	Permeation Impedance Factor[b]
Incoloy 800	660	0.32 atm H_2O	150 days	167
Incoloy 800	660	0.70 atm H_2O	150 days	178
Incoloy 800	660	0.94 atm H_2O	150 days	419
Incoloy 800	660	0.94 atm H_2O	150 days	319
Incoloy 800	520	0.94 atm H_2O	150 days	41
Incoloy 800	725	0.94 atm H_2O	150 days	148
Vanadium	350-700	10^{-5} torr[c]	62 days	>100 to <1000
446 SS	1038	air	d	1000
Fe-Cr-Al	1093	air	1 day	1000
Incoloy 800	800	e	83 days	100-1000
21-6-9 SS	500-400	HNO_3	f	100-1000

[a] Reference 17.

[b] The permeation impedence factor is that by which permeation rates are reduced.

[c] Residual H_2O and O_2.

[d] Preoxidized for non-disclosed time.

[e] A process gas of 43.5% H_2, 35% H_2O, 8.9% CH_4, 6.9% CO, and 5.7% CO_2.

[f] Samples apparently pickled in HNO_3 bath for few minutes.

noted that the Incoloy data refer to experiments in which the downstream side of the metal B membrane was being continuously oxidized by high-temperature steam, while tritium diffused through thereby reducing the permeation by increasing the energy of activation for entry. The conditions are thus rather remote from those of our present concern. The data on the other materials refer to high-temperature permeation experiments.

More pertinent results were reported by W. A. Swansiger, et al.(18) who used deuterium and tritium to compare the permeability of two stainless steels with and without oxide layers. For each steel, a clean surface was carefully prepared and protected against oxidation with a palladium coating; while a comparable sample, without palladium was lightly oxidized by treatment with nitric acid and "Nitradd."* The steels chosen were 21 Cr-6Ni-9Mn, modified A-286, and 309S. For the first of these, permeation data were obtained over the temperature range 95°C to 430°C, and an Arrhenius expression was obtained from which the values presented in Table 3.6 were derived. It will be seen that the room temperature difference between oxidized and clean samples

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*Nitradd is a chemical cleaner produced by Turco Products, Wilmington, CA.

amounts to four orders of magnitude. Less extensive data were obtained on the other two steels which showed very similar behavior to the 21-6-9.

Table 3.6

Permeability of Coated Steel to Tritium[a]

Treatment	T°C	P cm^3 (STP)
21 Cr-6Ni-9Mn steel, Pd-coated	25	2.7×10^{-14}
	100	5.7×10^{-12}
	200	5.1×10^{-10}
21 Cr-6Ni-9Mn steel, treated with nitric acid and "Nitradd"	25	4.7×10^{-18}
	100	1.9×10^{-14}
	200	2.1×10^{-11}

[a] Reference 27.

Tison(19) reported that a stainless steel (Z2CN18-10) with an oxide coat of about 2000 Å had, below 200°C, a permeability too low to measure in his appartus, i.e.; below 10^{-11} cc(STP)·cm·cm^{-2}·s^{-1}·atm$^{-1/2}$.

Part of aluminum's high resistance to permeation is due to the thin oxide film that is naturally present unless special precautions have been taken. Louthan, Caskey, and Dexter(20) circumvented its effect at least partially, by conducting deuterium permeation experiments in which the upstream side of the sample was in contact with lithium deuteride. This presumably gave results that were nearly a measure of the bulk permeability of aluminum. The permeabilities were in fact over an order of magnitude greater than in the absence of lithium deuteride.

Strehlow and Savage(9) oxidized 405 stainless steel and found that its permeability to hydrogen was thereby reduced several hundred fold. Similar reductions were found with Incoloy 800. The effectiveness of the oxide depended on the conditions of its formation, and so did the way in which permeability depended on hydrogen pressure. With defect-free oxide films, dependence was on the first power rather than on the square root of the pressure, indicative of molecular diffusion.

Oxidation also had a beneficial effect on a 430 type stainless steel which contained 2 weight percent aluminum. Van Deventer, et al.(21) found that its permeability was 1/30 that of ordinary 430; and that after oxidizing at 730°C, it was further reduced by a factor of nearly 150. The same authors sputter-coated a 321 stainless steel with layers of aluminum and/or Al_2O_3, but found relatively disappointing permeability reductions of the order of 10 to 30 fold.

McGuire(22) reported that 304 SS oxidized for 200 hours at 750°C had a twenty-fold more reduction in permeation rate than one oxidized for 750 hours at 550°C. The 750°C film had a high concentration of manganese and chromium oxides located within 200 Å of surface.

3.4 Isotope Effects

It was stated above that tritium and normal hydrogen (protium) permeabilities show only a small difference. It arises from the combined effect of differences in solubility and in diffusion coefficient, neither of which is large. In general, so large an uncertainty is attached to permeability measurements (because of difficulty in attaining exact reproducibility of conditions) that isotope effects introduce negligible perturbations. Measurements made with one isotope can be taken as valid for another. A few examples of experimental comparisons will illustrate the point.

Bell and Redman(23) found that for nickel at 500°C the protium-tritium permeability ratio is 1.55. Data obtained over a range of temperatures indicated that the ratio fell to unity at room temperature, and approached the square root of the ratio of the atomic masses, i.e., 1.73 at high temperatures. Tritium permeabilities on aluminum that agreed "reasonably well" with protium data were reported by Ihle.(24) Louthan, Caskey, and Dexter(25) found that deuterium and tritium permeabilities in commercial aluminum alloys in the range 200-400°K conformed to the $\sqrt{m_D/m_T}$ relationship, while Louthan, Derrick, Donovan, and Caskey(25) found the same relation among the permeabilities of protium, deuterium, and tritium in pure iron in the range, room temperature to 253°C.

The same relation between tritium and deuterium in type 304L stainless steel was reported by Louthan, Donovan, and Caskey.(26) Swansinger(27) measured deuterium and tritium permeabilities on a palladium-coated 21-6-9 stainless steel, and found the ratios 1.65 at 25°C and 2.29 at 200°C. Tison, et al.(19) obtained deuterium and protium permeabilities on three steels over a range of temperatures. Typical ratio values, at 200°C, were 1.14, 1.26, and 1.55. Stickney(3) quotes British results in which tritium permeability in stainless steels was three- to four-fold slower than that of hydrogen. Quick and Johnson(28) found a permeability ratio of 1.44 for protium to deuterium in 310 stainless steel - a value very close to the square root of the mass ratio, 1.73.

In conclusion, tritium permeabilities are never greater than those of normal hydrogen; they may however, be smaller by a factor of two.

3.5 Embrittlement by Hydrogen and/or Helium

Gove and Charles(1) determined the rate of uptake of hydrogen (not necessarily all of which difffuses out), in the temperature range 50 to 400°C for a chromium-molybdenum steel of the type typically employed for hydrogen storage cylinders. Embrittlement occurred when hydrogen solubility in the carbon steel exceeded 2 mL per 100 grams. At a pressure of 11 atmospheres and 50°C, the hydrogen concentration approached 0.15 mL/100 g. At 140°C, the concentration approached was 0.4 mL/100g. Walker and Chandler(29) performed threshold stress intensity measurements on aluminium, 321 SS, and a Mn-Mo-Ni SS (ASTM A-533-B for welded pressure vessels). At ambient temperatures, there was no reduction in monitored mechanical properties below 100 atm.

Although there does not appear to be a potential problem with hydrogen embrittlement of the waste containers (because of the low anticipated tritium pressures involved), there may well be a problem with embrittlement of certain metals by the helium daughter produced from tritium decay within the metallic lattice.

Aluminum is generally considered to be immune to embrittlement by hydrogen or helium, but it can occur if enough gas is absorbed.(20) Farrell and Houston(30) reported that in the presence of radiation-induced damage and a gas content in aluminum of 2200 appm (ppm on an atomic basis) helium and tritium, severe loss of mechanical properties occurred.

The effect of hydrogen on the mechanical properties of stainless steels has usually been considered to be independent of isotope type. However, analysis of long-term exposure to tritium is complicated by the fact that it decays to helium. Some earlier studies(26,31,32) concluded that degradation of mechanical properties due to the presence of helium in austenitic stainless steel (maximum concentration 50 appm helium) occurred only after high temperature annealing caused helium bubble formation.

Louthan, et al.(20,32) on the basis of short-term simulation of long-term tritium decay effects concluded that helium had little effect on the mechanical properties studied of 304L and 309S stainless steels exposed to more than one atmosphere at 27°C for 25-50 years.

More recent experimentation has revealed a potential concern for helium embrittlement in tritium-processing equipment or CTR (controlled thermonuclear reactor) inner ("first") walls.(33) Austenitic stainless steel samples thermally charged with hydrogen and tritium revealed little difference in mechanical properties (usually tested are loss of ductility and yield strength change) when testing was conducted immediately after charging. However, dramatic differences were noted in aged specimens, which exhibited time dependent ductility losses. No evidence was provided that bubble formation was required to cause degradation. Additionally, evidence(34) for ambient temperature helium degradation (280 appm ^{3}He) in 304 L and 21-6-9 stainless steels tested 66 months after charging with tritium was presented when dramatic changes in both ductility and fracture mode were noted. Even if the concern is real in the area of high-temperature reactor technology, it may not be of importance in waste containerization. And, in fact, the magnitude of a problem in a container could probably be mitigated by changes in design, e.g., thickness, use of a protective liner, different metal, etc.

Thomas and Sisson(35) found that below 900°K, more than 99% of introduced helium is retained in the sample, regardless of heat treatment conditions. Initially, the tensile specimens of 304 L and 21-6-9 SS were charged (500 appm ^{3}He) at 354°C for 17 months under 47 mPa and subsequently stored for 66 months at 270°K. The total room temperature exposure after aging was approximately 7 months. Surprisingly, the fraction of ^{3}He released varied inversely with the ^{3}He content. Similar experiments(36) on tritium-soaked samples of a variety of metals indicated that over 90% of the helium atoms generated during low-temperature storage were retained in the solid during subsequent thermal desorption.

Donovan(37) has reported that helium, produced by tritium decay, affects the strength and ductility of 304L, 309, and 21-6-9SS. In general, the effects are very temperature dependent. These stainless steels fail after high temperature annealing by intergranular fracture due to helium bubble formation on grain boundaries. However, high temperature annealing was not necessary to cause helium embrittlement. Helium charged 21-6-9SS was severely embrittled and failed intergranularly at room temperature. The probable reason given was that tritium was trapped at microstructural features and that decay caused high localized concentrations and subsequent embrittlement.

Calculations have been performed(38) to determine ^{3}He concentrations after 100 years of tritium containment (at 10 atm and 348 °K) in 9.5 mm thick 304L and 309S SS vessels. At the inner surface, ^{3}He may be as much as 1900 appm (approximately 6.0 cc(STP) He/cc iron).

Bisson and Wilson(39) have given the following explanation for the deleterious effects of small amounts of helium trapped in a metal. (Helium is normally not that soluble in a metal, but tritium is and decays to helium). Helium trapped in a face-centered cubic lattice has a high binding energy for other helium atoms. Continual trapping of helium atoms by previously trapped helium atoms is energetically favored. The energy of the decay of tritium is insufficient to disrupt the crystal lattice of the metal. Although the helium does not have sufficient energy to recoil a substantial distance, it will subsequently migrate or diffuse through the metal via thermally-induced forces until it meets another helium atom. Five helium interstitials clustered together will spontaneously drive a metal atom off its lattice site creating a self-interstitial and a vacancy containing the five helium atoms. Also, beta particles from those tritium atoms which decay near the surface of a metal will provide a reducing atmosphere, which will tend to react to some extent with any protective oxide layer, increasing uptake of additional tritium.

Based on loss of ductility (measured as reduction in % elongation) at 700°C, the alloy most resistant to helium embrittlement from a choice of 304, 304L, 316, 316L, and 316H stainless steels is 316H (H = high carbon).(40) Compared to 316 SS, both (316+Ti) and 12R72 retained more uniform and total elongation in the presence of helium. Nickel-based alloys all suffered reductions in uniform and total elongation due to helium. Alloy TZM was the only alloy not adversely affected by helium. Generally, high ductility comes at the expense of yield strength. In terms of waste containerization, ductility may not be of prime importance.

3.6 Practical Significance of Permeation Rates

It is of interest to examine the significance of some of the tabulated permeabilities in terms of loss of tritium from a 210-L drum, having an inside surface area of 2.0×10^4 cm^2. Let us imagine it has a 1/4 in-thick wall, and contains pure tritium gas at 1 atmosphere, how may curies will escape in a year? If $P = 10^{-13}.cc(STP).cm.cm^{-2}.s^{-1}.atm^{-1/2}$ (or, by the conversion shown in Table 3.1, $P = 10^{-4}$ L(STP)·0.25 in./ 20,000 cm^2/yr/atm), and since 1 L of tritium at STP contains 2.6×10^3 Ci, a simple multiplication gives the loss through the drum as 0.26 Ci. Considering that 210 L of tritium at STP would contain a total of 5.45×10^5 Ci, this represents a fractional loss of 4.8×10^{-7}. Table 3.1 shows a wide range of permeability values, larger and smaller than the middle-case calculation discussed here. Since many common materials are available with permeabilities suitable for a tritium waste container, additional criteria will be of more importance.

3.7 Summary

There are common metals such as alloyed aluminum and some austenitic stainless steels which are sufficiently impermeable to hydrogen and its isotopes to be used in containerization of tritium gas. Further reductions in permeability can be achieved by polishing the contacted surface. Laminated materials and permeation-resistant coatings may also lower permeability but at the same time may threaten container integrity because they are susceptible to mechanical and thermal shock. Tritium decay to helium inside the metallic lattice may lead to embrittlement of the container wall.

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4. CONTAINER OPTIONS

4.1 Existing Container Designs

Containers designed specifically for gaseous or liquid tritiated wastes have been proven successful during short-term testing and use.(1-8) The design of two of the packages currently being implemented are summarized in several of the following sections.

4.1.1 Monsanto Mound Laboratories Package for Tritiated Liquid Wastes(2,7)

Tritiated water and vacuum pump oil are packaged in a similar way. Twenty-seven liters of waste water, containing approximately 1000 Ci/L, is poured onto a cement-plaster mixture in a polyethylene drum. In the case of vacuum pump oil, 25 L, containing approximately 50 Ci/L, is poured onto vermiculite in a polyethylene drum. The 27-L liner is placed inside a 30-gallon metal drum centered inside a 55-gallon drum containing 4 gallons of asphalt (see Figure 4.1). Vermiculite or Absorbal is then poured between the two drums to a level approximately 2 inches below the top of the 30-gallon drum lid. The remaining void volume is filled with more asphalt, and the 55-gallon drum lid is sealed with Silicone RTV and a bolted clamp ring. A similar procedure is followed for octane, containing 2 to 6 kCi per package, except that vermiculite-adsorbed octane in three polyethylene bottles replaces the 27-gallon polyethylene liner and the 30-gallon metal drum. The bottles are similarly placed into a 55-gallon drum and then placed within a 85-gallon drum. All voids are filled with vermiculite and asphalt.

From the liquid waste packages, the total fractional release of tritium was 10^{-5} after 8 years. A linear plot of time versus total permeation in mCi showed a constant permeation rate. The higher the curie value for the drum contents, the higher was the permeation rate (slope). An extrapolated value for 100 years amounted to a loss of less than 3 Ci. Maximum tritium release in a storage time of seven half-lives of tritium (approximately 85 years) would be about 0.002% of the total tritium contained in the packages. These estimates do not include the release of tritium in the form of gas or generated tritiated gases.

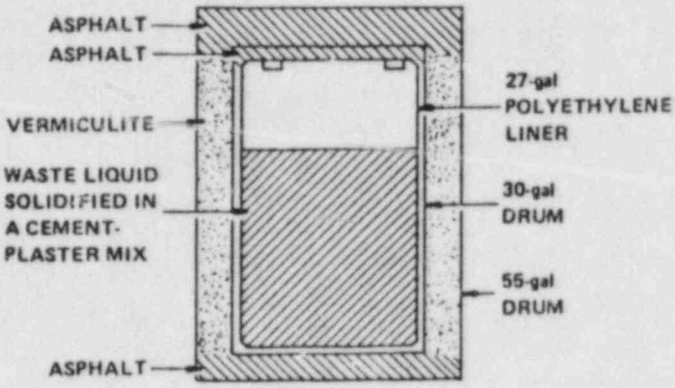

Figure 4.1 Schematic of tritiated waste package.(2)

4.1.2 DuPont Savannah River Laboratory Shipping Container for Tritium(4,5)

A maximum amount of 32.6 kCi of molecular tritium can be shipped from the Savannah River Laboratory under a maximum pressure of 20.2 psia at 25°C in a 12-L, 1.57 mm thick 347 SS primary vessel, encased within a flanged cast aluminum alloy secondary vessel (flat-or dome-topped), and surrounded by 9.9 cm thick Mil-F-26862-A Type II insulation in a 30-gallon carbon steel shipping container (18.25 in. I.D. x 26.99 in. I.H.) See Figure 4.2 for the LP-12 outer container specifications. The design of the LP-50 shipping container is similar to that of the LP-12 but uses a 60-gallon outer drum.

At 78°C, the permeation rate through the primary vessel at 14.7 psia is 7.6×10^{-6} cc(STP)·s^{-1}. Calculations show that it should take 216 days to reach this equilibrium rate. At 37°C, the time required for the permeation rate to reach an equilibrium value of 7.6×10^{-7} cc(STP)·s^{-1} is calculated to be 28 years. Loss through the container valve is reported to be less than 10^{-8} atm·cc(STP)·s^{-1}.

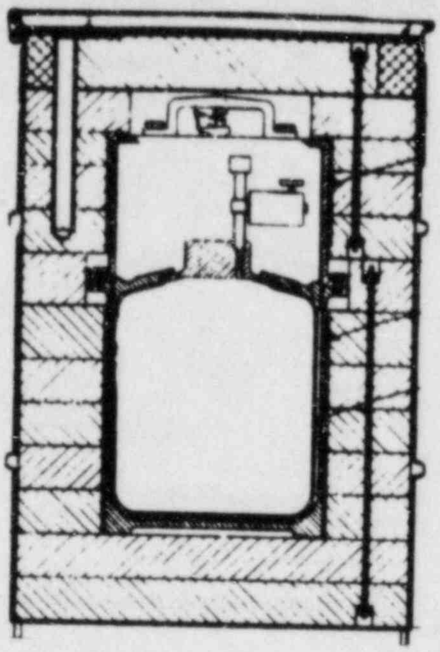

Figure 4.2 Specification for DuPont Outer Shipping Container for LP-12 Tritium Package.(5) (Specifications for inner containers are described in detail in Ref. 5).

Outer Shipping Container LP-12 Specification

Drum, Carbon Steel per Military Standard MS24209-2 With the Following Exceptions:

1. Body and cover to be 0.048 inch thick (18 gauge) material.
2. Inside height to be 26.99 + 0.12 inches.
3. Three 5/16 inch-diameter holes drilled one inch below top of curl of body approximately 120°C apart. Each hole to be covered on both sides with lead tape of minimum thickness of 0.005 inch. Bonding of tape to be resistant to sun and water.
4. Locking ring to have drop forged lugs. Lugs to be drilled with good alignment for 3/8 inch bolt. Lugs to be drilled 1/8 inch diameter, approximately 3/8 inch above edge of bolt holes for seal wires. Length of locking ring to allow 1/2 minimum to 3/4 maximum end separation when completely closed without gasket.
5. Locking bolt and nut to be 3/8 - 16 unc hex zinc or cadmium plated. Bolt 4 inches long and threads 2-1/4 inches long minimum. Material ASTM A325 or equal with hardness 23-35 RC.
6. No gasket allowed.
7. Paint body, over, and locking ring as follows:
    a. All surfaces must be clean and free of rust, oil, and other foreign material. (Sandblasting may be required for rusted material.)
    b. Primer-apply one caot Sherwin-Williams "Kromik" metal primer #E41N1. (May be applied over shop primer.) Thickness 1.5 mils or 300 sq ft/gal. Dry 18 hours.
    c. Finish coats-apply two coats Shewin Williams "Kem-Lustral" (KL) enamel mixed to match Federal Standard 595 color chip number 34-087.* Thickness 2 mils/coat or 250 sq ft/gal/coat. Minimum recoat drying time-16 hours. Minimum drying time for handling-24 hours.

*Approximate mixing proportions are below:

Sherwin-Williams Number	Percent Volume
F65B2	40
F65Y2	20
D64T1	30
F65W3	10

8. Containers to be received from vendor assembled.

4.2 Proposed Packaging of Tritiated Waste

The need for long-term containment of mixed tritiated wastes has resulted in the generation of data bases presented in the previous sections of this report. Many designs for a tritiated waste package from the utilization of this data are possible.

Based on our evaluations with respect to corrosion in soil, burst strength, permeability and hydrogen/helium embrittlement, conservative choices for candidate metals would include an alloyed aluminum primary container and a copper or austenitic stainless steel overpack.

4.2.1 Aluminum Primary Containment Vessel

Alloyed aluminum appears to be a good choice for the primary containment vessel on the basis of hydrogen permeation data and resistance to embrittlement by hydrogen or helium.

Compensation has to be made for the much lower burst strength of aluminum as compared to stainless steel and copper. The dimensions and design of the aluminum containment vessel can be varied to increase the allowable internal pressure, using standard formulas derived from pressure vessel technology.(9,10)

The thickness of the aluminum cylindrical shell, and its top and bottom will vary depending on the maximum allowable stress of the alloy chosen, on the head type chosen (e.g., flat circular, hemispherical, or ellipsoidal), and on any allowance made for corrosion. Based on an arbitrarily set limit. i.e., a hydrogen permeation rate of 7×10^{-8} atm·cc(STP)·s^{-1},(5) and assuming a permeability value of 1.4×10^{-15} (from Table 3.1) for aluminum and its alloys at 100°C, the thickness required for a 210-L aluminum vessel (at a pressure of 50 psig) is calculated to be 0.01 mm. If a more realistic thickness for a pressure vessel is assumed, i.e., 6.35 mm, the calculated permeation rate is 3.1×10^{-10} atm cc(STP)·s^{-1}. Thickness suggested on the basis of permeability alone is insufficient with regards to an allowable internal pressure of 50 psig and a corrosion allowance of 0.125 in.

The aluminum flanged vessel (11-1/32 in. x 9-5/8 in. I.D.) described as part of the LP-12 package was constructed of 356-T51 Al/Si/Cu/Mg alloy. The shell wall, top, and bottom were 0.188 in., 0.25 in., and 0.31 in. thick, respectively. The maximum allowable pressure calculated for the top and bottom heads was 69 psig.(6) using a maximum allowable bolt stress value of 20,000 psi.(9) The maximum allowable pressure calculated for the shell was 195 psig, using a maximum allowable stress (S) value at 70°C of 6200 psi for a 356-T71* alloy.(9) Upon substitution into the same equations values of 22 in. for the outside diameter of the aluminum cylindrical shell and 50 psig as maximum allowable pressure, the following thickness values were obtained:

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*The T designates method of heat treatment. 356-T71 is equivalent to ASME SB-26 and ASTM SG-70-A.

thickness of shell, 0.105 in.; thickness of bottom, 1.08 in.; thickness of top, 0.88 in. With a corrosion allowance of approximately 0.125 in., the minimum shell thickness is calculated to be 0.25 in. It should be noted that 356-T51 is readily weldable,(11,12) an important consideration(13) in hydrogen pressure vessel construction.[*]

4.2.2 Stainless Steel or Copper Overpack

The proposed use of 304 and 316 stainless steel and copper as overpack materials was made on the basis of their corrosion resistance in soils (Section 1) and on their burst strength (Section 2). On the basis of weld integrity and corrosion resistance, 304 L and 316 L stainless steels would be superior to 304 and 316 stainless steels due to reduced sensitization, while maintaining the same level of resistance to soil corrosion. Copper is usually joined by methods other than welding.

The lifetime of a copper overpack can be estimated based on a linear extrapolation of its maximum pitting rate. Estimation of the lifetime of a stainless steel overpack, however, is problematical in that currently available data does not support a simple linear extrapolation of maximum pitting. Field testing of 316 stainless steel showed no evidence of pitting after 14 years of burial. Additional long-term field testing would be required to determine maximum pitting rate.

Field tests in tidal marsh soil conducted at Charleston, South Carolina constitute conservative estimates in comparison with predicted lifetimes at drier sites, such as Beatty, Nevada or Hanford, Washington. It is assumed that the maximum pit penetration rate is constant. See Table 4.1.

The cost of a 1/4"-thick 304 L stainless steel 55-gallon capacity "drum" is estimated at approximately \$500; for 316L approximately \$900. A copper container of the same design is estimated at approximately \$1000, and the cost of the inner aluminum can is estimated at approximately \$300.[**] The cost estimates assume that the capability of the fabrication houses is present obviating the need for custom or "hand-built" construction. In most instances the capability of manufacturers is typically 16 gauge and occasionally 12 gauge which is substantially thinner than over 1/4" specification. Custom made drums may raise the total cost by a factor of five. The cost estimates do not take into account certification testing which could substantially increase the final cost of the product.

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[*] Pressure vessel is defined as one operated above 15 psig.

[**] These are 1981 cost estimates.

Table 4.1

Expected Lifetime for 0.25 in. Thick Copper and 0.25 in. Stainless Steel Plates in Tidal Marsh Soil

	Metals	Expected Lifetime
Copper[a]	deoxidized	350 yrs.
	tough pitch	250 yrs.
Stainless[b] Steel	AISI 304[c]	250 yrs.

[a] Estimates are based on NBS data shown in Table 1.11, at test site 63.

[b] Estimates are based on data shown in Table 1.6 at test site 63.

[c] Sensitized AISI 304 in Sagemoor sandy loam soil showed severe non-uniform attack, as seen in Table 1.9.

4.3 Reduction of Internal Corrosion

Assuming that the metal containment vessel, in our example, aluminum, may be in contact with all of the following: gaseous tritium, water, organic solvents, (aromatic and/or aliphatic), and any possible radiolytically- or microbially-generated products, a coating or liner that is chemically resistant, e.g., polypropylene, might be added to the waste package. Some cast aluminum alloys are customarily sealed by impregnation with polyester resin to reduce porosity.(14) (See Tables 4.2 and 4.3.)

Table 4.2

Substances Corrosive to Aluminum[a]

Acid, hydrochloric, 1 N, 2 N
Acid, nitric, 2-5%
Acid, nitric fuming
Acid, phosphoric, 20-80%
Acid, sulfuric, conc.
Acid, sulfurous
Acids
Acid, anhydrous
Acid, (2-75%)
Alkaline solutions (mild)
Alkaline solutions, e.g., sodium carbonate
Alkaline, soda solutions
Alkalies
Allyl alcohol
Allyl chloride
Allylamine
Ammonia, condensing steam
Amyl chloride
Barium hydroxide
Brines
Bromine water
Bromoform
Calcium chloride, saturated
Carbon tetrachloride
Chloramine-T
Chlorinated aromatics
Chlorine water
Chloroform
Detergents
Ethanol
Ethyl formate
Ethylene glycol
Glycol-water, 30:70
Hydrogen peroxide
Hydrogen peroxide, alkaline
Iodoform
Javelle water
dl-Lactic acid; sarcolatic acid
Latex coagulation
Lead paint pigments or
Lead soaps
Magnesium oxychloride
Methanol
Methyl bromide
Methyl chloride
Methyl iodide
Polyalkene glycol fluids
Potassium carbonate
Potassium chloride
Potassium cyanide
Potassium sulfide
Seawater
Soap, alkaline
Sodium acetate, solid or solu.
Sodium carbonate, solid
Sodium carbonate, 1-10%
Sodium chloride, 3.5%
Sodium cyanide
Sodium hydroxide, 1-4%
Sodium hydroxide 0.3 N - 0.5 N
Sodium hypochlorite contained in bleaches
Sodium phosphate, monobasic
Sodium phosphate, dibasic
Sodium phospate, tribasic
Sodium sulfide
Sodium trichloro acetate, 50%
Synthetic detergents
Trichloroethylene
Water, natural surface

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[a] Reference 15.

Table 4.3

Corrosives Which Induce Intergranular Corrosion in Austenitic Stainless Steel[a]

Acetic acid
Acetic acid + salicylic acid
Ammonium nitrate
Ammonium sulfate
Ammonium sulfate + sulfuric acid
Calcium nitrate
Chromic acid
Chromium chloride
Copper sulfate
Crude oil[b]
Fatty acids
Ferric chloride
Ferric sulfate
Formic acid
Hydrocyanic acid
Hydrocyanic acid + sulfur dioxide
Hydrofluoric acid + ferric sulfate
Lactic acid
Lactic acid + nitric acid
Maleic acid
Oxalic acid
Phenol + naphthenic acid
Phosphoric acid
Phthalic acid
Salt spray
Seawater
Silver nitrate + acetic acid
Sodium bisulfate
Sodium hydroxide + sodium sulfide
Sodium Hypochlorite
Sulfite cooking liquor
Sulfite solution
Sulfite digester acid (calcium bisulfite + sulfur dioxide)
Sulfamic acid
Sulfur dioxide (wet)
Sulfuric acid
Sulfuric acid + acetic acid
Sulfuric acid + copper sulfate
Sulfuric acid + ferrous sulfate
Sulfuric acid + methanol
Sulfuric acid + nitric acid
Sulfurous acid
Water + Starch + sulfur dioxide
Water + aluminum sulfate

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[a] Reference 15, p. 533.

[b] Petroleum contains sulfuric and some salt water brine.

4.3.1 Chemical-Resistant Coatings

Permeation-resistant coatings, such as in-situ formed chemical conversion coatings, oxides, and glasses (vitreous enamels), were discussed in Section 3. One disadvantage of these coatings (and of Portland cement-based ones) is the sensitivity to mechanical and thermal shock. The chemical-resistant coatings discussed here are assumed to be polymeric in origin. It should be noted that the use of any coating, without benefit of periodic inspection, must be evaluated for possible adverse effects.

The main function of a chemical-resistant coating, is to protect the substrate from corrosive gases and liquids. It may also serve other functions, such as radiation protection and/or impermeability. Polymeric coatings enable the use of a variety of structural materials, which otherwise on the basis of corrosion resistance would be unsuitable, e.g., carbon steel in an aqueous environment. In a number of cases, polymeric coatings are used for their own sake, since they afford protection from corrosion in media in which no other material can be employed. For example, epoxy coatings are used in hydrochloric acid solutions because stainless steel alone cannot be employed.(16) (See Appendices A and B).

The ability of a coating to fulfill its protective function will be dependent on all the properties of the coating, including its inertness and its impermeability to the corroding agent. The main factors which are responsible for the decompositon of a coating are the temperature and nature of the corrosive agent, temperature and pressure gradients, radiation and mechanical stresses. Particularly important is the coating method and quality of its adhesion to the substrate.

The failure of a coating is conventionally expressed as its service life. Published data on a coating's behavior in corrosive media may serve to identify clearly unsuitable coatings, but do not necessarily establish suitability for all purposes. For example, variables that can seriously undermine the protection afforded by a coating include the presence of pinholes because the coating is too thin; conditions of curing; additives to the coating; accelerated corrosion due to symbiotic relationship of a mixture of corrosive agents. Additionally, service life in published data is evaluated using different definitions for failure of a coating.

In estimating the service life of a coating, the chemical inertness of the base polymer often proves to be the determining factor. All aspects of a coatings' environment must be considered. For example, poly(vinyl butyral), laquer or baked enamel, is known for its impermeability to water but is dissolved in the presence of alcohol. Epoxies and silicones are also subject to some chemical action. Accelerated testing results will not insure that the coating will survive for the intended length of time; only a rough approximation of service life is obtained.

Often, especially if the coating thickness is to exceed 10 mils, a filler (e.g., fiberglass) is added. If too much filler is added, the CVPC (critical volume pigment concentration) is exceeded, permeability increases sharply and pinholes appear. Furthermore, if the coating is too thick, adhesion to the substrate is adversely affected.

Protective coatings can also reduce permeability. For example, although not directly related to a waste container, some silicone resins have been used as a protective coating for 2-mil thick cold-rolled steel sputter-coated (3 μ thick) with gold and tantalum to reduce hydrogen permeation.(17) The pure resins which can be used include Dow Corning 804, 805, 806A, 808, and 847; General Electric SR111, SR 112, SR53, SR82, SR119, SR124, and SR125; and Union Carbide Ucarsil 104. For thin films (less than 1 mil) SR53 and Ucarsil 104 were preferred, while for thicker films (1-3 mils) Dow Corning 808, General Electric SR 111, SR 112, SR 119, and SR125 were preferred. A plain gold coating decreased hydrogen permeation by a factor of 5, silicone resin alone by a factor of 6, and Au+Ta+resin by a factor of several thousand.

It has been reported that a particularly suitable organic protective material(17) is a silicone resin marketed in spray can form under the name of Vac-Seal(17) by Space Environment Labs of Boulder, Colorado. (A compilation(18) of similar polymerics, used in satellites mainly for their low outgassing characteristics is available. This list includes protective paints. Some of the materials need to be pre-heated before use).

4.3.2 Moisture Barriers

Lining materials are available for both internal and external use with waste packages. The permeabilities to water of some plastics are given in Table 4.4, which does not include values for elastomers.(19,20) In terms of internal aqueous corrosion, even in the absence of known significant amounts of water, certain oil-oxidizing bacteria may contain enough water to enable them to oxidize oil, resulting in the formation of enough water to keep them growing.(21) The minimum amount of water necessary for this to occur has not been determined.

External to the waste package, trench liner materials are used in shallow land burial.(22) Figure 4.3 depicts estimates of the service life and in-place cost (1976) for some moisture barriers. The average service life of these polymeric liners is predicted to be 25 years. Asphalt-coated vertical shafts augered in Bandlier tuff are used at LASL for disposal of tritiated wastes(22) Tritiated water vapor from these shafts was being released (0.3 to 0.6%) to the surrounding tuff. In 1976, special tritium waste packaging requirements were implemented, which specified various degrees of encapsulation in asphalt, using 210-L steel drums as a final container. These wastes were placed in a new disposal shaft and the leach rates ranged from 0.5 to 0.7%, indicating no improvement.

Most natural soils seem to contain enough moisture to satisfy the oxygenated water requirements of bacterial degradation, particularly of asphalt.(23,24) Among the synthetic liners known to have good resistance to soil microorganisms are CSPE(chlorosulfonated polyethylene), CPE (chlorinated polyethylene), and HDPE (high density polyethylene). PVC (polyvinyl chloride)

Table 4.4

Permeability of Polymers to Water[a,b]

Material	P
Poly(vinylidene chloride)	0.02
Poly(tetrafluoroethylene)	0.03
Fluorinated ethylene-propylene copolymer	0.04
Poly(ethylene)-high density (linear)	0.05
Poly(propylene)	0.10
Poly(trifluorochloroethylene)	0.10
Chlorinated polyether	0.10
Vinylidene chloride-vinyl chloride copolymer	0.15
Poly(ethylene)-low density (branched)	0.20
Poly(vinyl fluoride)	0.24
Tetrafluoroethylene-ethylene copolymer	0.24
Poly(vinylidene fluoride)	0.35
Poly(ethylene terephthalate)	0.50
Poly(vinyl chloride)-rigid	0.60
Ionomer resin	0.60
Nylon 12	0.70
Nylon 11	0.80
Poly(amide)	0.93
Ethylene-propylene rubber	1.00
Phenoxy	1.00
Epoxy/amine thermoset	1.20
Nylon 610	1.40
Methylpentene polymer	1.70
Nylon 69	2.50
Poly(butene)	2.50
Poly(butadiene) rubber	2.50
Poly(methylmethacrylate)-unmodified	3.30
Poly(methyl methacrylate)-modified	3.50
Poly(styrene)	4.20
Acrylonitrile-butadiene-styrene copolymer	4.20
Nylon 6	4.40
Nylon 66	5.00
Poly(carbonate)	5.00
Poly(sulfone)	5.10
Ethylene-vinyl acetate copolymer	5.10
Acrylonitrile-styrene copolymer	5.20
Poly(acetal)	6.60
Acrylonitrile-styrene copolymer	7.50
Nitrocellulose	25.0
Poly(vinyl acetate)	26.0
Poly(urethane)	30.0
Bitumen[c]	46.0
Cellulose acetate	70.0
Cellophane	130
Poly(vinyl alcohol)	1500

[a] Permeability is in g·mil·day^{-1}·100 sq. in.$^{-1}$. To convert to cc(STP)·cm·year^{-1}·area of 55-gallon drum, multiply P by 530.

[b] Reference 19.

[c] Reference 20, not polymeric.

generally has poor resistance to soil microorganisms, unless a biocide has been added during compounding.

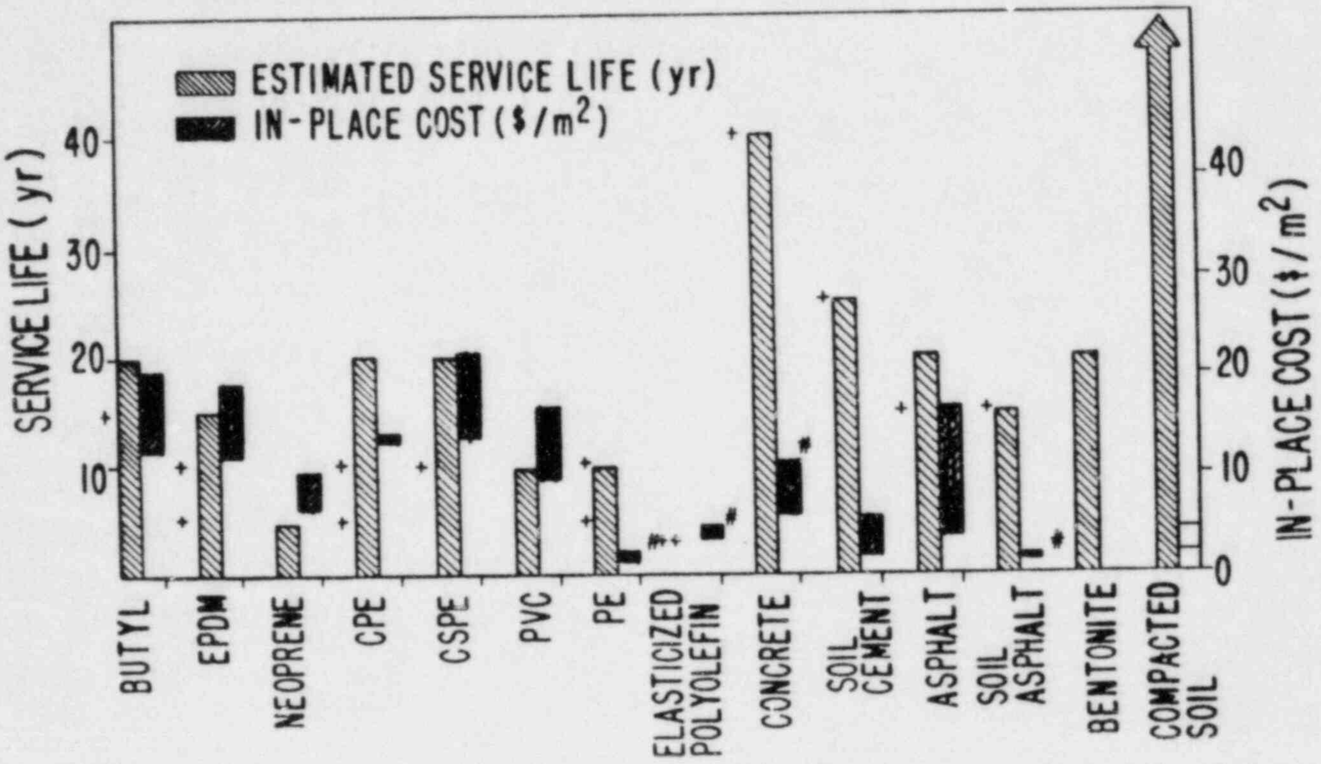

Figure 4.3 Comparison of expected service life as moisture barrier versus in-place cost (1976): (a) Ref. 22; (b) +, is the radwaste estimate; (c) ++, no estimate is available; (d) #, the cost does not include construction of subgrade or earth cover; (e) cost estimate includes excavation, installation, back-filling, compaction, and seeding (glacial till).

4.4 Summary

Some information about containers designed specifically for either tritium gas or tritiated liquid wastes is available in the literature. From corrosion data in Section 1 and from permeability data in Section 3, several tritiated waste packages, constructed of ordinary metals, are given as possible design utilizations of the data bases presented in the previous sections. Additionally, if significant internal chemical corrosion, aqueous or non-aqueous, is anticipated from the waste itself, many polymeric coatings are available as barriers to organic solvents, water, and, in some cases, to gaseous tritium. In lieu of coatings, whose satisfactory use is often dependent on periodic inspection which is not possible in a sealed container, polymeric internal liners may prove to be of benefit, providing they are not a threat to container integrity because of gas generation through radiolytic and biodegradative mechanisms. Of course, external moisture protection can be increased by use of these same materials as outer coatings and/or trench liners.

4.5 References

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5. SUMMARY AND CONCLUSIONS

Tritiated waste generated in the United States is mainly composed of tritium gas and tritium-contaminated organic solvents sorbed onto Speedi-Dri. Because of the lack of a solid waste form, it is important to develop packages for tritium wastes which will maintain their integrity for the period of containment. Since many common materials are available with permeabilities suitable for a tritium gas waste container, additional criteria, such as resistance to soil corrosion and burst strength are of more importance in the package design.

Based on results of field tests conducted by the National Bureau of Standards in soil groups corresponding to those of the waste disposal sites at Beatty, NV, Barnwell, SC, and Hanford, WA, the following metals were most resistant to soil corrosion: copper, 304 and 316 stainless steels with cathodic protection, and titanium. It is also noted that these containerized tritiated wastes should be segregated from other wastes in the trench because evidence exists that the corrosion chemistry of a particular disposal trench depends highly on the waste forms previously placed in the trench. An evaluation of the extension of container lifetime afforded by cement overpacking cannot be made at the present time due to a lack of existing experimental data.

For a maximum of 1000 Ci of tritium gas per container, the design pressure limits of a copper or stainless steel 6.35 mm-thick, 210-L overpack would not be exceeded. For a maximum of 20 Ci of activity per 210-L drum of tritium organic waste, no significant radiolytic gas generation is expected. In the case of gas generated by microbial degradation of tritium-contaminated organic waste, the maximum allowable carbon content per metal overpacked container was estimated to be in the range of 34 to 929 g for the pressure limits of interest, assuming a worst-case scenario. However, the total amount and rate of gas evolution from biodegradation and resulting pressure build-up over a period of 100 to 200 years of containment is unknown, due to lack of experimental data.

One possible design for high-integrity tritium waste container would consist of a cast alloyed aluminum primary containment vessel inside a copper or austenitic stainless steel overpack. Polymeric materials may be added to the package for internal or external corrosion protection.

APPENDIX A

CHEMICAL RESISTANCE OF RUBBER, RESIN, STEEL, ALUMINUM, LEAD, GLASS, AND CONCRETE LINING MATERIALS.(15)

Table A lists all those solvents denoted by a letter in Table B and should be referred to when indicated in the chemical listing. Always use the lowest temperature recommendation shown for either the chemical or the solvent.

Table B shows lining materials, chemicals, solvents, concentration and temperature limits for use. The lining materials are described across the top as column headings. The various rubber groups are listed in their approximate order of relative cost, with natural rubber being the lowest. The chemicals are listed on the left hand side. These tables contain not only the common names of the chemicals, but also any names which may be synonymous.

To the immediate right of the chemicals is a list of letters that denote the common solvents for the chemical. In some instances, a reference is given to "See Solvents." This indicates that the chemical is solid, insoluble in water. The chemical will be dissolved in a solution of one of the indicated solvents or a solvent characteristic of the application.

In the columns headed "Concentration," either the word "Any" or a percent concentration will appear. Any concentration refers to a water solution of a chemical from very weak to a saturation value. The percent concentration refers to a limiting ratio of chemical to water in weight percent. If the concentration is left blank, then generally that chemical will be used in its pure form and not in solution with any other compound.

The temperatures shown in the tables are for pure chemicals. The rows of figures to the extreme right of the chemicals, each in a column for a given lining material, indicate the maximum recommended temperature which will give satisfactory service with the tank lining. In some instances, a lining material will be given a rating of 75°F for a particular chemical. This indicates that the chemical was determined to be satisfactory at room temperature, has a possibility for use and could be tried at somewhat higher temperatures. A blank space in any material column indicates no available data.

Code: Unmarked chemicals are liquids at room temperature.
*Indicates a solid at room temperature.
** Indicates a gas at room temperature.
x Lining material not recommended.
- No information available.

Table A: Solvent Code

CHEMICAL RESISTANCE FOR LINING MATERIALS

Index	Solvent	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
a	Alcohol	Any	80	x	185	120	110	110	100	150	210	150	210	210	75
aa	Acetic Acid	Any	70	110	100	x	x	x	180	75	170	170	x	400	x
ac	Acetone		x	x	150	x	x	x	100	400	180	180	210	210	75
al	Aluminum Salt Solution	Any	150	185	150	200	180	150	100	x	90	75	75	160	x
am	Ammonia Salt Solution	Any	150	150	185	200	200	150	150	x	75	75	70	190	x
b	Benzene	Any	x	x	x	x	x	x	180	100	100	100	70	210	x
ba	Butyl Acetate	Any	x	x	x	x	x	-	x	70	70	75	70	180	x
cb	Carbon Bi (Di) Sulfide	Any	x	x	x	x	x	x	x	75	70	180	180	180	75
cl	Chloroform	Any	x	x	x	x	x	x	x	x	130	130	130	210	75
ct	Carbontetrachloride	Any	x	x	x	x	x	150	200	75	70	70	100	210	75
cy	Cyclohexanol	Any	x	x	x	x	x	-	-	70	70	x	70	75	-
dg	Diethylene Glycol	Any	150	185	180	180	180	150	-	130	170	100	70	180	x
di	Dioxane	Any	x	-	x	x	x	x	-	100	100	70	70	180	x
e	Ether	Any	x	-	x	x	110	x	x	70	70	70	70	130	75
ea	Ethyl Acetate	Any	x	-	100	x	x	x	75	75	100	130	70	210	x
ed	Ethylene Dichloride	Any	x	x	x	x	x	x	200	150	150	120	150	210	x
eg	Ethylene Glycol	Any	150	185	185	150	180	150	75	100	70	120	-	210	-
es	Esters	Any	x	-	80	x	x	x	75	75	100	90	70	140	x
fe	Ferric Salt Solutions		150	180	150	150	200	150	75	x	70	x	x	210	x
g	Gasoline	Any	x	-	x	x	100	100	75	170	70	170	170	170	-
gl	Glycerine	Any	150	-	150	150	180	x	75	110	150	200	70	210	x
h	Acid Solutions Except	Any	120	120	150	150	110	150	140	x	100	100	x	250	x
	Organic Acids	Any	80	80	100	70	80	120	110	x	130	100	x	230	x
	Hydrochloric (HCl)	38	150	185	x	x	x	80	150	x	x	x	x	210	x
	Sulfuric (H_2SO_4)	50	80	150	100	80	80	150	170	x	x	x	200	400	x
	Nitric (HNO_3)	25	x	-	75	x	x	115	120	x	175	x	x	400	x
hc	Hydrocarbons	Any	x	x	x	x	x	-	-	75	-	-	-	75	-
ho	Alkaline or Basic Solutions	Any	150	185	185	200	150	150	100	75	140	x	x	x	75
k	Kerosine	Any	x	-	x	x	150	150	-	170	70	170	170	170	-
ke	Ketones	Any	x	x	x	x	x	x	70	150	150	150	150	180	70
m	Methanol	Any	100	-	185	100	150	120	100	150	150	90	150	210	75
me	Monobutyl Ether	Any	x	x	80	x	110	-	x	70	90	90	70	110	-
mo	Mineral Oil	Any	x	-	x	x	150	150	-	110	70	170	110	170	-
n	Naptha	Any	x	x	x	x	x	x	70	70	70	70	-	75	x
o	Mineral Oils	Any	x	-	x	x	130	130	-	100	70	150	100	170	-
os	Organic Solvents	Any	x	x	x	x	x	x	75	100	130	75	75	130	75
pe	Petroleum Ether (Ligroin)	Any	x	x	x	x	x	-	-	110	110	110	-	140	-
ph	Petroleum Hydrocarbons	Any	x	x	x	x	x	-	-	100	100	100	-	130	-
py	Pyridine	Any	x	-	100	x	x	-	70	125	100	100	100	210	75
t	Toluene	Any	x	x	x	x	x	70	150	150	150	150	150	150	-
ta	Tartaric Acid	Any	150	185	185	100	150	150	75	x	150	70	x	175	75
tu	Turpentine	Any	x	x	x	x	150	x	75	70	70	70	70	210	x
vo	Vegetable Oil	Any	x	x	100	x	150	-	-	170	70	70	170	170	-
w	Water	Any	150	170	185	200	150	150	-	70	75	75	75	75	75
xy	Xylene	Any	x	x	x	x	x	70	x	150	150	75		75	x

Table B: Chemical Resistance for Lining Materials

The list of "Chemical Resistance of Lining Materials" shows recommended maximum temperatures for concentration as water solutions against the lining. For chemicals insoluble in water, 100% liquid is listed or a reference to solvents is given.

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Acetaldehyde	a, ac, b, e, g, n, t, tu, xy, w	Any	x	-	80	x	x	x	x	125	210	210	75	600	x
Acetic Acid	a, e, gl, w	10	150	150	150	150	x	x	220	75	180	180	x	400	x
		25	80	150	150	x	x	x	210	75	180	180	x	400	x
		50	x	120	80	x	x	x	180	75	180	180	x	400	x
Glacial		100	x	100	80	x	x	x	200	75	180	180	x	400	x
Acetic Aldehyde	a, ac, b, e, g, n, t, tu, xy, w	Any	x	-	80	x	x	x	x	125	210	210	75	600	x
Acetic Anhydride	a, e, w	25	x	120	150	x	x	x	80	170	180	70	-	210	x
		50	x	-	80	x	x	x	80	-	180	70	-	210	x
Acetic Ester	a, cl, e, w	Any	x	-	100	x	x	x	75	75	100	130	70	210	x
Acetic Ether	a, cl, e, w	Any	x	-	100	x	x	x	75	75	100	130	70	210	x
Acetic Oxide	a, e, w	25	x	120	150	x	x	x	-	170	180	70	-	210	x
		50	x	-	80	x	x	x	-	-	180	70	-	210	x
Acetone	a, cl, e, o, w	Any	x	x	150	x	x	x	100	400	180	180	210	210	75
Acetoacetic Ester	a, w	Any	80	-	80	x	x	x	-	75	170	75	-	75	-
Acetophenone	os, w	Any	x	-	80	x	x	x	-	200	350	150	150	175	-
Acetylbenzene	os, w	Any	x	-	80	x	x	x	-	200	350	150	150	175	-
Acetylene **	a, ac, w	Any	80	80	80	80	80	80	200	400	180	75	75	75	75
Acetylene Tetrabromide	a, e,	100	-	-	x	x	x	x	-	-	-	-	-	-	-
Acetylene Tetrachloride	a, e	100	-	-	x	x	x	x	75	75	-	x	75	75	-
Acetyl Oxide	a, e, w	25	x	120	150	x	x	x	-	170	180	70	-	210	x
		50	x	-	80	x	x	x	-	170	180	70	-	210	x
Acrylamide		150	-	120	-	-	-	-	-	-	-	-	-	-	-
Acrylonitrile	os, w	Any	80	80	x	x	x	-	x	-	-	-	-	-	-
Adipic Acid	w	Any	80	80	x	x	x	-	-	-	-	-	-	-	-
Agar-agar *	aa, gl, w	Any	150	185	185	180	180	150	200	x	70	175	-	-	-
Agricultural Lime *	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Air **		Any	150	185	185	200	200	150	-	-	-	-	-	-	-
Airshow		Any			x		70								
Air-slaked Lime *	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Alcohol	a, e, w	Any	80	x	185	120	110	110	100	150	210	150	210	210	75
Aldehyde	a, ac, b, e, g, n, t, tu, xy, w	Any	x	-	80	x	x	x	x	125	210	210	75	600	x
Algaroth Powder *	HCl	See Solvent													
Allyl Chloride	a, cl, e, pe	100	x	-	x	x	x	-	75	x	125	x	x	-	75
Allomaleic Acid *	a, w	Any	80	-	-	-	-	-	-	75	-	-	-	-	-
Alpha Chloropropylene	a, cl, e, pe	100	x	-	x	x	x	-	75	x	125	x	x	-	75
Alpha Chlorotoluene	a, e	100	x	-	x	x	x	-	x	x	100	x	100	210	x
Alpha Hydroxypropionic Acid	a, e, gl, w	50	120	-	150	80	80	130	100	x	70	70	x	200	x
Alpha Hydroxytoluene	a, cl, e, w	Any	x	-	185	x	x	-	-	75	100	100	100	210	x
Alum *		Any	150	185	185	200	200	150	210	x	200	110	-	170	-
Alumina Trihydrate* h, ho		See Solvents													
Aluminum Acetate Solution *	w	Any	150	185	120	120	120	-	75	x	150	75	75	210	x
Aluminum Ammonium Sulfate	gl, w	Any	150	185	150	120	120	-	-	x	180	-	-	-	-
Aluminum Bromide *	a, e, cl, w	Any	150	185	120	180	180	150	-	x	75	75	-	180	-
Aluminum Chloride *	a, e, w	Any	150	185	150	200	200	150	220	x	70	x	x	180	x
Aluminum Flouride *	w	Any	150	185	185	200	200	150	-	x	75	100	75	x	75
Aluminum Gel *	h, ho	See Solvent													
Aluminum Hydroxide *	h, ho	See Solvent													
Aluminum Nitrate *	a, ac, w	Any	150	185	185	200	200	150	75	x	75	100	-	100	x
Aluminum Potassium Sulfate *	w	Any	150	185	185	200	180	150	200	x	150	70	100	200	180
Aluminum Sodium Sulfate *	w	Any	150	185	185	200	200	150	200	x	200	x	75	75	-

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Aluminum Sulfate *	w	Any	150	185	185	200	200	150	200	x	180	x	100	200	x
American Ashes *	w	Any	150	185	180	200	180	150	150	100	180	x	x	180	75
Aminobenzene	a, b, e	100	x	x	75	x	x	150	x	70	70	100	75	210	75
Aminodimethylbenzene	a, e	100	x	-	100	x	x	x	-	-	-	-	-	100	-
Aminoethanol	a, cl, ct, w	Any	80	-	140	80	80	-	210	150	150	75	-	210	200
Aminoxylene	a, e	100	x	-	100	x	x	x	-	-	-	-	-	100	-
Ammonia Alum	gl, w	Any	150	185	120	120	120	150	-	x	180	-	-	-	-
Ammonia Water		38	150	150	185	200	200	150	200	75	200	75	100	210	75
Ammoniated Citric Acid		Any	150	185	185	150	110	150	-	-	-	-	-	-	-
Ammonium Bifluoride	a,w	10	x	x	x	x	80	100	70	x	x	-	x	x	-
Ammonium Carbonate *	w	Any	150	185	185	200	200	150	75	140	70	150	-	200	75
Ammonium Chloride *	a, gl, w	Any	150	185	185	200	200	150	200	x	100	x	x	210	x
Ammonium Fluoride		Any	80	x	150	100	100	80	180	x	x	x	70	x	x
Ammonium Hydrate		38	150	185	185	200	200	150	200	75	200	75	100	210	75
Ammonium Hydroxide		38	150	x	185	200	200	150	200	75	200	75	100	210	75
Ammonium Metaphosphate		Any	150	185	185	200	200	150	-	70	100	75	-	210	-
Ammonium Murate *	a, gl, w	Any	150	185	185	200	200	150	200	x	100	x	x	210	x
Ammonium Nitrate *	a, ho, w	Any	150	150	185	200	200	150	200	80	200	140	x	210	x
Ammonium Pers ate *	w	Any	150	185	185	200	200	150	180	x	70	x	70	210	-
Ammonium Phosphate *	w	Any	150	185	185	200	200	150	-	x	70	x	70	75	75
Ammonium Sulfate *	w	Any	150	185	185	200	200	150	200	x	150	x	70	210	x
Amyl Acetate	a, e	100	x	-	x	x	x	x	75	75	70	70	-	210	-
Amyl Alcohol	a, e, w	Any	150	150	180	180	180	150	200	70	70	75	-	140	-
Amyl Borate		Any	x	-	x	x	100	-	-	-	-	-	-	-	-
Amyl Carbinol	a, e	100	x	-	-	x	120	100	-	-	-	-	-	140	-
Amyl Chloride	a, e	100	x	-	-	x	x	x	75	x	70	x	x	210	-
Amyl Chloronapthalene		Any	x	-	x	x	80	x	-	-	-	-	-	-	-
Amyl Hydrate	a, e, w	Any	150	-	180	180	180	150	-	70	70	75	-	140	-
Amyl Napthalene		100	x	-	x	x	x	x	-	-	-	-	-	-	-
Anderol L-774			x	x	-	-	-	x	-	-	-	-	-	-	-
Anhydrite *	gl, ho	See Solvents													
Anhydrous Ammonia **			x	x	x	x	x	x	-	170	200	170	-	75	-
Aniline	a,b,e	100	x	x	75	x	x	150	x	70	70	100	75	210	75
Aniline Chloride *	a, e, w	Any	80	x	x	-	x	x	75	x	x	x	x	210	x
Aniline Dyes			80	x	80	x	x	x	-	75	-	-	-	170	-
Aniline Hydrochloride *	a, e, w	Any	80	x	x	-	x	x	75	x	x	x	x	210	x
Aniline Oil	a, b, e	100	x	x	75	x	x	150	x	70	70	100	75	210	75
Aniline Salts *	a, e, w	Any	80	x	x	-	x	x	85	x	x	x	x	210	x
Animal Fats			x	x	x	x	80	150	-	-	-	-	-	-	-
Ant Oil	a, b, e	100	x	-	185	x	x	x	x	100	140	100	100	210	75
Antichlor *		Any	100	150	150	160	160	100	-	-	70	-	70	210	-
Antimony Chloride *	HCl	See Solvent													
Antimony Oxychloride *	HCl	See Solvent													
Apple Acid *	a, e, w	Any	80	150	x	x	x	120	140	x	150	75	75	150	x
Aqua Ammonia		30	150	150	185	150	100	80	200	75	200	75	100	210	75
Aqua Fortis		See Nitric Acid													
Aqua Regia			x	x	x	x	x	x	-	x	x	x	-	75	-
Arachidonic Acid			x	80	150	x	80	80	200	x	200	200	x	400	x
Aragonite *	h	See Solvent													
Arsenic Acid *	a, gl, ho, w	Any	150	-	150	150	150	150	75	x	150	x	x	150	x
Askerel (Transformer Oil)			x	x	x	x	x	x	75	75	-	75	-	75	-
Asphalt			x	x	x	80	150	150	-	170	170	70	170	170	-
ASTM Oil #1,2&3			x	x	x	150	180	150	-	170	170	170	170	170	-
ATE	hc	100	x	-	-	x	x	-	-	-	-	-	-	-	-
Azotic Acid		See Nitric Acid													
Baking Soda *	w	Any	150	185	185	200	200	150	75	100	150	x	-	150	-
Banana Oil	a, e	100	x	-	x	x	x	x	75	75	70	70	-	210	-
Bardol B			x	x	x	x	x	x	-	170	170	170	170	170	-
Barium Carbonate *	h (except H_2SO_4)	See Solvents							200						

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Barium Chloride *	w	Any	150	185	185	200	200	150	200	70	120	x	75	100	x
Barium Hydrate *	a, e, w	Any	150	185	185	200	200	150	-	100	150	x	x	180	75
Barium Hydroxide *	a, e, w	Any	150	185	185	200	200	150	-	100	150	x	x	180	75
Barium Monohydrate *	a, e, w	Any	150	185	185	200	200	150	-	100	150	x	x	180	75
Barium Monosulfide *	w	Any	150	185	185	200	200	150	75	100	150	x	x	100	-
Barium Octahydrate *	a, e, w	Any	150	185	185	200	200	150	-	100	150	x	x	180	75
Barium Sulfate *	Conc. H_2SO_4	See Solvent													
Barium Sulfide *	w	Any	150	185	185	200	200	150	180	100	150	x	x	100	-
Barite *	Conc. H_2SO_4	See Solvent													
Basic Iron Sulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Battery Acid		See Sulfuric Acid													
Beer			80	80	80	80	-	80	x	70	170	170	-	-	-
Beet Sugar Liquor			80	80	150	80	80	150	-	170	170	170	170	170	-
Bengal Gelatin	aa, gl, w	Any	150	185	185	180	180	150	200	x	70	175	-	-	-
Benzaldehyde	a, e, w	Any	x	x	75	x	x	x	x	x	150	70	x	210	75
Benzene	a, aa, ac, cb, ct, e	Any	x	x	x	x	x	x	x	100	100	100	70	210	x
Benzene Carbanol	a, e, w	Any	x	-	75	x	x	150	x	x	150	70	x	210	75
Benzene Carboxylic Acid		Any	150	-	-	150	-	-	75	x	150	150	x	210	x
Benzene Sulfonic Acid *	a, w	10	-	-	70	-	-	140	200	x	120	x	70	210	-
Benzoic Acid		Any	150	150	-	150	-	-	200	x	150	150	x	210	x
Benzoic Aldehyde	a, e, w	Any	x	-	75	x	x	150	x	x	150	70	x	210	75
Benzol	a, aa, ac, cb, ct, e	Any	x	x	x	x	x	x	180	100	100	100	70	210	x
Benzol Hydride	a,aa,ac,cb,ct,e	Any	x	-	x	x	x	150	x	x	150	70	x	210	75
Benzophenol	a, ab, cl, e, ho, gl, o, w	Any	x	x	100	x	x	x	x	110	200	175	70	250	x
Benzyl Alcohol	a, cl, e, w	Any	x	-	185	x	x	-	100	75	100	100	100	210	x
Benzyl Benzoate	a, cl, e	100	x	-	80	x	x	-	-	100	100	70	-	180	-
Benzyl Chloride	a, e	100	x	-	x	x	x	-	x	x	100	x	100	210	x
Betula Oil	aa, e, w	Any	x	-	80	-	x	x	75	75	-	75	-	75	-
Bismuth Carbonate *	HCl, HNO_3	See Solvents													
Bismuth Oxycarbonate *	HCl, HNO_3	See Solvents													
Bismuth Subcarbonate *	HCl, HNO_3	See Solvents													
Black Sulfate Liquor		Any	75	185	150	100	200	150	200	170	-	-	-	-	-
Black Ash *	w	Any	150	185	185	200	200	150	75	100	150	x	x	100	-
Blanc Fixe *	Conc. H_2SO_4	See Solvents													
Bleaching Powder *	a, w	35	70	150	150	x	x	150	75	x	x	x	-	210	-
Blown Linseed Oil	a, cl, cb, e, t	100	x	-	150	80	180	130	75	75	70	70	-	200	-
Blue Copperas * Copper Sulfate	gl, w	Any	150	175	185	200	200	150	100	x	180	x	130	200	x
Blue Salts *	a, w	Any	150	185	185	200	200	150	100	x	70	x	70	120	x
Blue Vitriol *	gl, w	Any	150	175	185	200	200	150	100	x	180	x	130	180	x
Boiled Linseed Oil	a, cb, cl, e, t	100	x	-	150	80	180	130	75	75	70	70	-	200	-
Boletic Acid *	a, w	Any	80	-	-	-	x	-	-	75	-	-	-	-	-
Borax *	w, gl	Any	150	150	185	200	180	150	-	-	150	-	-	75	-
Borax Decahydrate *	w, gl	Any	150	-	185	200	180	150	-	-	150	-	-	75	-
Boracic Acid *	w	Any	150	185	185	200	200	150	150	x	200	100	130	300	x
Bordeaux Mixture *	w	Any	150	175	185	200	200	150	100	x	180	x	130	180	x
Boric Acid *	w	Any	150	185	185	200	200	150	200	x	200	100	130	300	x
Brake Fluid, Veg.			x	-	150	100	150	-	-	-	-	-	-	-	-
Brimstone *	a, b, cb, ct, e	See Solvents													
Bromine	a, cb, cl, e, w	Any	x	x	x	x	x	x	x	x	x	x	x	75	x
Bromochloro Methane	os	100	x	x	x	x	x	x	-	150	150	x	70	210	-
Brown Acetate *	a, w	Any	80	-	180	x	120	-	130	70	130	70	70	150	-
Bunker Oil			x	x	x	80	150	150	-	170	170	170	170	170	-
Burnt Alum *	gl, w	Any	150	185	185	200	200	150	200	x	200	110	-	170	-
Butadiene		Any	x	-	-	x	70	-	70	75	75	75	-	75	-
Butane **		100	x	x	x	x	x	-	-	75	75	75	75	75	-
Butanoic Acid	a, e, w	Any	x	x	x	x	-	-	75	x	200	70	x	210	x
Butarol	a, e, w	Any	150	150	180	150	150	140	75	-	-	70	-	-	-
Butanone	a, e, o, w	Any	x	x	x	x	x	x	x	150	150	150	150	210	170
Butoxyethanol	ph, mo, w	Any	x	-	150	x	150	-	75	100	100	100	150	180	-
Butter of Tin	a, cb, t, w	Any	150	150	150	x	150	150	75	x	x	x	x	210	-
Butter of Zinc *	a, e, gl, w	Any	150	185	185	150	150	150	100	x	100	x	75	210	x
Butyl Acetate	a, e, hc, w	Any	x	x	x	x	x	-	x	70	70	75	70	180	x
Butyl Acetate Ricinoleate			x	x	x	x	x	x	-	-	-	-	-	-	-
Butyl Acrylate	w	Any	x	x	x	x	x	x	-	-	-	-	-	-	-
Butyl Alcohol	a, e, w	Any	150	150	150	x	150	x	75	-	-	70	-	-	-
Butyl Carbitol	dg, me	100	x	x	180	-	150	-	-	-	-	-	-	-	-
Butyl Cellosolve	ph, mo, w	Any	x	-	150	x	150	-	75	100	100	100	150	180	-
Butyl Ether	os	100	x	x	x	80	150	140	-	-	-	-	-	-	-
Butyl Hyride **		100	x	x	x	x	x	-	-	75	75	75	75	75	-
Butyl Octadecanoate *	a, e, mo, vo	See Solvents													
Butyl Stearate *	a, e, mo, vo	See Solvents													
Butyric Acid	a, e, w	Any	x	x	x	x	-	-	75	x	200	70	x	210	x
Butyric Alcohol	a, e, w	Any	150	x	180	150	150	140	75	-	-	70	-	-	-
Cajeputene	a	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Cake Alum *	w	Any	150	185	185	200	200	150	100	x	180	x	100	200	x

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fiberglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Calamine	a, cl, ct, w	Any	80	-	140	80	80	-	210	150	150	75	-	210	200
Calcine Liquor			-	-	200	-	200	-	-	-	-	-	-	-	-
Calcite *	h	See Solvents													
Calcium Acetate *	a, w	Any	80	-	180	x	120	-	130	70	130	70	70	150	-
Calcium Bisulfite	a, w	Any	120	150	120	120	200	150	75	x	180	x	x	75	x
Calcium Carbonate *	h	See Solvents													
Calcium Chlorate *	a, w	Any	150	-	185	200	200	150	200	140	150	140	-	210	x
Calcium Chloride *	a, w	Any	150	185	185	200	200	150	200	140	130	x	x	210	x
Calcium Hydrate	gl, h w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Calcium Hydroxide *	gl, h, w	Any	150	185	185	200	200	150	200	100	200	x	x	x	75
Calcium Hypochlorite *	w	15	80	150	150	x	80	150	200	70	70	70	x	210	75
Calcium Nitrate *	a, ac, w	Any	150	185	185	200	200	150	100	100	130	70	x	100	x
Calcium Oxychloride *	w	15	150	150	185	x	80	150	75	70	70	70	x	210	75
Calcium Sulfate *	gl, ho	See Solvents							200						
Calcium Sulfide *	h, w	Any	150	185	185	150	200	150	75	100	100	70	-	75	-
Calcium Silico-aluminate *		Any	80	-	-	x	x	-	-	-	-	-	-	-	-
Caliche Liquor *	a, gl, w	Any	150	180	185	200	150	150	100	130	170	75	x	210	75
Cane Sugar Liquor			150	150	150	200	200	-	-	170	170	200	170	170	-
Caproic Aldehyde		100	x	-	150	80	x	x	-	-	-	-	-	-	-
Caproxl Alcohol	e, a	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Caproyl Alcohol	a, e,	100	x	-	x	x	120	100	-	-	-	-	-	-	-
Capryl Alcohol	a, cl, e	100	x	-	x	x	100	x	140	-	-	-	-	140	-
Caprylic Alcohol	a, cl, e	100	x	-	x	x	100	x	140	-	-	-	-	140	-
Carbamide *	a, b, e, w	Any	150	185	150	150	150	150	100	70	180	180	-	200	-
Carbitol			x	-	150	x	150	-	70	150	150	150	150	180	x
Carbazotic Acid *	a, b, cl, e, w	Any	x	-	-	x	x	x	75	x	70	x	x	210	x
Carbolic Acid	a, cl, e, gl, ho, o, w	Any	x	-	100	x	x	x	x	110	200	175	70	250	x
Carbon Bisulfide	a, b, e, w	Any	x	x	x	x	x	x	80	75	70	180	180	180	75
Carbon Disulfide	a, b, e, w	Any	x	x	x	x	x	x	80	75	70	180	180	180	75
Carbon Dioxide **			150	185	185	200	200	150	200	170	170	170	170	170	75
Carbon Monoxide **			x	x	80	x	x	x	200	700	700	350	75	700	75
Carbon Tetrachloride	a, b, cl, e, n, o	100	x	x	x	x	x	150	80	75	70	70	100	210	75
Carbonic Acid		Any	150	185	185	200	200	150	75	70	150	70	x	210	x
Carboxybenzene		Any	150	-	-	150	-	-	75	x	150	150	x	210	x
Casein			160	-	-	150	-	-	75	-	150	150	-	75	75
Castor Oil	a, b, cb, cl, e	100	80	-	150	120	150	-	-	110	170	200	170	170	-
Caustic Baryta *	a, e, w	Any	150	185	185	200	200	150	-	100	150	x	x	180	75
Caustic Lime *	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Caustic Potash *	a, e, gl, w	Any	150	185	185	200	150	150	140	x	150	x	x	x	75
Caustic Soda *	a, gl, w	Any	150	185	185	200	150	150	200	100	200	x	110	x	100
Cellosolve	mo, ph, w	Any	x	-	150	x	x	-	75	100	100	100	150	180	-
Cellosolve Acetate	hc, w	Any	x	-	150	x	150	-	x	-	-	-	-	-	-
Cellosolve Butyl	mo, ph, w	Any	x	-	150	x	150	-	75	100	100	100	150	180	-
Celulose Acetate *	ac, ea, ed, xy	See Solvents													
Cellulubes			x	-	100	x	x	-	-	-	-	-	-	-	-
Cetylic Acid *	a, e	See Solvents													
Ceylon Gelatin *	aa, gl, w	Any	150	185	185	180	180	150	200	x	70	175	-	-	-
Chalk *	h	See Solvents													
Chile Niter *	a, gl, w	Any	150	180	150	200	150	150	100	180	200	75	x	210	75
Chile Nitrate *	a, gl, w	Any	150	180	150	200	150	150	100	180	200	75	x	210	75
Chile Saltpeter *	a, gl, w	Any	150	180	150	200	150	150	100	180	200	75	x	210	75
Chinabean Oil	a, cb, cl, e	100	x	-	x	80	120	-	-	110	170	170	-	-	-
Chinawood Oil	cb, cl, e, o	100	x	-	x	120	120	-	-	110	150	170	-	-	-
Chinese Gelatin *	sa, gl, w	Any	150	185	185	180	180	150	200	x	70	175	-	-	-
Chlorine Aqueon		Any	x	-	x	-	-	-	-	-	-	-	-	-	-
Chlorine Dioxide **	ho, w	Any	x	-	x	x	x	x	200	x	x	70	-	75	-
Chlorine Gas, Dry	ho, w		x	x	x	x	x	150	200	-	70	-	-	-	-
Wet			x	185	x	x	x	150	200	-	-	-	-	-	-
Liquid			x	x	x	x	x	x	100	70	-	-	70	75	-
Water		3	150	150	x	x	x	150	180	-	x	-	-	-	-
Chlorine Trifluoride **			x	-	x	x	-	-	75	75	-	75	-	75	-
Chlorinated Lime *	a, w	35	70	150	150	x	x	150	75	x	x	x	-	210	-
Chlorinated Salt Brine			70	150	x	x	-	-	-	-	-	-	-	-	-
Chlorinated Solvents	a, e, es, o, os		x	-	x	x	x	x	-	75	-	-	-	75	-
Chlorinated Tar Camphor	b, ct, o	100	x	x	x	x	x	x	75	150	150	x	150	210	-
Chloroethyl Alcohol	os, w	Any	x	-	80	x	x	x	140	150	150	150	150	210	-
Chloroacetic Acid *	a, e, w	10	x	x	150	x	x	x	200	-	70	-	-	-	-
Chloroacetone	a, cl, e, w	Any	x	x	x	x	x	x	-	x	-	x	150	180	x
Chloroallylene	a, cl, e, pe	100	x	-	x	x	x	-	75	x	125	x	x	-	75
Chloroazotic Acid		See Aqua Regia													
Chlorobenzene	os	100	x	x	x	x	x	x	80	150	150	150	150	210	75
Chlorobromomethane	os	100	x	x	x	x	x	x	-	150	150	x	70	210	-
Chlorobutadiene	a, w	Any	x	x	x	x	x	x	-	75	125	70	-	210	x
Chloroethane **	os, w	100	x	-	x	x	x	x	x	200	200	150	150	210	x
Chloroform	a, b, e, n, n, w	Any	x	x	x	x	x	x	x	x	130	130	130	210	75
Chlorohydric Acid		See Hydrochloric Acid													
Chloromethane **	a, b, cl, ct, os, w	Any	x	-	80	x	x	x	75	x	100	x	-	210	-
Chloropentane	a, e	100	x	-	-	x	x	x	75	x	70	x	x	210	-
Chloroprene	a, w	Any	x	-	x	x	x	-	-	75	125	70	-	210	x
Chloropropanone	a, cl, e, w	Any	x	x	x	x	x	x	-	x	-	x	150	180	x
Chloropropene	a, cl, e, pe	100	x	-	x	x	x	-	75	x	125	x	x	-	75
Chloropropylene	a, e, cl, pe	100	x	x	x	x	x	-	75	x	120	x	x	-	75
Chloropropylene Oxide	os	100	x	-	x	x	x	x	75	130	200	75	75	75	-
Chloronapthalene	b, cl, o	100	x	x	x	x	x	x	75	150	150	x	150	210	-
Chloro Nitro Ethane		100	x	x	x	x	x	x	-	-	-	-	-	-	-
Chlorosulfonic Acid		100	x	x	x	x	x	x	x	75	80	70	-	210	x
Chlorotoluene	a, n, ae, b, cl	100	x	-	x	x	x	-	x	x	100	x	100	210	x
Chlorotrifluoroethylene	a, b, ke		x	-	x	-	x	x	-	-	-	-	-	-	-
Chlorox		5	x	120	150	x	100	150	75	x	70	x	-	75	-
Chrome Alum *	w	Any	150	185	185	200	200	150	75	x	75	x	70	140	-
Chrome Ammonium Alum *	a, w	Any	150	185	185	200	200	150	75	x	75	x	70	140	-
Chromic Acid	e, w	10	x	-	100	x	x	150	150	x	70	70	130	210	x
		25	x	-	75	x	x	120	x	x	70	x	130	210	x
		50	x	-	x	x	x	80	x	70	70	x	130	210	x
		80	x	-	x	x	x	-	x	75	x	x	130	210	x

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Chromic Anhydride		See Chromic Acid													
Chromicoat			x	-	-	x	-	-	-	x	70	-	-	x	-
Chromium Ammonium Sulfate *	a, w	Any	150	185	185	200	200	150	75	x	75	x	70	140	-
Chromium Potassium Sulfate *	w	Any	150	185	185	200	200	150	75	x	75	x	70	140	-
Chromium Trioxide		See Chromic Acid													
Cinene	a	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Circo Light Process Oil			x	x	-	150	180	150	-	-	-	-	-	-	-
Citric Acid *	a, e, w	Any	-	-	135	150	-	150	200	x	180	100	x	210	x
Cleaners Naptha		100	x	-	x	x	80	80	-	-	-	-	-	-	-
Cocoanut Oil	a, cb, cl, e	100	x	x	150	-	120	-	-	-	-	-	-	-	-
Cod Liver Oil	a, cb, cl, e, ea, oe	100	x	x	150	-	120	-	-	-	-	-	-	-	-
Cologne Spirits	a, cl, e	100	150	-	185	150	150	150	170	-	180	100	-	-	-
Copperas * Ferrous Sulfate	w	Any	150	185	185	200	200	150	75	x	70	75	-	210	x
Copper Arsenate *	h, ho	See Solvents													
Copper Chloride *	w	Any	150	150	185	200	200	150	200	x	x	x	x	150	x
Copper Cyanide *	h, ho	See Solvents							200						
Copper Nitrate *	a, w	Any	150	185	185	200	200	150	120	x	180	x	-	210	-
Copper Sulfate *	gl, w	Any	150	175	185	200	200	150	200	x	180	x	130	200	x
Corn Oil	b, cb, cl, e	100	x	-	100	x	x	150	-	170	170	170	170	170	-
Corn Syrup	a, gl, w	Any	120	-	185	120	120	150	-	170	170	170	170	170	-
Corrosive Sublimate *	a, e, gl, py, w	Any	150	185	150	x	150	150	-	70	70	-	-	210	-
Cottonseed Oil	a, b, cb, cl, e	100	x	x	100	150	150	140	-	170	170	170	170	170	-
Creosote	a, e, o	100	x	-	x	x	x	-	-	75	150	70	x	210	x
Cresyl Alcohol	a, e, gl, ho, w	Any	x	-	x	x	x	x	75	75	100	100	x	210	x
Cresylic Acid	a, e, gl, ho, w	Any	x	-	x	x	x	x	75	75	100	100	x	210	x
Cresol	a, e, gl, ho, w	Any	x	-	x	x	x	x	75	75	100	100	x	210	x
Crude Oil			x	70	x	x	180	150	-	-	-	-	-	-	-
Cryolite *	al, fe	See Solvents	150	185	180	180	180	150							
Cryscoat F H Rinse		0.1	x	-	-	x	-	-	-	70	70	-	70	70	-
Cryscoat HC			x	-	-	x	-	-	-	x	70	-	x	70	-
Cryscoat LT & SW			x	-	-	x	-	-	-	x	70	-	x	x	-
Cryscoat 47, 87, 89, & 89M			x	-	-	x	-	70	70	70	70	-	x	70	-
Crystal Ammonia *	w	Any	-	185	185	200	200	150	75	140	70	150	-	200	75
Cupric Chloride *	w	Any	150	150	185	200	200	150	100	x	x	x	x	150	x
Cupric Cyanide *	h, ho	See Solvents													
Cupric Nitrate *	a, w	Any	150	185	185	200	200	150	120	x	180	x	-	210	-
Cupric Sulfate *	gl, w	Any	150	150	185	200	200	150	100	x	180	x	130	200	x
Cyclohexane	os	100	x	-	x	x	80	80	75	70	70	70	70	75	x
Cyclohexanone	os	100	x	-	x	x	x	x	75	x	70	70	70	75	-
Cymene	a, cl, e	100	x	-	x	x	x	x	-	-	-	-	-	-	-
DBP	os, w	Any	x	-	75	x	x	-	75	150	150	150	130	180	-
DDT & Kerosine			x	-	x	150	150	150	75	x	70	70	70	75	-
Decanol	a, e	100	x	-	x	x	100	x	140	-	-	-	-	140	-
Decyl Alcohol	a, e	100	x	-	x	x	100	x	140	-	-	-	-	140	-
Deionized Water			150	-	150	150	200	150	-	-	-	180	-	-	-
Denatured Alcohol		100	150	150	150	150	180	150	-	-	-	-	-	-	-
Developing Solution		Any	150	-	185	200	200	150	-	x	70	-	70	210	-
Diacetic Acid	a, w	Any	80	-	80	x	x	x	-	75	170	75	-	75	-
Diacetic Ester	a, w	Any	80	-	80	x	x	x	-	75	170	75	-	75	-
Diamine	a, w	Any	-	-	100	x	-	-	75	x	75	75	x	75	-
Diaminoethane	a, e, w,	Any	80	-	100	80	80	-	-	75	75	70	-	210	-
Dibenzyl Ether	os	100	x	-	75	x	x	x	-	75	170	170	170	170	-
Dibromoethane	w	Any	x	-	x	x	x	x	75	70	75	x	70	75	75
Dibutyl Ether	os	100	x	x	x	80	150	140	-	-	-	-	-	-	-
Dibutylamine	a, e, hc	100	x	-	x	x	x	x	-	75	-	-	-	75	-
Dibutyl Phthalate	os, w	Any	x	-	75	x	x	-	75	150	150	150	130	180	-
Dichlorobenzine	a, b, e,	100	x	-	x	x	x	-	x	70	70	70	150	200	-
Dichlorodifluoromethane	os, w	100	x	-	x	x	x	x	-	x	75	70	100	75	-
Dichloroethane		100	x	-	75	x	x	x	180	100	100	70	100	210	x
Dichloromethane	a, e	100	x	-	x	x	x	x	-	100	70	100	70	75	-
Dichlorotetrafluoroethane		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Dicyclohexylamine	os, w	Any	x	-	x	x	x	-	-	-	-	-	-	-	-
Diester Syn. Lub Oil		100	x	x	x	x	x	x	-	-	-	-	-	-	-
Diethylamine	a, w	Any	100	-	140	120	x	x	75	x	100	70	x	180	75
Diethylene Dioxide	os, w	Any	x	-	x	x	x	x	-	100	100	70	70	180	x
Diethylene Ether	os, w	Any	x	-	x	x	x	x	-	100	100	70	70	180	x
Diethylene Glycol	a, ac, e, eg, w	Any	150	185	180	180	180	150	-	130	170	100	70	180	x
Diethylene Glycol Dialky Ether			x	-	150	x	150	-	75	x	70	x	x	210	x
Diethylene Glycol Monoalkyl Ether			x	-	150	x	150	-	75	x	70	x	x	210	x
Diethylene Glycol Monoalkyl Ether Acetate	dg, me	100	x	x	180	-	150	-	-	-	-	-	-	-	-
Diethylene Glycol Monobutyl Ether	dg, me	100	x	x	180	-	150	-	-	-	-	-	-	-	-
Diethylene Oxide	os, w	Any	x	-	x	x	x	x	-	100	100	70	70	180	x
Diethyl Ether	a, b, cl, n, o, w	Any	x	-	x	x	120	x	x	70	70	70	70	150	75
Diethyl Oxalate	a, e, ea, os, w	Any	x	-	x	x	x	x	-	-	-	70	-	75	-
Diethyl Oxide	a, b, cl, n, o, w	Any	x	-	x	x	120	x	x	70	70	70	70	150	75
Diethyl Sebacate			x	-	x	x	x	x	-	-	-	-	-	-	-
Digallic Acid *	a, ac, w	Any	100	150	185	x	x	150	75	x	180	x	x	210	x
Dihydroxysuccinic Acid *	a, e, w	Any	150	185	185	100	150	150	75	x	150	70	x	175	75
Dihydroxydiethyl Ether	a, ac, e, eg, w	Any	150	185	180	180	180	150	-	130	170	100	70	180	x
Di-isopropyl Ether	os, w	Any	80	-	x	x	80	-	-	-	-	-	-	-	-
Di-isopropyl Ketone		100	x	-	x	x	x	x	-	-	-	-	-	-	-
Dimethyl Aniline	a, e	100	x	-	100	x	x	x	-	-	-	-	-	100	-
Dimethyl Benzene	a, e	100	x	x	x	x	x	150	x	150	150	75	-	75	x
Dimethyl Carbinol	a, e, w	Any	120	-	120	120	120	120	-	75	70	70	75	210	-

CHEMICAL RESISTANCE FOR LINING MATERIALS

	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Dimethyl Formamide	os, w	Any	x	-	100	x	x	x	x	-	-	-	-	-	-
Dimethyl Ketone	a, cl, e, o,	Any	x	x	150	x	x	x	100	400	180	180	210	210	75
Dimethyl Methane **			x	-	x	x	x	x	-	75	75	75	75	75	-
Dinitro Toluene *	a, e	See Solvents													
Dioctyl Phthalate	mo	100	x	-	100	x	x	x	140	75	70	-	-	75	-
Dioctyl Sebacate		100	x	-	100	x	x	x	-	-	-	-	-	-	-
Dioxane	os, w	Any	x	-	x	x	x	x	-	100	100	70	70	190	x
Dioxethylene Ether	os, w	Any	x	-	x	x	x	x	-	100	100	70	70	180	x
Dipentene	a	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Diphenyl *	a, e	See Solvents													
Diphenyl Ether *	a, e	See Solvents							120						
Diphenyl Oxide *	a, e	See Solvents													
Dipping Acid		See Sulfuric Acid													
DMF	os, w	Any	x	-	100	x	x	x	-	-	-	-	-	-	-
DNT *	a, e	See Solvents													
Dodecanoic Acid *	a, e	See Solvents													
DOP	mo	100	x	-	100	x	x	x	75	75	70	-	-	75	-
Douglas Fir Oil		100	x	-	-	x	150	-	-	-	150	-	-	-	-
Dowlume W40		100	x	-	x	x	x	x	-	-	-	-	-	-	-
Dow Purifloc C-31			150	-	-	150	150	-	-	-	-	-	-	-	-
Dowtherm A	a, ct, e	100	x	-	x	85	75	x	-	170	-	170	-	-	-
Dowtherm E		100	x	-	x	x	x	x	75	75	-	x	-	75	-
Drycid (1)			70	100	-	85	-	70	70	x	70	-	x	70	-
Dutch Liquid		100	x	-	75	x	x	x	180	100	100	70	100	210	x
Dutch Oil		100	x	-	75	x	x	x	180	100	100	70	100	210	x
Electrolyte Acid	See sulfuric acid														
EMK	a, e, o, w	Any	x	x	x	x	x	x	x	150	150	150	150	210	170
Engravers Acid		See Nitric Acid													
epi	os	100	x	-	x	x	x	x	75	130	200	75	75	75	-
Epichlorohydrin	os	100	x	-	x	x	x	x	75	130	200	75	75	75	-
Epsom Salts *	a, gl, w	Any	150	185	185	200	200	150	75	100	150	100	140	210	x
Essence of Myrbane *	a, b, e, w	Any	x	-	80	x	x	x	75	170	150	150	70	210	-
Ethanethiol	a, e, n, w	Any	x	-	x	x	x	x	-	x	150	150	x	200	-
Ethanoic Acid		See Acetic Acid													
Ethanal	a, ac, b, e, g, n, t, tu, xy, w	Any	x	-	80	x	x	x	x	125	210	210	75	600	x
Ethanol	a, cl, e	100	150	150	185	150	150	150	170	-	180	100	-	-	-
Ethanolamine	a, cl, ct, w	Any	80	80	140	80	80	-	210	150	150	75	-	210	200
Ether	a, b, cl, n, o, w	Any	x	-	x	x	120	x	x	70	70	70	70	150	75
Ethine **	a, ac, w	Any	80	80	80	80	80	80	200	400	180	75	75	75	75
Ethyl Acetate	a, cl, e, w	Any	x	-	100	x	x	x	x	75	100	130	70	210	x
Ethyl Acetic Acid	a, e, w	Any	x	x	x	x	-	-	75	x	200	70	x	210	x
Ethyl Acetoacetate	a, w	Any	80	-	80	x	x	x	-	75	170	75	-	75	-
Ethyl Acrylate		100	x	-	x	x	x	x	-	120	70	-	-	75	-
Ethyl Alcohol	a, cl, e	100	150	150	185	150	150	150	100	-	180	100	-	-	-
Ethyl Aldehyde	a, ac, b, e, g, n, t, tu, xy, w	Any	x	-	80	x	x	x	x	125	210	210	75	600	x
Ethyl Benzene	a, b, cl, e, w	Any	x	-	x	x	x	x	140	75	150	150	150	210	75
Ethyl Butanoate	a, e	100	x	-	x	x	x	x	140	180	180	100	150	210	-
Ethyl Butyrate	a, e	100	x	-	x	x	x	x	140	180	180	100	150	210	-
Ethyl Cellulose *	os	See Solvents													
Ethyl Chloride **	os, w	100	x	x	x	x	x	x	x	200	200	150	150	210	75
Ethylene Alcohol	a, cl, e	100	x	175	185	150	180	150	75	100	70	120	-	210	-
Ethylene Bromide	w	Any	x	-	x	x	x	x	75	70	75	x	70	75	75
Ethylene Chloride		100	x	-	75	x	x	x	x	150	70	150	-	210	75
Ethylene Chlorohydrin	os, w	Any	x	-	80	x	x	x	80	150	150	150	150	210	-
Ethylene Diamine	a, e, w	Any	80	-	100	80	80	-	-	75	75	70	-	210	-
Ethylene Dibromide	w	Any	x	-	x	x	x	x	75	70	75	x	70	75	75
Ethylene Dichloride		100	x	x	x	x	x	x	x	150	150	120	150	210	x
Ethylene Glycol	a, e, w	100	150	185	185	150	180	150	200	100	70	120	-	210	-
Ethylene Glycol Monobutyl Ether	mo, ph, w	Any	x	-	150	x	150	-	75	100	100	100	150	180	-
Ethylene Glycol Monobutyl Ether Acetate	hc, w	Any	x	-	150	x	150	-	x	-	-	-	-	-	-
Ethylene Oxide **	os, w	Any	x	-	x	x	x	x	x	75	200	75	70	300	75
Ethyl Ether	a, b, cl, n, o, w	Any	x	-	x	x	120	x	x	70	70	70	70	150	75
Ethyl Hydroxide	a, cl, e	100	150	-	185	150	150	150	185	-	180	100	-	-	-
Ethyl Mercaptan	a, e, n, w	Any	x	-	x	x	x	x	-	x	150	150	x	200	-
Ethyl Oxalate	a, e, ea, os, w	Any	x	-	x	x	x	x	-	-	-	70	-	75	-
Ethyl Oxide	a, b, cl, n, o, w	Any	x	-	x	x	120	x	x	70	70	70	70	150	75
Ethyl Pentachlorobenzene		Any	x	-	x	x	x	x	-	-	-	-	-	-	-
Ethyl Silicate	a	100	x	-	180	180	180	150	-	75	-	-	-	210	-
Ethyl Sulfahydrate	a, e, n, w	Any	x	-	x	x	x	x	-	x	150	150	x	200	-
Exsiccated Alum *	gl, w	Any	150	185	185	200	200	150	200	x	200	110	-	170	-
Fat Lime *	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Fatty Acids			x	80	150	x	80	80	200	x	200	200	x	400	x
Ferric Chloride *	a, gl, w	Any	150	185	185	80	200	150	200	x	x	x	x	210	x
Ferric Nitrate *	a, w	Any	150	185	185	200	200	150	200	x	70	x	-	210	-
Ferric Perchloride *	a, gl, w	Any	150	185	150	80	200	150	200	x	x	x	x	210	x
Ferric Sesquichloride *	a, gl, w	Any	150	185	150	80	200	150	200	x	x	x	x	210	x

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Ferric Sesquisulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Ferric Subsulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Ferric Sulfate *	w	Any	150	185	185	200	200	150	200	x	70	x	75	210	x
Ferric Trichloride *	a, gl, w	Any	150	185	185	80	200	150	200	x	x	x	x	210	x
Ferric Trisulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Ferrous Chloride *	a, w	Any	150	185	185	80	200	150	200	x	70	x	x	210	x
Ferrous Nitrate		Any	150	185	185	200	200	150	200	-	-	-	-	-	-
Ferrous Sulfate *	w	Any	150	185	185	200	200	150	200	x	70	75	-	210	x
Fertilizer Solutions															
Aqua Ammonia & Nitrogen Solution (non-press)		25	150	150	185	200	200	150	200	75	200	100	100	-	-
Ammonium Phosphate (Neutral)			150	150	150	180	80	150	200	-	200	-	-	-	-
Balanced Mix (Complete Analysis)			150	150	150	180	100	150	200	-	200	-	-	-	-
Nitrogen (Low Pressure)		41	80	100	180	120	120	150	200	75	200	100	100	-	-
Filter Alum *	w	Any	150	185	185	200	200	150	100	x	180	x	100	200	x
Firwood Oil			x	-	x	x	150	-	-	-	150	-	-	-	-
Flaxseed Oil	a, cb, cl, e, tu, pe	100	x	-	150	180	180	130	75	75	70	70	-	200	-
Flores Martis *	a, gl, w	Any	150	185	150	80	200	150	200	x	x	x	x	210	x
Florinated Cyclec Ether		100	x	-	x	x	x	x	-	-	-	-	-	-	-
Flowers of Sulfur *	a, b, cb, ct, e	See Solvents													
Fluoboric Acid	a, w	65	150	-	x	80	150	150	-	-	-	-	-	-	-
Fluorine **		100	x	-	x	-	x	x	450	300	350	350	200	300	x
Fluorobenzene	a, e	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Fluorochloroethylene		100	x	-	x	x	x	x	-	-	-	-	-	-	-
Fluorolube	a, b, ke		x	-	x	-	x	x	-	-	-	-	-	-	-
Fluosilicic Acid	w	10	100	185	185	150	150	150	75	x	70	x	70	x	-
		50	80	185	185	80	80	150	75	x	70	x	70	x	-
Formaldehyde**	a, e, w	40	80	x	150	80	80	150	150	x	100	150	70	210	x
Formic Acid	a, e, w	Any	x	x	150	150	-	80	100	x	150	70	x	210	x
Formic Aldehyde**	a, e, w	40	80	x	150	80	80	150	100	x	100	150	70	210	x
Formonitrile	a, e, w	Any	80	-	150	x	x	150	120	x	150	70	x	210	-
Fraud's Reagent	w	10	150	-	150	x	x	150	200	x	x	x	-	210	x
Freons**		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Fuel Oil (Acidic)		100	x	-	x	150	150	150	-	-	150	-	-	170	-
Fumaric Acid *	a, w	Any	80	-	-	-	x	-	-	75	-	-	-	-	-
Furan	a, e	100	x	-	x	x	x	-	-	-	-	-	-	-	-
Furfural	a, b, e	100	x	-	185	x	x	x	x	100	140	100	100	210	75
Furfuran	a, e	100	x	-	x	x	x	-	-	-	-	-	-	-	-
Fusel Oil	a, e, w	Any	150	-	180	180	180	150	-	70	70	75	-	140	-
Gallic Acid *	a, e, gl, w	Any	150	-	150	x	x	150	-	x	140	130	-	75	-
Gallotanic Acid *	a, ac, w	Any	100	150	185	x	x	150	75	x	180	x	x	210	x
Gasoline		100	x	-	x	x	100	100	100	170	70	170	170	170	-
Gaultheria Oil	aa, e, w	Any	x	-	80	-	x	x	75	75	-	75	-	75	-
Gelatin *	aa, gl, w	Any	150	-	185	180	180	150	200	x	70	175	-	-	-
Glauber's Salt *	gl, w	Any	150	-	150	200	200	150	100	140	180	150	140	210	x
Glucose	a, gl, w	Any	120	-	185	120	120	150	-	170	170	170	170	170	-
Glue	gl, h, w	Any	120	-	x	150	150	150	-	170	100	170	170	170	-
Glycerine	a, w	Any	150	-	150	150	180	x	75	110	150	200	70	210	x
Glycerol	a, w	Any	150	-	150	150	180	x	75	110	150	200	70	210	x
Glyceryl Triacetate	a, e, os, w	Any	x	-	80	80	80	x	-	-	-	70	-	75	-
Glyceryl Trioleate	a, cl, ct, e	Any	x	-	100	80	120	-	-	-	-	-	-	-	-
Glyceryl Tripalmitate *	cl, e	See Solvents													
Glycol		100	120	150	150	120	150	150	200	75	70	75	-	210	-
Glycol Chlorohydrin	os, w	Any	x	-	80	x	x	x	140	150	150	150	150	210	-
Glycol Alcohol	a, w	Any	150	-	150	150	180	x	75	110	150	200	70	210	x
Graham's Salt *	w	Any	150	150	185	200	200	150	-	x	70	x	-	210	-
Grain Alcohol	a, e, cl	100	150	150	185	150	150	150	170	-	180	100	-	-	-
Grain Oil	a, e, w	Any	x	x	150	100	150	150	-	70	70	75	-	140	-
Gray Acetate *	a, w	Any	80	-	180	x	120	-	130	70	130	70	70	150	-
Grease Oil	a, b, cb, cl, e	100	x	-	75	x	100	-	-	-	70	-	-	-	-
Green Copperas *	w	Any	150	-	185	200	200	150	75	x	70	75	-	210	x
Greenland Spar *	al, fe	See Solvents													
Green Sulfate Liquor			120	150	150	150	150	150	-	110	-	-	-	-	-
Green Vitriol *	w	Any	150	150	185	200	200	150	75	x	70	75	-	210	x
Gypsum *	ho, am, h,	See Solvents													
Halite *	a, gl, w	Any	150	185	185	200	160	150	75	75	70	x	100	120	75
Hartshorn *	w	Any	-	185	185	200	200	-	75	140	70	150	-	200	75
Heavy Spar *	Conc. H_2SO_4	See Solvents													
Hepar Calis *	h, w	Any	150	185	185	150	200	150	75	100	100	70	-	75	-
Heptyl Carbinol	a, cl, e	100	x	-	x	x	100	x	170	-	-	-	-	170	-
Hexachlorodiphenylmethane		100	x	x	x	x	x	x	75	75	-	75	-	75	-
Hexadecanoic Acid *	a, e	See Solvents													
Hexahydrobenzene	os	100	x	-	x	x	80	80	75	70	70	70	70	75	x
Hexahydropyridine	a, e, w	Any	x	-	x	-	x	-	-	-	-	-	-	-	-
Hexaldehyde		100	x	-	150	80	x	x	-	-	-	-	-	-	-
Hexamethylene	os	100	x	-	x	x	80	80	75	70	70	70	70	75	x
Hexanaphthane	os	100	x	-	x	x	80	80	75	70	70	70	70	75	x
Hexane	a, ac, e	100	x	-	x	80	120	120	-	75	-	75	-	75	-
Hexanedioic Acid	w	Any	80	80	x	x	x	-	-	-	-	-	-	-	-
Hexanol	a, e	100	x	-	x	x	120	100	-	-	-	-	-	140	-

CHEMICAL RESISTANCE FOR LINING MATERIALS

	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Hexone	os, w	Any	x	-	75	x	x	x	70	150	150	150	150	210	-
Hexyl Alcohol	a, e	100	x	-	x	x	120	100	-	-	-	-	-	140	-
Hydrated Lime	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Hydraulic Oil		100	x	-	x	x	150	-	-	-	-	-	-	-	-
Hydrazine	a, w	Any	-	-	100	x	-	-	75	x	75	75	x	75	-
Hydrazinobenzene		Any	80	-	x	x	x	x	-	-	-	-	-	-	-
Hydrobromic Acid		100	100	-	150	x	x	150	150	x	x	x	x	210	x
Hydrochloric Acid	w	15	150	185	x	x	120	150	200	x	x	x	x	210	x
		38	150	185	x	x	x	80	200	x	x	x	x	210	x
Hydrocyanic Acid	a, e, w	20	150	-	150	x	x	150	120	-	70	70	x	210	-
		98	80	-	150	x	x	150	120	75	70	75	70	210	-
Hydrofluoric Acid	w	10	75	120	180	x	80	150	120	x	x	x	75	x	-
		20	x	120	180	x	x	100	120	x	x	x	75	x	-
		48	x	x	150	x	x	100	-	x	x	x	70	x	-
		75	x	x	75	x	x	70	x	x	x	x	x	x	x
(Anhydrous)			x	x	x	x	x	x	-	-	-	-	-	-	-
Hydrofluorosilicic Acid		10	100	180	185	150	150	150	75	x	70	x	70	x	-
Hydrofluosilicic Acid		50	80	80	185	150	150	150	75	x	70	x	70	x	-
Hydrogen **	a, e, w	Any	x	-	x	x	x	x	75	600	600	600	75	75	75
Hydrogen Bromide **	w	Any	100	-	150	x	x	150	150	x	x	x	x	210	x
Hydrogen Carboxylic Acid	a, e, w	Any	x	x	150	150	150	80	75	x	150	70	x	210	x
Hydrogen Chloride **	w	See Hydrochloric Acid													
Hydrogen Cyanide	a, e, w	Any	80	-	150	x	x	150	120	75	70	75	70	210	-
Hydrogen Dioxide	a, w	10	80	x	x	x	80	100	100	x	100	100	x	210	-
Hydrogen Fluoride	w	20	x	-	x	x	80	100	200	x	x	x	75	x	-
Hydrogen Peroxide	a, w,	10	80	x	x	x	80	100	140	x	100	100	x	210	-
Hydrogen Sulfate		See Sulfuric Acid													
Hydrogen Sulfide **	a, w	Any	x	x	150	x	x	140	75	70	100	70	70	75	75
Hydroquinol *	a, e, w	Any	80	-	x	x	x	120	120	70	70	70	70	125	x
Hydroquinone *	a, e, w	Any	80	-	x	x	x	120	120	70	70	70	70	125	x
Hydrosilicfluoric Acid		See Fluosilicic Acid													
Hydrous Aluminum Oxide *	h, ho	See Solvents													
Hydroxyacetic Acid *	a, e, w	10	x	x	100	x	x	x	-	-	200	-	70	210	-
Hydroxipropane Tricarboxylic Acid	a, e, w	Any	150	150	185	150	110	150	120	x	180	100	x	210	x
Hydroxybenzene *	a, cl, e, gl, ho, o, w, cb,	Any	x	x	100	x	x	x	x	110	200	175	70	210	x
Hydroxyethylamine	a, cl, ct, w	Any	80	-	140	80	80	-	210	150	150	75	-	210	200
Hydroxysuccinic Acid *	a, e, w	Any	80	150	x	x	x	120	140	x	150	75	75	150	x
Hypnone *	os, w	Any	x	-	80	x	x	x	-	200	350	150	150	175	-
Hypo *	t, w	Any	150	185	185	200	200	150	150	x	70	-	70	210	-
Hypochlorous Acid		5	120	150	x	x	x	120	150	x	x	x	x	150	75
Icestone *	al, fe	See Solvents													
IPA	a, e, w	Any	120	-	120	120	120	120	-	75	70	70	75	210	-
Iron Chloride *	a, gl, w	Any	150	185	185	80	200	150	200	x	x	x	x	210	x
Iron Dichloride *	a, w	Any	150	-	185	80	200	150	75	x	70	x	x	210	x
Iron Nitrate *	a, w	Any	150	185	185	200	200	150	100	x	70	x	-	210	-
Iron Perchloride *	a, gl, w	Any	150	185	185	80	200	150	200	x	x	x	x	210	x
Iron Persulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Iron Protochloride *	a, w	Any	150	-	185	80	200	150	75	x	70	x	x	210	x
Iron Sulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Iron Sesquichloride *	a, gl, w	Any	150	185	185	80	200	150	200	x	x	x	x	210	x
Iron Susquisulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Iron Tersulfate *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Iron Trichloride *	a, gl, w	Any	150	185	185	80	200	150	200	x	x	x	x	210	x
Iron Vitriol *	w	Any	150	-	185	200	200	150	75	x	70	75	-	210	x
Isobutanol	a, e, w	Any	80	-	100	80	80	80	-	-	-	-	-	-	-
Isobutyl Alcohol	a, e, w	Any	80	-	100	80	80	80	-	-	-	-	-	-	-
Iso-Octane		100	x	-	x	80	120	-	-	-	-	-	-	-	-
Isopropanol	a, e, w	Any	80	-	185	120	120	80	-	75	70	70	75	210	-
Isopropyl Acetate	os, w	Any	x	-	80	x	x	-	-	75	-	-	-	210	-
Isopropyl Alcohol	a, e, w	Any	120	-	120	120	120	120	-	75	70	70	75	210	-
Isopropyl Chloride	e, m, w	Any	x	-	x	x	x	-	-	-	-	-	-	-	-
Isopropylcarbinol	a, e, w	Any	80	-	100	80	80	80	-	-	-	-	-	-	-
Isopropyl Ether	os, w	Any	80	-	x	x	80	-	-	-	-	-	-	-	-
Isopropyldieneacetone	a, e, w	Any	x	-	x	x	x	-	-	75	70	-	-	75	-
Isopropyltoluene	a, e, cl	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Japanese Gelatin	aa, gl, w	Any	150	185	185	180	180	150	200	x	70	175	-	-	-
Jet Fuel															
Type A&A1: Kerosine			x	-	x	x	150	150	-	170	70	170	170	170	-
Type B: Gasoline-Kerosine			x	-	x	x	100	100	75	170	70	170	170	170	-
JP-1: Naptha-Kerosine			x	-	x	x	120	150	-	-	-	-	-	-	-
JP-3: Gasoline-Kerosine			x	-	x	x	100	100	75	170	70	170	170	170	-
JP-4: Gasoline-Petroleum			x	-	x	x	100	100	75	170	70	170	170	170	-
JP-5&6: Kerosine			x	-	x	x	120	150	-	-	-	-	-	-	-
JPx			x	-	x	x	120	x	-	-	-	-	-	-	-
Kerosine			x	-	x	x	150	-	150	170	70	170	170	170	-

CHEMICAL RESISTANCE FOR LINING MATERIALS

	Solvents	Concentration	Natural Rubber	Hard Pubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Ketohexamethylene	os	Any	x	-	x	x	x	x	75	x	70	70	70	75	-
Ketopropane	a, cl, e, o, w	Any	x	x	150	x	x	x	100	400	180	180	210	210	75
Kurrol's Salt		Any	150	150	185	200	200	150	-	x	70	x	-	210	-
Labarraque's Solution *	w	20	x	-	x	x	x	120	75	x	x	x	x	150	75
Lactic Acid	a, e, gl, w	50	120	150	150	80	80	130	200	x	70	70	x	200	x
Lactol		100	x	x	x	x	100	-	-	-	-	-	-	-	-
Lacquer Solvents		Any	x	-	x	x	x	-	-	75	170	170	-	-	-
Lard Oil	a, b, cb, cl, e	100	x	-	75	x	100	-	-	-	70	-	-	-	-
Lauric Acid *	a, e	See Solvents													
Layor Caranga *	aa, gl, w	Any	150	185	185	180	180	150	200	x	70	175	-	-	-
Lead Acetate *	a, gl, h, w	Any	80	-	120	80	80	120	200	x	100	x	x	200	x
Lead Arsenate *	HNO_3	See Solvents													
Lead Nitrate *	a, w	Any	120	-	180	120	120	120	75	x	130	x	100	210	-
Lead Styphnate *	w	Any	120	175	185	180	120	120	-	-	-	-	-	-	-
Lead Sulfate *	h, w	Any	120	-	185	180	120	120	75	x	150	x	150	180	75
Lead Trinitroresorcinate *	w	Any	120	175	185	180	120	120	-	-	-	-	-	-	-
Leucogen *	w	Any	150	185	185	200	160	150	75	x	100	x	70	x	x
Lichenic Acid *	a, w	Any	80	-	-	-	x	-	-	75	-	-	-	-	-
Lime *	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Lime Acetate *	a, w	Any	80	-	180	x	120	-	130	70	130	70	70	150	-
Lime Bleach *	a, w	Any	120	-	150	-	-	-	-	-	-	-	-	-	-
Lime Hydrate *	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Limonene	a	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Lime Saltpeter *	a, ac, w	Any	150	185	185	200	200	150	100	100	130	70	x	100	x
Limestone	h	See Solvents													
Linoil		100	x	x	x	-	x	-	-	-	-	-	-	-	-
Linoleic Acid	os	100	x	-	x	x	x	-	200	x	500	500	x	600	x
Linolenic Acid	os	100	x	80	150	x	80	80	200	-	70	70	-	-	-
Linolic Acid	os	100	x	-	x	x	x	-	200	x	500	500	x	600	x
Linseed Oil	a, cb, cl, e, tu, pe	100	x	-	150	180	180	130	200	75	70	70	-	200	-
Liquid Oxygen		100	x	x	x	x	x	x	-	-	-	-	-	-	-
Liquid Petroleum Gas		100	x	x	x	x	x	x	-	-	-	-	-	-	-
Liquid Rosin			x	-	x	x	150	150	200	100	400	x	-	600	-
Lubricating Oils			x	x	x	120	150	150	-	170	170	170	170	170	-
Lube Oils			x	x	x	120	150	150	-	170	170	170	170	170	-
Lye		Any	150	185	185	200	150	150	100	75	150	x	x	x	75
Lysol	a, w		150	-	150	150	150	-	-	-	-	-	-	-	-
Macassargum *	aa, gl, w	Any	150	185	185	180	180	150	200	x	70	175	-	-	-
Maddrell's Salt		Any	150	150	185	200	200	150	-	x	70	x	-	210	-
Magnesia Alba *	h	See Solvents													
Magnesium Bisulfite	w	Any	120	-	120	120	120	-	-	-	100	x	100	70	x
Magnesium Carbonate *	h	See Solvents							150						
Magnesium Chloride *	a, w	Any	150	185	185	200	200	130	200	70	70	x	x	140	x
Magnesium Hydrate *	am, h, w	Any	150	185	185	200	200	130	75	70	70	x	x	140	-
Magnesium Hydroxide *	am, h, w	Any	150	185	185	200	200	130	75	70	70	x	x	140	-
Magnesium Nitrate *	a, w	Any	150	185	185	200	200	150	75	70	70	70	-	210	-
Magnesium Sulfate *	w, a, gl	Any	150	185	185	200	200	150	200	110	150	110	140	210	x
Maize Oil	b, cb, cl, e	100	x	-	100	x	x	150	-	170	170	170	170	170	-
Maleic Acid *	a, h, w	25	80	150	x	x	x	120	200	x	70	70	-	210	-
Maleic Anhydride *	ac, cl, e, hc	See Solvents													
Maleinic Acid *	a, b, w	25	80	150	x	x	x	120	100	x	70	70	-	210	-
Malic Acid *	a, e, w	Any	80	150	x	x	x	120	140	x	150	75	75	150	x
Manganese Sulfate *	w	Any	150	150	185	200	200	150	75	-	-	-	-	200	x
Marble	h	See Solvents													
Marl *	h	See Solvents													
MEA	a, cl, ct, w	Any	80	-	140	80	80	-	210	150	150	75	-	210	200
MEK	a, e, o, w	Any	x	x	100	x	x	x	x	150	150	150	150	210	170
Mercuric Chloride *	a, e, gl, py, w	Any	150	185	150	x	150	150	200	x	x	x	x	200	x
Mercuric Cyanide *	a, w	Any	150	-	150	x	150	150	75	-	70	x	-	150	x
Mercurous Nitrate *	HNO_3, w	Any	150	-	150	80	80	150	70	-	140	x	x	210	-
Mercury Bichloride *	a, e, gl, py, w	Any	150	185	150	x	150	150	75	x	x	x	x	200	x
Mercury Vapor			x	-	x	x	x	x	-	-	-	-	-	-	-
Mesityl Oxide	a, e, w	Any	x	-	x	x	x	-	-	75	70	-	-	75	-
Methanal	a, e, w	40	80	x	150	80	80	150	100	x	100	150	70	210	x
Methanol	a, e, w	Any	100	-	185	100	150	120	100	150	150	90	150	210	75
Methanecarboxylic Acid		See Acetic Acid													
Methyl Acetate	hc, w	Any	x	-	x	x	x	-	-	75	-	-	-	75	-
Methyl Acrylate	w	Any	x	-	x	x	x	-	-	75	-	75	-	75	-
Methyl Alcohol	a, e, w	Any	100	-	185	100	150	120	100	150	150	90	150	210	75
Methylbenzene	a, b, e	100	x	x	x	x	x	150	170	170	170	170	170	170	-
Methyl Butanol	a, e, w	Any	150	-	180	180	180	150	-	70	70	75	-	140	-
Methyl Butyl Ketone	a, e, w	Any	x	-	150	x	x	x	x	-	-	150	-	-	-
Methyl Chloride **	a, b, cl, ct, os, w	Any	x	-	80	x	x	x	75	x	100	x	-	210	-
Methylene Chloride	a, e	100	x	-	x	x	x	x	x	100	70	100	70	75	-
Methylene Chlorobromide	os	100	x	x	x	x	x	x	-	150	150	x	70	210	-
Methylene Dichloride	a, e	100	x	-	x	x	x	x	-	100	70	100	70	75	-
Methyl Ethyl Ketone	a, e, o, w	Any	x	x	100	x	x	x	x	150	150	150	150	210	170
Methyl Hexyl Carbinol	a, cl, e	100	x	-	x	x	100	x	150	-	-	-	-	175	-
Methyl Isobutenyl Ketone	a, e, w	Any	x	-	x	x	x	-	-	75	70	-	-	75	-

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Methyl Isobutyl Ketone	a, c, w	Any	x	-	75	x	x	x	70	150	150	150	150	210	-
Methyl Isopropyl Ketone	w, os	Any	x	-	x	x	x	x	-	-	-	-	-	-	-
Methyl Merthacrylate	w	Any	x	-	x	x	x	x	-	x	70	70	-	75	-
Methylphenol	a, e, gl, ho, w	Any	x	-	x	x	x	x	75	75	100	100	x	210	x
Methyl Polysiloxanes		100	x	-	x	x	180	-	-	-	-	-	-	-	-
Methylpropanol	a, e, w	Any	80	-	100	80	80	80	-	-	-	-	-	-	-
Methylpropylbenzene	a, cl, e	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Methyl Salicylate	aa, e, w	Any	x	-	80	-	x	x	75	75	-	75	-	75	-
Milk Acid	a, e, gl, w	50	120	-	150	80	80	130	100	x	70	70	x	200	x
Milk of Magnesia *	am, h, w	Any	150	185	185	200	200	130	75	70	70	x	x	140	-
Milk, Whole			100	-	100	100	100	100	170	170	150	200	-	170	-
Mineral Oil		100	x	-	x	x	150	150	-	110	70	170	110	170	-
Mineral Pitch			x	x	x	80	150	150	-	170	170	70	170	170	-
Mineral Spirits		100	x	x	x	x	x	x	75	75	70	75	-	75	x
Mineral Thinner		100	x	x	x	x	x	x	75	75	70	75	-	75	x
Mineral Turpentine *	a, b, e	See Solvents													
Mirabilite *	gl, w	Any	150	-	185	200	200	150	100	140	180	150	140	210	x
Molasses	w	Any	150	185	185	200	200	150	-	-	-	-	-	-	-
Molysite *	a, gl, w	Any	150	135	180	80	200	150	200	x	x	x	x	210	x
Monobromo Benzene		Any	x	-	x	x	x	x	-	-	-	-	-	100	-
Monobromotrifluoromethane **		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Monochloroacetic Acid *	a, e, w	10	x	x	150	x	x	x	200	-	70	-	-	-	-
Monochloro Benzene		Any	x	-	x	x	x	x	x	75	70	-	x	210	-
Monochlorodifluoromethane **		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Monochlorotrifluoromethane **		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Monoethanolamine	a, cl, ct, w	Any	80	80	140	80	80	-	210	150	150	75	-	210	200
Monomethylether		100	x		80	x	100	x	-	-	-	-	-	-	-
Monosodium Acid Methanearsenate		25	-	185	200	180	-	-	-	-	-	-	-	-	-
Monovinyl Acetate		100	x	-	-	x	x	-	-	-	-	-	-	-	-
Monsel's Salt *	w	Any	150	185	185	200	200	150	75	x	70	x	75	210	x
Morea Premic			150	-	150	-	-	-	-	-	-	-	-	-	-
Morrhua Oil	ae, a, cb, cl, e, pe	100	x	x	150	-	120	-	-	-	-	-	-	-	-
Motor Spirits		100	x	-	x	x	100	100	75	170	70	170	170	170	-
Muriatic Acid		See Hydrochloric Acid													
Mustard			x	-	-	-	-	-	-	-	-	-	-	-	-
Muthman's Liquid	a, e	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Myristic Acid *	a, e	See Solvents													
Naptha		100	x	x	x	x	x	x	100	75	70	75	-	75	x
Napthalene *	a, b, e	See Solvents													
Napthenic Acid	hc, os, w	Any	x	-	x	-	x	-	-	130	200	130	-	210	-
Napthylbenzene	a, b, e	100	x	x	x	x	x	150	170	170	170	170	170	170	-
Natural Gas **			x	x	x	x	x	x	-	170	170	170	170	170	-
Navee		-	-	-	-	-	70	-	-	-	-	170	-	-	-
Nickel Acetate *	a, w	Any	80	185	-	-	-	-	-	-	70	-	-	75	-
Nickel Chloride *	ho, w	Any	150	185	150	200	200	150	200	x	70	x	100	140	-
Nickel Nitrate *	a, w	Any	150	185	150	200	200	150	200	70	70	x	70	210	-
Nickel Salts *	a, w	Any	150	185	185	200	200	150	100	x	70	x	70	120	x
Nickel Sulfate *	a, w	Any	150	185	185	200	200	150	200	x	70	x	70	120	x
Nicotine Bentonite		Any	150	-	185	200	200	150	-	-	-	-	-	-	-
Nicotine Sulfate *	a, e, w	Any	150	-	185	200	200	150	-	-	70	70	-	75	-
Niter *	a, gl, w	Any	150	180	185	200	180	150	150	130	130	180	70	210	75
Niter Cake *	w	Any	150	185	185	200	160	150	100	x	150	x	70	200	x
Nitric Acid		10	x	-	100	x	x	150	125	x	200	70	x	400	x
		25	x	-	75	x	x	115	125	x	175	x	x	400	x
		40	x	-	x	x	x	100	80	x	140	x	x	400	x
Concentrated			x	-	x	x	x	x	x	x	70	70	x	210	x
Fuming			x	-	x	x	x	x	x	x	70	75	-	150	-
Nitrobenzene *	a, b, e, w	Any	x	-	80	x	x	x	75	170	150	150	70	210	-
Nitrocalcite *	a, ac, w	Any	150	185	185	200	200	150	100	100	130	70	x	100	x
Nitro Ethane	w	Any	80	-	80	x	x	80	-	75	75	75	-	75	-
Nitrogen **		100	150	185	185	200	200	-	-	-	-	-	-	-	-
Nitrogen Dioxide **	w	Any	See Nitric Acid												
Nitrogen Fertilizer Solution			150	185	150	150	150	150	-	-	-	-	-	-	-
Nitrogen Peroxide **	w	Any	See Nitric Acid												
Nitrogen Tetraoxide **			See Nitric Acid												
Nitrohydrochloric Acid		Conc.	x	x	x	x	x	x	-	x	x	x	-	75	-
Nitro Methane	w	Any	80	-	80	x	x	80	-	75	75	75	-	75	-
Nitromuriatic Acid			x	x	x	x	x	x	-	x	x	x	-	75	-
Nitropropane	w	Any	x	-	80	-	x	80	-	75	75	75	-	75	-
Nitroxanthic Acid *	a, b, cl, e, w	Any	x	-	-	x	x	x	75	x	70	x	x	210	x
Norge Niter *	a, ac, w	Any	150	185	185	200	200	150	100	100	130	70	x	100	x
Norway Saltpeter *	a, ho, w	Any	150	150	185	200	200	150	100	100	130	70	x	100	x
Norwegian Saltpeter *	a, ac, w	Any	150	185	185	200	200	150	100	100	130	70	x	100	x
NPN		100	-	-	120	-	-	120	-	-	-	-	-	-	-
Octadecatrienoic Acid	os	100	x	80	150	x	80	80	200	-	70	70	-	-	-
Octadecenoic Acid	a, e, os	100	x	-	x	x	150	150	x	70	100	70	x	210	x
Octafluorocyclobutane		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Octanol	a, cl, e	100	x	-	x	x	100	x	140	-	-	-	-	140	-

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fibreglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Octyl Alcohol	a, cl, e	100	x	-	x	x	100	x	140	-	-	-	-	140	-
Oil of Bitter Almonds	a, e, w	Any	x	-	75	x	x	150	x	x	150	70	x	210	75
Oil of Mirbane *	a, b, e, w	Any	x	-	80	x	x	x	75	170	150	150	70	210	-
Oil of Vitriol		See Sulfuric Acid													
Oil, SAE		100	x	x	x	-	150	150	-	-	150	-	-	-	-
Oakite Acid Materials (1)		See Solvents													
Oakite Alkaline Materials (1)		Any	150	185	185	200	150	150	100	75	75	-	-	x	-
Oakite OC 31 (1)			70	100	-	85	-	70	-	x	70	-	70	70	-
OC 32 (1)			70	100	-	85	-	70	-	x	x	-	x	70	-
OC 33 (1)			x	x	-	-	-	x	-	x	70	-	x	70	-
OC 34 (1)			x	x	-	x	-	x	-	x	70	-	70	x	-
OC 36 (1)			70	100	-	85	-	-	-	x	70	-	70	70	-
OC 84H (1)			70	100	-	85	-	-	-	x	x	-	x	70	-
OC 84M (1)			70	100	-	85	-	-	-	x	x	-	x	70	-
OC 85 (1)			x	x	-	x	-	-	-	x	70	-	70	70	-
OC 88 (1)			x	x	-	70	-	-	-	x	70	-	70	70	-
OC 131 (1)			70	100	-	85	-	-	-	x	70	-	70	70	-
O Chromicoat			x	-	-	x	-	-	-	x	70	-	-	x	-
Cryscoats 47, 87, 89, 89M			x	-	-	x	-	70	70	70	70	-	x	70	-
Cryscoat FH rinse			x	-	-	x	-	-	-	70	70	-	70	70	-
Cryscoat HC			x	-	-	x	-	-	-	x	70	-	x	70	-
Cryscoats LT & SW			x	-	-	x	-	-	-	x	70	-	x	x	-
O Drycid (1)			70	100	-	85	-	70	70	x	70	-	x	70	-
OFM 184 (1)			70	100	-	85	-	-	-	x	x	-	x	70	-
O Stripper SA			x	x	-	x	-	-	-	x	x	-	x	70	-
Oakite Solvent Materials			x	x	x	x	x	x	x	70	70	-	-	-	-
Orthoboric Acid *	w	Any	150	185	185	200	200	150	150	x	200	100	130	300	x
Oleic Acid	a, e, os	100	x	-	x	x	150	150	200	70	100	70	x	210	x
Olein	a, cl, ct, e	100	x	-	100	80	120	-	-	-	-	-	-	-	-
Oleum Spirits			x	-	x	x	x	x	x	70	70	-	75	400	x
Olive Oil	a, cb, cl, e	100	x	-	100	80	120	-	-	-	-	-	-	-	-
Ortho-dichlorobenzene		100	x	-	x	x	x	x	75	75	-	x	-	75	-
Ortho-hydroxybenzoic Acid *	a, ac, b, e, cu, w	Any	80	-	80	x	x	x	75	x	100	70	100	210	x
Oxalic Acid *	a, e, w	10	150	150	185	200	150	130	200	x	70	70	x	210	75
Oxygen **		100	x	-	100	100	100	100	-	-	-	-	-	-	-
Oxymethelene **	a, e, w	40	80	x	150	80	80	150	100	x	100	150	70	210	x
Ozone **			x	-	80	80	x	100	-	-	-	-	-	-	-
Painter's Naptha		100	x	x	x	x	x	x	75	75	70	75	-	75	x
Palm Oil	a, cb, cl, e	100	x	-	x	x	150	-	-	-	-	-	-	-	-
Palmitic Acid *	a, e	See Solvents													
Palmitinic Acid *	a, e	See Solvents													
Palmitin *	cl, e	See Solvents													
Paper Alum *	w	Any	150	185	185	200	200	150	100	x	180	x	100	200	x
Paradihydroxybenzene *	a, e, w	Any	80	-	x	x	x	120	120	70	70	70	70	125	x
Paraform *	ho, w	Any	x	-	x	x	x	-	75	70	70	70	-	75	75
Paraformaldehyde *	ho, w	Any	x	-	x	x	x	-	75	70	70	70	-	75	75
Patent Alum *	w	Any	150	185	185	200	200	150	100	x	180	x	100	200	x
Pear Alum *	w	Any	150	185	185	200	200	150	100	x	180	x	100	200	x
Pearl Ash *	w	Any	150	185	180	200	180	150	150	100	180	x	x	180	75
Pear Oil	a, e	100	x	-	x	x	x	x	75	75	70	70	-	210	-
Pentachlorodiphenyl			x	x	x	x	x	x	75	75	-	75	-	75	-
Pentachlorodiphenyl Ketone			x	x	x	x	x	x	75	75	-	75	-	75	-
Pentachlorodiphenyl Oxide			x	x	x	x	x	x	75	75	-	75	-	75	-
Pentachloroethylbenzene			x	x	x	x	x	x	75	75	-	75	-	75	-
Pentachlorophenylbenzoate			x	x	x	x	x	x	75	75	-	75	-	75	-
Pentamethylene Amine	a, e, w	Any	x	-	-	x	x	-	-	-	-	-	-	-	-
Pentasodium Triphosphate *	w	Any	x	-	-	x	x	-	-	-	-	-	-	-	-
Perchlorethylene	a, e, o, w	Any	x	-	x	x	x	x	-	120	120	100	70	75	-
Perchloric Acid	w	10	150	-	150	x	x	150	100	x	x	x	-	210	x
Perchloromethane	a, b, cl, e, n, o, w	Any	x	x	x	x	x	150	200	75	70	70	100	210	75
Permanent White *	Con. H_2SO_4	See Solvents													
Peroxide	a, w	10	80	x	x	x	80	100	120	x	100	100	x	210	-
		30	x	x	x	x	x	80	120	x	100	100	x	210	-
Peroxydol*	gl, w	Any	150	-	185	200	200	150	-	70	70	x	x	140	-
Peroxyhydrate	gl, w	Any	150	-	185	200	200	150	-	70	70	x	x	140	-
Petrol		100	x	-	x	x	100	100	75	170	70	170		170	-
Petroleum Oil			x	x	x	100	180	150	-	-	-	-		-	-
Petroleum Spirits		100	x	x	x	x	x	x	75	75	70	75	-	75	x
Petroleum Thinner		100	x	x	x	x	x	x	75	75	70	75	-	75	x
Phenetole		Any	x	-	x	x	x	x	-	-	-	-	-	-	-
Phenol	a, cl, gl, ho	Any	x	-	100	x	x	x	200	110	200	175	70	210	x
Phenol Polysiloxane	o, w, cb, e	100	x	-	x	x	180	-	-	-	-	-	-	-	-
Phenol Trinitrate *	a, b, cl, e, w	Any	x	-	-	x	x	x	75	x	70	x	x	210	x
Phenylamine	a, b, e	100	x	x	75	x	x	150	x	70	70	100	75	210	75
Phenylbenzene		Any	x	-	x	x	x	x	-	-	-	-	-	-	-
Phenylcarbinol	a, cl, e, w	Any	x	-	185	x	x	-	-	75	100	100	100	210	x
Phenyl Chloride	os	100	x	x	x	x	x	x	175	150	150	150	150	210	75
Phenylethane	a, b, cl, e, w	Any	x	-	x	x	x	x	140	75	150	150	150	210	75
Phenyl Ether *	a, e	See Solvents													
Phenyl Ethyl Ether		Any	x	-	x	x	x	-	-	-	-	-	-	-	-
Phenylformic Acid		Any	150	-	-	150	-	-	75	x	150	150	x	210	x
Phenyl Hydrazine		Any	80	-	x	x	x	x	-	-	-	-	-	-	-
Phenylic Acid *	a, cb, cl, e, gl, ho, o, w	Any	x	-	100	x	x	x	x	110	200	175	70	210	x
Phenylmethane	a, b, e	100	x	x	x	x	x	150	170	170	170	170	170	170	-
Phenyl Methyl Ketone	os, w	Any	x	-	80	x	x	x	-	200	350	150	150	175	-
Phenylsulfonic Acid *	a, w	10	-	-	70	-	-	140	-	x	120	x	70	210	-
Phosphate Esters		Any	x	-	120	x	x	-	-	-	-	-	-	-	-
Phosphoric Acid		50	150	185	185	180	80	150	200	x	130	x	200	300	x
		85	150	-	120	150	x	140	200	x	-	x	70	210	x
		106	x	-	120	-	-	-	200	x	-	x	70	400	x
Phospholeum		106	x	185	185	x	-	-	200	x	-	x	70	400	x
Phosphoric Anydride *	w	See Phosphoric Acid													
Pickle Alum *	w	Any	150	185	185	200	200	150	100	x	180	x	100	200	x
Picric Acid *	a, b, cl, e, w	Any	x	-	-	x	x	x	75	x	70	x	x	210	x

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fiberglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Picronitric Acid *	ab, cl, e, w	Any	x	-	-	x	x	x	75	x	70	x	x	210	x
Pimelic Ketone	os	100	x	-	x	x	x	x	75	x	70	70	70	75	-
Pinene		100	x	-	-	x	x	-	-	-	-	-	-	-	-
Pine Oil (150, 220, 230, & NFXI)			x	-	-	x	150	-	-	-	150	-	-	-	-
Piperidine	a, e, w	Any	x	-	-	-	x	-	-	-	-	-	-	-	-
Plating Solutions															
Antimony			130	180	185	-	-	-	-	-	-	-	-	-	-
Arsenic			100	-	-	-	-	-	-	-	-	-	-	-	-
Brass			100	-	185	-	-	150	-	-	-	-	-	-	-
Cadmium			150	-	150	150	150	150	-	-	-	-	-	-	-
Chrome			x	-	x	x	x	120	-	-	-	-	-	-	-
Cobalt			150	-	150	150	150	150	-	-	-	-	-	-	-
Copper			100	-	180	-	-	140	-	-	-	-	-	-	-
Gold			100	x	180	-	-	150	-	-	-	-	-	-	-
Iron			100	-	-	-	180	150	-	-	-	-	-	-	-
Lead			150	-	150	150	150	150	-	-	-	-	-	-	-
Nickel			100	-	-	-	-	150	-	-	-	-	-	-	-
Platium			-	-	-	200	-	-	-	-	-	-	-	-	-
Silver			100	-	150	-	-	150	-	-	-	-	-	-	-
Tin			-	150	150	-	-	150	-	-	-	-	-	-	-
Plating Solutions															
Zinc			100	-	150	-	-	150	-	-	-	-	-	-	-
Zinc on Aluminum			-	-	-	-	-	150	-	-	-	-	-	-	-
Polyformaldehyde *	ho, w	Any	x	-	x	x	x	-	75	70	70	70	-	75	75
Polyoxymethylene *	ho, w	Any	x	-	x	x	x	-	75	70	70	70	-	75	75
Potash *	w	Any	150	185	180	200	180	150	150	100	180	x	x	180	75
Potash Alum *	w	Any	150	185	185	200	180	150	200	x	150	70	100	200	180
Potassa *	a, e, gl, w	Any	150	185	185	200	150	150	100	75	130	x	x	x	75
Potassium Acetate *	a, w	Any	120	175	150	-	120	150	75	75	100	x	-	180	75
Potassium Alum *	w	Any	150	185	185	200	180	150	200	x	150	70	100	200	180
Potassium Carbonate *	w	Any	150	185	180	200	180	150	150	100	180	x	x	180	75
Potassium Chloride *	c, w	Any	150	185	185	150	150	150	200	70	150	70	70	210	x
Potassium Cupro Cyanide *	w	Any	150	-	150	-	-	150	-	100	70	x	x	75	-
Potassium Cyanide *	a, gl, w	Any	150	-	150	150	150	150	120	70	100	x	x	100	75
Potassium Di (Bi) chromate *	w	Any	x	x	150	x	150	150	200	130	150	140	130	180	x
Potassium Hydrate *	a, e, gl, w	Any	150	185	185	200	150	150	100	75	130	x	x	x	75
Potassium Hydroxide	a, e, gl, w	Any	150	185	185	200	150	150	100	75	130	x	x	x	75
Potassium Muriate *	a, w	Any	150	185	185	150	150	150	75	70	150	70	70	210	x
Potassium Nitrate *	a, gl, w	Any	150	180	185	200	180	150	200	130	130	180	70	210	75
Potassium Oxide	w	Any	150	185	185	200	150	150	100	75	130	x	x	x	75
Potassium Permanganate *	w	Any	x	185	130	x	150	150	200	75	100	100	x	130	75
Potassium Sulfate *	w	Any	150	185	185	200	180	150	200	70	100	100	70	130	75
Potassium Sulfite *	a, w	Any	150	185	180	150	150	140	-	-	100	-	-	120	-
Potato Oil	a, e, w	Any	150	-	180	180	180	150	-	70	70	75	-	140	-
Potato Spirit	a, e, w	Any	150	-	180	180	180	150	-	70	70	75	-	140	-
Propane **			x	-	x	x	x	x	-	75	75	75	75	75	-
Propanol	a, e, w,	Any	120	-	120	120	120	120	-	75	70	70	75	210	-
Propanone	a, cl, e, o, w	Any	x	x	150	x	x	x	100	400	180	180	210	210	75
Propene **			x	-	x	x	x	-	-	75	75	75	75	75	-
Propenenitrile	os, w	Any	80	80	x	x	x	-	-	-	-	-	-	-	-
Propyl Acetate	a, hc, k, o	100	x	-	80	x	x	-	-	-	-	-	-	75	-
Propylacetone	a, e, w	Any	x	-	150	x	x	x	-	-	-	150	-	-	-
Propyl Alcohol	a, e, w	Any	120	-	120	120	120	120	-	-	-	70	-	75	-
Propylene **			x	-	x	x	x	-	-	75	75	75	75	75	-
Propylformic Acid	a, e, w	Any	x	x	x	x	-	-	75	x	200	70	x	210	x
Propyl Nitrate		100	-	-	120	-	-	120	-	-	-	-	-	-	-
Protochloride *	a, w	Any	150	-	185	80	-	-	-	-	-	-	-	-	-
Prussic Acid	a, e, w	Any	80	-	150	x	x	150	120	75	70	75	70	210	-
Purple Salt *	w	Any	x	185	130	x	150	150	-	75	100	100	x	130	75
Pyridine	a, b, e, w	Any	x	-	100	x	x	-	x	125	100	100	100	210	75
Pyroacetic Ether	a, cl, e, o, w	Any	x	x	150	x	x	x	100	400	180	180	210	210	75
Pyroligneous Acid	a, w	Any	x	-	100	x	x	-	75	x	70	70	-	140	-
Pyromucic Aldehyde	a, b, e	100	x	-	185	x	x	x	x	100	140	100	100	210	75
Pyrrole	a, e, h	100	x	-	x	x	x	-	-	-	-	-	-	-	-
Quinol *	a, e, w	Any	80	-	x	x	x	120	120	70	70	70	70	125	x
Raw Linseed Oil	a, cb, cl, e, pe	100	x	-	150	180	180	130	75	75	70	70	-	200	-
Red Oil	a, e, os	100	x	-	x	x	150	150	x	70	100	70	x	210	x
Red Potassium Chromate *	w	Any	x	x	150	x	150	150	75	130	150	140	130	180	x
Refined Linseed Oil	a, cb, cl, e, tu, pe	100	x	-	150	180	180	130	75	75	70	70	-	200	-
Ricinus Oil	a, b, cb, cl, e	100	80	-	150	120	150	-	-	110	170	200	170	170	-
Rock Salt *	a, gl, w	Any	150	185	185	200	160	150	75	75	70	x	100	120	75
Saccharose Solutions		Any	120	-	120	120	120	-	-	-	150	70	130	150	75
Saccharum Solutions		Any	120	-	120	120	120	-	-	-	150	70	130	150	75
Salammoniac *	a, w, gl	Any	150	185	185	200	200	150	200	x	100	x	x	210	x
Sal Chalybis *	w	Any	150	-	185	200	200	150	75	x	70	75	-	210	x
Salicylic Acid *	a, ac, b, e, tu, w	Any	80	-	80	x	x	x	75	x	100	70	100	210	x
Sal Soda *	w	Any	150	185	185	200	200	-	70	120	100	x	x	140	75
Salt Cake *	gl, w	Any	150	-	185	200	200	150	100	140	180	150	140	210	x
Salt of Lemery *	w	Any	150	185	185	200	180	150	75	70	100	100	75	130	75
Salt of Tartar *	w	Any	150	185	180	200	180	150	150	100	180	x	x	180	75
Saltpeter *	a, gl, w	Any	150	180	185	200	180	150	150	130	130	180	70	210	75
Salt Water			150	185	185	200	180	150	75	75	70	x	100	130	75
Sand Acid	w	50	80	185	x	80	80	150	75	x	70	x	70	x	-
Sea Salt *	a, gl, w	Any	150	185	185	200	180	150	75	75	70	x	100	130	75
Seed Oil	a, b, cb, cl, e	100	x	x	100	150	150	140	-	170	170	170	170	170	-
Separan NP-10	a ac, w		150	-	-	-	-	-	-	-	-	-	-	-	-
Sewage			x	-	150	180	180	150	200	x	70	110	-	-	-
Silicate Esters		Any	x	-	150	x	180	-	-	-	-	-	-	-	-
Silicofluoric Acid	w	50	80	185	x	80	80	150	75	x	70	x	70	x	-
Silicone Grease		100	x	-	x	-	180	-	-	-	-	-	-	-	-
Silicone Oils		100	x	-	x	x	180	-	-	-	-	-	-	-	-
Silver Nitrate *	a, e, gl, w	Any	150	-	150	200	180	150	200	x	130	x	x	210	-
Skydrol		100	x	-	130	x	x	-	-	-	-	-	-	-	-
Slaked Lime *	gl, h, w	Any	150	185	185	200	200	150	100	100	200	x	x	x	75
Soap Solutions			150	185	150	180	180	-	-	170	70	70	170	170	-
Soda *	w	Any	150	185	185	200	200	-	70	120	100	x	x	140	75
Soda Alum *	w	Any	150	-	185	200	200	150	100	x	200	x	75	75	-
Soda Ash *	w	Any	150	185	185	200	200	-	70	120	100	x	x	140	75

CHEMICAL RESISTANCE FOR LINING MATERIALS

	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fiberglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Soda Niter *	a, gl, w	Any	150	180	185	200	150	150	100	130	170	75	x	210	75
Soda Saltpeter *	a, gl, w	Any	150	180	185	200	150	150	100	130	170	75	x	210	75
Sodium Acid Carbonate *	w	Any	150	185	185	200	200	150	75	100	150	x	-	150	-
Sodium Acid Sulfate *	w	Any	150	185	185	200	160	150	75	100	150	x	-	150	-
Sodium Acid Sulfite *	w	Any	150	185	185	200	160	150	75	x	100	x	70	x	x
Sodium Alumino Silicate *		See Solvents													
Sodium Aluminum Fluoride *	al, fe	See Solvents													
Sodium Aluminum Sulfate *	w	Any	150	-	185	200	200	150	100	x	200	x	75	75	-
Sodium Bicarbonate *	w	Any	150	185	185	200	200	150	75	100	150	x	-	150	-
Sodium Bisulfate *	w	Any	150	185	185	200	160	150	200	100	150	x	-	150	-
Sodium Bisulfite *	w	Any	150	185	1d5	200	160	150	75	x	100	x	70	x	x
Sodium Borate *	w	Any	150	-	185	200	180	150	-	-	150	-	-	75	-
Sodium Carbonate *	w	Any	150	185	185	200	200	-	100	120	100	x	x	140	75
Sodium Chloride *	a, gl, w	Any	150	185	185	200	160	150	200	75	70	x	100	130	75
Sodium Cyanide *	a, w	Any	150	185	150	150	160	150	200	100	100	x	x	210	75
Sodium Dioxide *	w	Any	150	-	185	200	200	120	180	75	100	100	x	140	-
Sodium Disulfite *		Any	100	150	150	160	160	100	-	-	70	-	70	210	-
Sodium Fluoaluminate *	al, fe	See Solvents													
Sodium Hexametaphosphate *	w	Any	150	150	185	150	150	150	170	-	180	100	-	-	-
Sodium Hydrate	a, gl, w	Any	150	185	185	200	150	150	100	75	130	x	x	x	75
Sodium Hydroxide	a, gl, w	Any	150	185	185	200	150	150	100	75	130	x	x	x	75
Sodium Hypochlorite *	w	5	x	120(2)	120	x	x	120	75	x	x	x	x	150	75
	w	20	x	120	80	x	x	120	175	x	x	x	x	150	75
Sodium Hyposulfite *	t, w	Any	150	185	185	200	200	150	-	x	70	-	70	210	-
Sodium Metaborate Peroxy-hydrate *	gl, w	Any	150	-	185	200	200	150	-	100	100	x	x	140	-
Sodium Metaphosphate		Any	150	185	185	200	200	150	-	x	70	x	-	210	-
Sodium Nitrate *	a, gl, w	Any	150	180	185	200	150	150	200	130	170	75	x	210	75
Sodium Perborate *	gl, w	Any	150	-	185	200	200	150	-	100	100	x	x	140	-
Sodium Peroxide *	w	Any	150	-	185	200	200	120	-	75	100	100	x	140	-
Sodium Phosphate *	a, w	Any	150	185	135	200	200	150	-	150	150	x	150	210	-
Sodium Pyroborate *	gl, w	Any	150	-	135	200	180	150	-	-	150	-	-	75	-
Sodium Sesquicarbonate *	w	Any	150	185	185	200	200	-	70	120	100	x	x	140	75
Sodium Silicate Sulfate		Any	150	-	185	200	200	-	200	170	170	x	x	-	-
Sodium Stannic Chloride	a, cb, t, w	Any	150	-	150	x	150	150	75	x	x	x	x	210	-
Sodium Sulfate *	gl, w	Any	150	-	150	200	200	150	200	140	180	150	140	210	x
Sodium Sulfate Decahydrate *	gl, w	Any	150	-	185	200	200	150	100	140	180	150	140	210	x
Sodium Subsulfite *	t, w	Any	150	185	185	200	200	150	-	x	70	-	70	210	-
Sodium Sulfite *	a, w	Any	150	185	185	200	200	150	100	70	150	70	70	x	75
Sodium Superoxide *	w	Any	150	-	185	200	200	120	-	75	100	100	x	140	-
Sodium Tetraborate *	w, gl	Any	150	-	185	200	180	150	-	-	150	-	-	75	-
Sodium Thiosulfate *	t, w	Any	150	185	185	200	200	150	-	x	70	-	70	210	-
Sodium Triphosphate *	w	Any	150	185	185	200	200	-	-	100	120	x	x	210	-
Sodium Tripolyphosphate *	w	Any	150	185	185	200	200	-	-	100	120	x	x	210	-
Soya Oil	a, cb, cl, e	100	x	-	x	80	120	-	-	110	170	170	-	-	-
Soybean Oil	a, cb, cl, e	100	x	-	120	80	120	-	-	110	170	170	-	-	-
Spirits of Turpentine	a, aa, cl, e	100	x	x	x	x	150	x	75	70	70	70	70	210	x
Spirits of Wine	a, cl, e	100	150	-	120	150	150	150	170	-	180	100	-	-	-
Stannic Chloride	a, cb, t, w	Any	150	-	150	x	150	150	200	x	x	x	x	210	-
Stannous Chloride *	a, ho, ta, w	Any	150	-	150	x	150	150	200	x	150	x	x	210	-
Starch Syrup	a, gl, w	Any	120	-	185	120	120	150	-	170	170	170	170	170	-
Stoddard's Solvent		100	x	-	x	x	80	x	-	-	-	-	-	-	-
Stearic Acid *	a, cb, cl, ct, e, w	Any	x	-	75	80	200	150	75	120	150	150	x	450	x
STPP *	w	Any	x	-	-	x	x	-	-	-	-	-	-	-	-
Stripper SA			x	x	-	x	-	-	-	x	x	-	x	70	-
Styrene	a, e		x	-	x	x	x	x	-	-	70	75	-	75	-
Sublimed White Lead *	h, w	Any	120	-	185	180	120	120	75	x	150	x	150	180	75
Sucrose Solution		Any	120	-	120	120	120	-	-	-	150	70	130	150	75
Sugar of Lead *	a, gl, h, w	Any	80	-	120	80	80	120	75	x	100	x	x	200	x
Sulfite Liquors		Any	120	-	120	120	120	-	-	x	100	x	100	170	x
Sulfamic Acid		Any	150	-	150	150	-	-	-	-	-	-	-	-	-
Sulfur *	a, b, cb, ct, c	See Solvents													
Sulfurated Lime *	h, w	Any	150	185	185	150	200	150	75	100	100	70	-	75	-
Sulfur Chloride	a, b, cb, e		x	-	x	x	x	-	100	x	x	x	70	150	-
Sulfur Dioxide **	a, e, w	Any	x	150	185	x	x	-	75	x	170	x	150	150	x
Sulfuretted Hydrogen **	a, w	Any	x	x	150	x	x	140	75	70	100	70	70	75	75
Sulfur Hexafluoride **	a, e, w	Any	x	-	80	x	x	-	-	75	-	-	-	-	-
Sulfur Monochloride	a, b, ch, e		x	-	x	x	x	-	100	x	x	x	70	150	-
Sulfur Subchloride	a, b, cb, e		x	-	x	x	x	-	100	x	x	x	70	150	-
Sulfuric Acid		10	150	185	185	180	150	150	170	x	70	x	200	400	x
		30	150	185	185	170	100	150	170	x	x	x	200	400	x
		50	80	150	150	80	80	150	170	x	x	x	200	400	x
		75	x	x	100	x	x	80	x	70	70	x	170	400	x
		95	x	x	x	x	x	x	x	70	70	x	75	400	x
Sulfuric Ether	a, b, cl, o, n, w	Any	x	x	x	x	120	x	x	70	70	70	70	150	75
Sulfurous Acid		10	x	150	150	x	x	130	75	x	70	70	70	210	x
		75	x	-	100	x	x	x	75	x	70	70	70	210	x
Sulfurous Acid Anhydride **	a, e, w	Any	x	150	x	x	x	-	75	x	170	x	150	150	x
Sulfurous Oxychloride			x	-	x	x	x	x	-	x	-	x	120	210	x
Superphosphoric Acid		106	-	-	160	-	-	-	200	x	-	x	70	400	x
Sweet Oil	a, cb, cl, e	100	x	-	100	80	120	-	-	-	-	-	-	-	-
Sweet Birch Oil	aa, e, w	Any	x	-	80	-	x	x	75	75	-	75	-	75	-
Table Salt *	a, w, gl	Any	150	185	185	150	160	150	75	75	70	x	100	130	75
Tallol			x	-	x	x	150	150	200	100	400	x	-	600	-
Tall Oil			x	-	x	x	150	150	200	100	400	x	-	600	-
Tannic Acid *	a, ac, w	Any	100	150	185	x	x	150	75	x	180	x	x	210	x
Tannin *	a, ac, w	Any	100	150	185	x	x	150	75	x	180	x	x	210	x
Tanning Solutions			100	150	150	160	160	100	-	-	70	-	70	210	-
Tar, Bituminous *	b, ch	See Solvents													
Tar Camphor *	a, b, e	See Solvents													
Tartaric Acid *	a, e, w	Any	150	185	185	100	150	150	75	x	150	70	x	175	75
TCA *	a, e, w	Any	x	-	x	x	x	x	-	x	x	x	x	210	-
TCP	os	100	80	-	185	x	x	x	-	75	150	x	-	75	-
TEA	a, cl, w	100	80	-	150	x	120	80	75	75	75	70	-	210	75
Terra Alba *	gl, ho	See Solvents													
Terra Ponderosa *	Con. H_2SO_4	See Solvents													
Terpineol	a, gl, ho, w	Any	x	-	x	x	x	-	-	-	-	75	-	75	-

CHEMICAL RESISTANCE FOR LINING MATERIALS	Solvents	Concentration	Natural Rubber	Hard Rubber	Butyl	Neoprene®	Buna N	PVC	Fiberglass Resins	Mild Steel	316 Stainless	Aluminum	Lead	Glass	Concrete
Tertiary Butyl Catechol		Any	x	-	80	80	x	x	-	-	-	-	-	-	-
Tertiary Butyl Mercaptan		Any	x	-	x	x	x	-	-	-	-	-	-	-	-
Tetrabromoethane	a, e	100	-	-	x	x	x	x	-	-	-	-	-	-	-
Tetrachloridifluoroethane		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Tetrachlorodifluoromethane		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Tetrachloroethane	a, e	100	-	-	x	x	x	x	75	75	-	x	75	75	-
Tetrachloromethane	a, b, cl, e, n, o, w	100	x	x	x	x	x	150	200	75	70	70	100	210	75
Tetradeconoic Acid *	a, e	See Solvents													
Tetra Ethyl Lead	os		x	-	x	-	120	80	-	-	-	-	-	-	-
Tetraethyl Orthosilicate	a	100	x	-	180	180	180	150	-	75	-	-	-	210	-
Tetrafluoromethane		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Tetrahydronapthalene	os	100	x	-	x	x	x	-	-	-	-	75	-	75	-
Tetralin	os	100	x	-	x	x	x	-	-	-	-	75	-	75	-
Trimethyl Pentane		100	x	-	x	80	120	-	-	-	-	-	-	-	-
Tetrol	a, e	100	x	-	x	x	x	-	-	-	-	-	-	-	-
Thenardite *	gl, w	Any	150	-	185	200	200	150	100	140	180	150	140	210	x
Thionyl Chloride			x	-	x	x	x	x	-	x	-	x	120	210	x
Tincal *	w	Any	150	-	185	200	180	150	-	-	150	-	-	75	-
Tin Chloride	a, cb, t, w	Any	150	-	150	x	150	150	75	x	x	x	x	210	-
Tin Crystals *	a, ho, ta, w	Any	150	-	150	x	150	150	120	x	150	x	x	210	-
Tin Dichloride *	a, ho, ta, w	Any	150	-	150	x	150	150	120	x	150	x	x	210	-
Tin Protochloride *	a, ho, ta, w	Any	150	-	150	x	150	150	120	x	150	x	x	210	-
Tin Salt *	a, ho, ta, w	Any	150	-	150	x	150	150	120	x	150	x	x	210	-
Tin Tetrachloride	a, cb, t, w	Any	150	-	150	x	150	150	75	x	x	x	x	210	-
Toluene	a, b, e	100	x	x	x	x	x	70	150	150	150	150	150	150	-
Transformer Oil		100	x	x	x	120	150	x	75	75	-	75	-	75	-
Transmission Fluid		100	x	x	x	x	100	x	-	-	-	-	-	-	-
Travertine *	h	See Solvents													
Triacetin	a, e, os, w	Any	x	-	80	80	80	x	-	-	-	70	-	75	-
Tributoxy Ethyl Phosphate	os	100	x	-	x	x	x	x	-	-	-	-	-	-	-
Tributyl Phosphate		100	x	-	x	x	x	x	-	75	-	-	-	130	-
Trichloroacetic Acid *	a, e, w	Any	x	-	x	x	x	x	-	x	x	x	x	210	-
Trichlorobenzene	a, e, es, os, o		x	x	x	x	x	x	75	85	-	75	-	75	-
Trichloroethane	a, e, es, os, o		x	-	x	x	x	x	-	75	-	-	-	75	-
Trichloroethylene	a, e, es, os, o		x	x	x	x	x	x	75	x	100	120	x	210	-
Trichloromethane	a, b, e, n, o, w	Any	x	x	x	x	x	x	x	x	130	130	130	210	75
Trichloromonofluoromethane		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Trichlorotrifluoroethane		100	x	-	x	x	x	x	-	x	75	70	100	75	-
Tricresyl Phosphate	os	100	80	-	185	x	x	x	-	75	150	x	-	75	-
Triethanol Amine	a, cl, w	Any	80	-	150	x	120	80	75	75	75	70	-	210	75
Triethyl Aluminum	hc	100	x	-	-	x	x	-	-	-	-	-	-	-	-
Triethyl Borane	os	100	x	-	-	x	x	-	-	-	-	-	-	-	-
Trifluorovinyl Chloride	a, b, ke		x	-	x	-	x	x	-	-	-	-	-	-	-
Trihydroxybenzoic Acid *	a, e, gl, w	Any	150	-	150	x	x	150	-	-	180	-	-	-	-
Trihydroxyethyl Amine	a, cl, w	Any	80	-	150	x	120	80	75	75	75	70	-	210	75
Trinitrophenol *	a, b, cl, e, w	Any	x	-	-	x	x	x	75	x	70	x	x	210	x
Triolein	a, cl, e, ct	100	x	-	100	80	120	-	-	-	-	-	-	-	-
Tripalmitin *	cl, e	See Solvents													
Tripolyphosphate *	w	Any	x	-	-	x	x	-	-	-	-	-	-	-	-
Trisodium Phosphate		Any	150	185	185	200	200	150	-	100	120	x	x	210	-
Tritolylphosphate	os	100	80	-	185	x	x	x	-	75	150	x	-	75	-
Tung Oil	e, cb, cl, o	100	x	-	x	120	120	-	-	110	150	170	-	-	-
Turpentine	a, aa, cl, e	100	x	x	x	x	150	x	75	70	70	70	70	210	x
Turpentine Substitute		100	x	x	x	x	x	x	75	75	70	75	-	75	x
Turps	a, aa, cl, e	100	-	x	x	x	150	x	75	70	70	70	70	210	x
Urea *	a, b, e, w	Any	150	185	150	150	150	150	100	70	180	180	-	200	-
Vegetable Oils			x	x	100	x	150	-	-	170	170	170	170	170	-
Versilube, F44 & F50		100	x	-	x	x	150	-	-	-	-	-	-	-	-
Vinegar	a, e, gl, w	8	150	150	150	150	x	x	200	75	180	180	x	400	x
Vinegar Naptha	a, cl, e, w	Any	x	-	100	x	x	x	75	75	100	130	70	210	x
Vinegar Salts *	a, w	Any	80	-	180	x	120	-	130	70	130	70	70	150	-
Vinyl Cyanide	os, w	Any	80	80	x	x	x	-	-	-	-	-	-	-	-
Vinyl Trichloride	a, e, ke, es	100	x	-	x	x	x	x	-	75	-	-	-	75	-
VM & P Naptha		100	x	x	x	x	x	x	75	75	70	75	-	75	x
Water		Any	150	185	185	200	150	150	-	70	75	75	75	75	75
Waterproofing Salt	w	Any	150	185	120	120	120	-	75	x	150	75	75	210	x
Whiskey		100	150	-	150	150	150	150	-	70	x	-	-	-	-
White Caustic *	a, gl, w	Any	150	185	185	200	150	150	100	75	130	x	x	x	75
White Copperas *	gl, w	Any	150	185	150	150	150	150	100	x	200	x	170	210	x
White Lead Sulfate *	h, w	Any	120	-	185	180	120	120	75	x	150	x	150	180	75
White Vitriol *	gl, w	Any	150	185	150	150	150	150	100	x	200	x	170	210	x
Whiting *	h	See Solvents													
Wine		100	150	-	150	150	150	150		x	70	x	-	-	-
Wintergreen Oil	e, aa, w	Any	x	-	80	-	x	x	75	75	-	75	-	75	-
Wood Alcohol	a, e, w	Any	100	-	185	100	150	120	100	150	150	90	150	210	75
Wood Oil	e, cb, cl, o	100	x	-	x	120	120	-	-	110	150	170	-	-	-
Wood Tar	a, e, o	100	x	-	x	x	x	-	-	75	150	70	x	210	x
Wood Vinegar	a, w	Any	-	-	100	x	x	-	75	x	70	70	-	140	-
Xylene	a, e	100	x	x	x	x	x	70	x	150	150	75	-	75	x
Xylidine	a, e	100	x	-	100	x	x	x	-	-	-	-	-	100	-
Zeolite *	w	Any	80	-	-		x	-	-	-	-	-	-	-	-
Zinc Acetate *	a, w	Any	150	-	150	x	x	150	-	-	-	-	-	-	-
Zinc Chloride *	a, e, gl, w	Any	150	185	185	150	150	150	100	x	100	x	75	210	x
Zinc Sulfate *	gl, w	Any	150	185	150	150	150	150	100	x	200	x	170	210	x
Zinc Vitriol *	gl, w	Any	150	185	150	150	150	150	100	x	200	x	170	210	x

APPENDIX B

INDUSTRIAL CHEMICAL CORROSION CHART FOR RESINS, STEEL, ALLOYS, TITANIUM, CERAMIC, AND RUBBERS.(15)

Code: A = Excellent
B = Good
C = Good to 80°F
D = Moderate effect (use under limited conditions)
E = Not recommended
F = Autocatalytic
X = Unknown

CHEMICAL	CPVC a	PVC b	EPOXY	POLYPRO	NORYL c	LUCITE d	KYNAR e	TEFLON f	SS 316 g	CARP 20 h	HAST. C i	TITANIUM	CERAMIC	NEOPRENE j	BUNA N k	HYPALON l	VITON m
ACETALDEHYDE	E	E	X	C	X	E	X	A	A	A	A	A	A	E	B	E	A
ACETIC ACID, 20%	B	B	B	A	A	A	A	A	A	A	A	A	A	D	D	A	E
ACETIC ACID, 80%	D	D	C	B	B	D	A	A	A	A	A	A	A	B	D	A	E
ACETIC ACID, GLACIAL	E	D	C	C	D	E	A	A	A	A	A	A	A	D	E	E	E
ACETIC ANHYDRIDE	E	E	X	A	E	E	D	A	D	C	A	A	A	A	A	A	E
ACETONE	E	E	B	B	X	E	D	A	A	A	A	A D	A	D	E	D	E
ALUMINUM CHLORIDE	A	A	A	A	A	A	A	A	D	D	A	D	A	A	A	A	A
ALUMINUM FLUORIDE	A	A	B	A	A	A	A	A	C	D	B	D	X	A	A	A	A
ALUMINUM SULFATE	A	A	A	A	A	A	A	A	D	B	A	A	A	A	A	A	A
AMMONIA, 10%	A	A	C	A	A	A	A	A	A	A	A	A	A	A	E	A	A
AMMONIUM CHLORIDE	A	A	A	A	A	A	A	A	D	C	A	A	A	A	A	A	A
AMMONIUM NITRATE	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A
AMMONIUM PERSULFATE	A	A	X	A	A	A	A	A	C	B	B	X	A	A	A	A	A
AMMONIUM PHOSPHATE	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
AMMONIUM SULFATE	A	A	A	A	A	A	A	A	B	A	A	A	A	A	B	B	B
AMYL ACETATE	E	E	C	E	E	E	A	A	A	A	A	A	A	E	E	E	E
AMYL ALCOHOL	B	B	X	X	D	E	A	A	A	A	A	A	A	A	B	B	B
AMYL CHLORIDE	E	E	C	X	E	E	A	A	C	A	A	X	A	X	X	E	A
ANILINE	E	E	C	C	E	E	A	A	A	A	A	A	A	E	E	B	A
AQUA REGIA	E	E	E	X	E	E	C	A	E	E	D-E	A	A	E	E	B	A
ARSENIC ACID	A	A	X	A	A	A	A	A	X	B	X	X	A	A	X	X	A
BARIUM CHLORIDE	A	A	A	A	A	A	A	A	C	B	A	A	A	A	B	B	B
BARIUM SULFATE	A	A	A	A	A	A	A	A	B	B	A	A	A	A	A	A	A
BEER	A	A	A	A	A	A	A	A	A	A	A	A	A	A	E	A	A
BENZALDEHYDE	E	E	X	C	E	E	C	A	A	A	A	A	A	E	E	E	E
BENZENE (BENZOL)	E	E	C	C	E	E	C	A	A	A	A	A	A	E	E	E	D
BENZOIC ACID	A	A	A	A	A	C	A	A	B	B	A	C	A	E	E	E	A
BORAX (SODIUM BORATE)	A	A	A	A	A	X	A	A	A	A	A	X	A	A	B	B	B
BORIC ACID	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B
BROMINE WATER	C	C	C	E	A	X	A	A	E	E	A	A	A	E	E	E	A
BUTYL ACETATE	E	E	C	E	E	X	C	A	B	B	A	X	A	X	B	E	E
BUTYRIC ACID	D	D	B	A	A	D	A	A	B	A	A	C	A	E	X	E	D
CALCIUM BISULFITE	A	A	A	A	A	X	A	A	B	B	A	C	A	A	A	A	A
CALCIUM CHLORIDE	A	A	A	A	A	A	A	A	C	A	A	A	A	A	A	A	A
CALCIUM HYPOCHLORITE	A	A	X	A	A	A	A	A	D	D	B	A	A	E	B	A	D
CALCIUM SULFATE	A	A	A	A	A	A	A	A	B	B	A	A	A	A	A	A	A
CARBON TETRACHLORIDE	C	C	C	C	E	X	A	A	B	B	A	A	A	E	E	E	A
CARBONIC ACID	A	A	B	A	A	A	A	A	B	A	A	X	A	A	B	B	B
CHLOROACETIC ACID	A	A	C	D	X	E	A	A	E	X	A	A	A	E	E	A	A
CHLORINE WATER	A	A	X	E	D	X	A	A	F	B	B	A	A	E	E	B	A
CHLOROBENZENE	E	E	X	C	E	E	A	A	A	A	A	X	A	E	E	E	A
CHLOROFORM	E	E	C	E	E	E	A	A	A	A	A	A	A	E	E	E	D
CHLOROSULFONIC ACID	C	C	X	E	X	E	E	A	D	D	A	A	A	E	E	X	E
CHROMIC ACID, 10%	A	A	D	A	A	A	A	A	B	A	A	A	A	E	E	A	A
CHROMIC ACID, 30%	A	A	E	A	E	A	A	A	B	A	A	A	A	E	E	A	A
CHROMIC ACID, 50%	E	E	E	A	E	D	A	A	C	B	A	A	A	E	E	A	A

CHEMICAL	CPVC	PVC	EPOXY	POLYPRO	NORYL	LUCITE	KYNAR	TEFLON	SS 316	CARP 20	HAST. C	TITANIUM	CERAMIC	NEOPRENE	BUNA N	HYPALON	VITON
CITRIC ACID	A	A	A	A	A	A	A	A	B	A	A	A	A	A	E	A	A
COPPER CHLORIDE	A	A	A	A	A	A	A	A	B	B	A	A	A	A	B	B	B
COPPER CYANIDE	A	A	D	A	A	A	A	A	A	A	A	A	A	A	B	X	B
COPPER NITRATE	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B
COPPER SULFATE	A	A	A	A	A	A	A	A	B	A	A	A	A	A	B	B	B
CRESYLIC ACID	B	B	X	X	X	X	A	A	A	A	A	A	A	X	X	X	A
ETHYL ACETATE	E	E	B	C	E	E	C	A	B	B	B	X	A	E	X	E	E
ETHYL CHLORIDE	E	E	C	E	E	E	A	A	A	A	B	A	A	D	E	D	A
ETHYLENE GLYCOL	A	A	A	A	A	A	A	A	B	A	A	X	A	A	B	B	B
FATTY ACIDS	A	A	A	A	A	D	A	A	A	A	A	A	A	B	A	X	B
FERRIC CHLORIDE	A	A	A	A	A	A	A	A	E	E	B-C	A	A	A	E	B	B
FERRIC NITRATE	A	A	A	A	A	A	A	A	B	A	B	A	A	A	B	B	B
FERRIC SULFATE	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B
FERROUS CHLORIDE	A	A	A	A	A	A	A	A	E	E	B	A	A	A	X	B	B
FERROUS SULFATE	A	A	A	A	A	A	A	A	D	B	A	A	A	A	X	B	B
FLUOBORIC ACID	A	A	X	A	B	B	A	A	B	A	A	E	E	A	X	B	X
FLUOSILICIC ACID	A	A	D	A	B	B	A	A	B	B	B	E	E	B	A	X	B
FORMALDEHYDE, 40%	B	B	A	A	A	A	A	A	A	A	A	A	A	A	B	B	E
FORMIC ACID	C	C	C	A	A	E	A	A	B	A	A	A	A	A	E	B	E
FREON 12 (WET)	C	C	B	A	A	X	X	A	E	X	X	X	A	C	B	E	A
FUEL OILS	A	A	X	C	A	X	D	A	A	A	A	A	A	A	B	B	B
FURFURAL	E	E	X	E	E	X	A	A	B	A	A	X	A	E	E	X	E
GASOLINE	C	C	B	E	E	E	A	A	A	A	A	E	A	E	B	E	A
GLYCERINE (GLYCEROL)	A	A	A	A	X	A	A	A	A	A	A	A	A	A	B	B	B
HEPTANE	A	A	B	C	E	X	A	A	A	A	A	X	A	D	A	B	B
HEXANE	C	C	C	C	X	X	A	A	A	A	A	X	A	A	X	B	B
HYDROBROMIC ACID, 20%	A	A	B	A	A	X	A	A	E	E	A	A	C	D	E	A	A
HYDROCHLORIC ACID, 0-25%	A	A	A	A	A	A	A	A	E	E	B–C	D	C	A	X	A	B
HYDROCHLORIC ACID, 25-37%	A	A	A	A	A	A	A	A	E	E	B–C	D	C	A	X	A	A
HYDROCYANIC ACID	A	A	X	A	A	A	A	A	A	A	A	X	C	X	B	X	A
HYDROFLUORIC ACID, 10%	C	C	X	A	A	A	A	A	C	C	B	E	E	A	X	A	A
HYDROFLUORIC ACID, 30%	C	C	X	B	D	D	A	A	C	C	B	E	E	A	X	A	A
HYDROFLUORIC ACID, 60%	D	D	X	B	E	D	A	A	C	C	B	E	E	E	X	D	A
HYDROFLUOSILICIC ACID, 20%	A	A	D	A	B	B	A	A	B	B	B	E	E	A	A	X	B
HYDROGEN PEROXIDE, 30%	A	A	C	A	X	A	A	A	B	A	A	B	X	D	E	A	A
HYDROGEN PEROXIDE, 50%	C	C	X	X	X	X	A	A	B	A	A	X	X	D	E	A	A
HYDROGEN PEROXIDE, 90%	E	E	X	X	X	X	C	A	B	A	A	X	X	E	E	D	A
HYDROGEN SULFIDE, AQ. SOL.	C	C	A	A	A	A	A	A	B	A	A	A	X	A	E	B	B
IODINE (IN ALCOHOL)	E	E	X	C	D	X	A	A	B	B	A	E	A	E	E	E	A
KEROSENE	B	B	A	C	X	A	A	A	A	A	A	A	A	E	B	E	A
KETONES	E	E	X	E	E	E	C	A	A	A	A	A	A	E	E	E	E
LACQUER THINNERS	D	D	X	C	E	E	X	A	A	A	A	A	A	E	E	X	X
LACTIC ACID	B	B	A	A	A	D	B	A	B	A	B	A	A	A	X	B	B
LEAD ACETATE	A	A	A	A	A	A	A	A	A	A	A	A	A	E	X	E	A
LUBRICATING OIL	C	C	X	C	X	A	A	A	A	A	A	A	A	E	A	D	A
MAGNESIUM CHLORIDE	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A	A	A
MAGNESIUM NITRATE	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
MAGNESIUM SULFATE	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
MALEIC ACID	A	A	B	A	A	X	A	A	B	A	A	A	A	X	X	A	A
METHYL ALCOHOL	C	C	X	A	A	X	A	A	A	A	A	A	A	A	B	B	D
METHYL CHLORIDE	E	E	X	E	E	E	A	A	A	A	A	A	A	E	E	E	A
METHYL ETHYL KETONE	E	E	C	C	E	E	E	A	A	A	A	A	A	E	E	E	E
METHYL ISOBUTYL KETONE	E	E	B	C	E	E	B	A	A	A	A	A	A	E	E	E	E
METHYLENE CHLORIDE	E	E	X	E	E	E	D	A	A	A	A	A	A	E	E	E	D
NAPTHA	B	B	A	C	X	E	A	A	A	A	A	A	A	E	D	E	A
NAPTHALENE	E	E	B	C	X	X	A	A	A	A	A	A	A	E	E	E	D
NICKEL CHLORIDE	A	A	A	A	A	A	A	A	B	B	A	A	A	A	B	B	B
NICKEL SULFATE	A	A	A	A	A	A	A	A	B	A	B	A	A	A	B	B	B
NITRIC ACID, 10%	A	A	X	A	A	D	A	A	B	A	A	A	A	E	E	A	A
NITRIC ACID, 20%	A	A	X	A	B	E	A	A	B	A	A	A	A	E	E	A	A
NITRIC ACID, 50%	A	A	X	C	E	E	A	A	B	A	A	A	A	E	E	E	A
NITRIC ACID, ANHYDROUS	E	E	X	E	E	E	D	A	B	A	B	A	A	E	E	E	B
NITRO BENZENE	E	E	X	C	E	E	B	A	B	A	B	A	A	E	E	E	E
OILS AND FATS	A	A	X	A	X	X	X	A	A	A	A	A	A	A	A	X	A
OLEIC ACID	A	A	A	C	A	X	A	A	B	B	B	X	A	D	A	D	D
OLEUM, 25%	E	E	E	X	E	E	E	A	X	X	A	X	A	E	E	E	A
OXALIC ACID	A	A	A	A	A	D	A	A	C	B	B	C	A	X	X	A	A
PHENOL	C	C	D	B	E	A	A	A	B	B	A	A	A	E	E	E	A

CHEMICAL	CPVC	PVC	EPOXY	POLYPRO	NORYL (PPO)	LUCITE	KYNAR	TEFLON	SS 316	CARP 20	HAST. C	TITANIUM	CERAMIC	NEOPRENE	BUNA N	HYPALON	VITON
PHOSPHORIC ACID, 0-50%	A	A	A	A	A	A	A	A	B	B	A	C	A	B	X	A	B
PHOSPHORIC ACID, 50-100%	B	B	D	B	A	A	A	A	B	B	A-B	C	A	B	X	A	B
POTASSIUM BICARBONATE	A	A	A	A	A	A	A	A	B	B	B	A	A	A	B	B	B
POTASSIUM BROMIDE	A	A	A	A	A	A	A	A	B	B	A	A	A	A	B	B	B
POTASSIUM CARBONATE	A	A	A	A	A	A	A	A	B	B	B	A	A	A	E	B	B
POTASSIUM CHLORATE	A	A	X	A	A	A	A	A	A	A	X	A	A	A	B	B	B
POTASSIUM CHLORIDE	A	A	A	A	A	A	A	A	D	C	A-B	A	A	A	B	B	B
POTASSIUM CYANIDE	A	A	B	A	A	A	A	A	A	B	B	A	A	A	B	B	B
POTASSIUM DICHROMATE	A	A	A	A	A	A	A	A	A	A	B	A	A	A	B	B	B
POTASSIUM HYDROXIDE	A	A	A	A	A	D	A	A	B	B	B	A-C	E	A	D	B	B
POTASSIUM NITRATE	A	A	A	A	A	A	A	A	B	B	B	A	A	A	B	B	B
POTASSIUM PERMANGANATE	A	A	B	A	A	A	A	A	B	B	A	A	A	A	B	B	B
POTASSIUM SULFATE	A	A	B	A	A	A	A	A	B	B	B	A	A	A	B	B	B
PROPYL ALCOHOL	C	C	X	X	X	X	A	A	A	A	A	A	A	A	B	B	B
SOAPS	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B
SODIUM ACETATE	A	A	A	A	A	A	A	A	B	B	B	A	A	D	E	A	E
SODIUM BICARBONATE	A	A	A	A	A	A	A	A	B	A	B	A	A	A	B	B	B
SODIUM BISULFATE	A	A	X	A	A	A	A	A	A	A	B	A	A	A	B	B	B
SODIUM BISULFITE	A	A	A	A	A	A	A	A	B	B	B	A	A	A	B	B	B
SODIUM CARBONATE	A	A	A	A	A	A	A	A	B	A	B	A	A	A	B	B	B
SODIUM CHLORATE	A	A	X	A	A	A	A	A	B	B	B	A	A	A	E	B	B
SODIUM CHLORIDE	A	A	A	A	A	A	A	A	B	B	B	A	A	A	B	B	B
SODIUM CYANIDE	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B
SODIUM HYDROXIDE, 20%	A	A	A	A	A	D	A	A	A	A	A	A	E	A	B	B	E
SODIUM HYDROXIDE, 50%	A	A	A	A	A	D	A	A	A	A	A	A	E	A	B	B	C
SODIUM HYPOCHLORITE	A	A	X	A	A	A	A	A	D	X	A-B	A	A	D	E	A	D
SODIUM NITRATE	A	A	A	A	A	A	A	A	A	A	B	A	A	A	B	B	B
SODIUM SILICATE	A	A	B	A	A	A	A	A	B	B	B	X	A	A	A	A	A
SODIUM SULFATE	A	A	A	A	A	A	A	A	A	A	A	X	A	A	B	B	B
SODIUM SULFIDE	A	A	X	A	A	A	A	A	B	B	B	A	A	A	E	B	B
STANNIC CHLORIDE	A	A	A	A	A	A	A	A	E	C	B	A	A	A	B	D	B
STEARIC ACID	A	A	B	C	X	X	A	A	A	A	A	A	A	D	E	D	A
STODDARDS SOLVENT	E	E	X	X	E	X	A	A	A	A	A	A	X	E	X	X	A
SULFURIC ACID, 0-10%	A	A	A	A	A	A	A	A	E	A	B	C	A	A	D	A	A
SULFURIC ACID, 10-75%	A	A	C	A	A	D	A	A	E	A	B	D	A	E	E	A	A
SULFURIC ACID, 75-100%	C	C	E	C	A	E	A	A	E	A	B	E	A	E	E	D	A
TANNIC ACID	A	A	A	A	X	X	A	A	B	B	B	A	A	A	E	B	B
TANNING LIQUORS	A	A	X	A	X	X	X	A	A	A	A	A	A	X	A	X	A
TARTARIC ACID	A	A	A	A	A	X	A	A	B	B	B	A	A	A	E	B	B
TETRAHYDROFURANE	E	E	X	C	E	X	D	A	A	A	A	X	A	X	E	X	X
TOLUENE (TOLUOL)	E	E	B	C	E	E	A	A	A	A	A	A	A	E	E	E	E
TRICHLOROETHYLENE	E	E	B	C	E	X	A	A	B	B	A	A	A	E	E	E	A
TRICRESYLPHOSPHATE	E	E	X	X	X	X	X	A	A	A	A	B	A	E	E	E	A
TURPENTINE	B	B	C	C	X	X	A	A	A	A	A	X	A	E	E	E	A
UREA	A	A	B	A	X	X	A	A	B	B	B	A	A	A	E	A	E
VINEGAR	A	A	B	A	A	A	A	A	A	A	A	A	A	A	E	B	B
WHITE LIQUOR (ACID)	A	A	X	X	A	X	A	A	A	A	A	X	A	X	A	X	A
XYLENE (XYLOL)	E	E	B	F	E	E	A	A	A	A	A	X	A	E	E	E	A
ZINC CHLORIDE	A	A	A	A	A	A	A	A	B	A	B	A	A	A	B	B	B
ZINC SULFATE	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A

[a] chlorinated poly(vinyl chloride)

[b] poly(vinyl chloride)

[c] modified polyphenylene oxide

[d] acrylic resin

[e] poly(vinylidene fluoride)

[f] poly(tetrafluoroethylene)

[g] stainless steel

[h] Carpenter 20Cb-3: austenitic Ni-Cr-Fe-Mo-Cb-Cu SS

[i] Hastelloy Alloy C: austenitic Ni-Cr-Fe-Mo-W SS

[j] poly(chloroprene)

[k] butadiene-acrylonitrile copolymer

[l] chlorosulfonated poly(ethylene) rubber

[m] vinylidene fluoride-hexafluoropropylene rubber

NRC FORM 335
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NRCM 1102
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13. ABSTRACT (200 words or less)

High-activity tritiated waste generated in the United States is mainly composed of tritium gas and tritium-contaminated organic solvents sorbed onto Speedi-Dri which are packaged in small glass bulbs. Low-activity waste consists of solidified and adsorbed liquids. In this report, current packages for high-activity gaseous and low-activity adsorbed liquid wastes are emphasized with regard to containment potential.

Containers for low-level radioactive waste containing large amounts of tritium need to be developed. An integrity may be threatened by: physical degradation due to soil corrosion, gas pressure build-up (due to radiolysis and/or biodegradation), rapid permeation of tritium through the container, and corrosion from container contents. Literature available on these points is summarized in this report.

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ALTERNATIVE CONTAINERS FOR LOW-LEVEL WASTES CONTAINING
LARGE AMOUNTS OF TRITIUM

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