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Aqueous Corrosion Rates for Waste Package Materials

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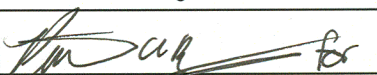

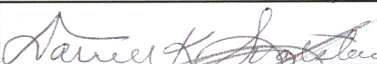
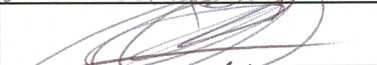

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CONTENTS

	Page
1. PURPOSE.....	1-1
2. QUALITY ASSURANCE.....	2-1
3. USE OF SOFTWARE	3-1
3.1 QUALIFIED SOFTWARE.....	3-1
3.2 EXEMPT SOFTWARE.....	3-1
4. INPUTS.....	4-1
4.1 DIRECT INPUTS	4-1
4.1.1 Waste Package Materials	4-1
4.1.2 Spent Fuels and Waste Forms.....	4-4
4.1.3 Steels and Alloys.....	4-4
4.1.4 Miscellaneous Materials	4-43
4.1.5 Miscellaneous Handbook Data	4-45
4.1.6 Titanium Grades 7 and 24.....	4-45
4.2 CRITERIA	4-47
4.3 CODES, STANDARDS, AND REGULATIONS.....	4-47
5. ASSUMPTIONS.....	5-1
5.1 ASSUMPTIONS CONCERNING STEEL TYPES INVESTIGATED IN THIS ANALYSIS.....	5-1
5.1.1 AM-350 Corrosion Rate	5-1
5.1.2 Use of Corrosion of Stainless Steel Type 302	5-1
5.2 ASSUMPTIONS CONCERNING ALLOYS INVESTIGATED IN THIS ANALYSIS.....	5-1
5.2.1 Corrosion of Inconel Alloys 600 and X-750.....	5-1
5.2.2 Density of Aluminum Alloys.....	5-2
5.3 ASSUMPTIONS CONCERNING MISCELLANEOUS MATERIALS	5-2
5.3.1 GdPO ₄ Mineralogy.....	5-2
5.4 ASSUMPTIONS CONCERNING GLASS FRACTURING	5-3
5.4.1 Cooling Fractures.....	5-3
5.4.2 Fractures Due to a Drop.....	5-3
5.4.3 Availability of Cooling Fractures	5-4
5.4.4 Reactivity of Glass Fractures.....	5-4
6. SCIENTIFIC ANALYSIS DISCUSSION.....	6-1
6.1 TYPES OF CORROSION	6-2
6.1.1 General Corrosion.....	6-2
6.1.2 Localized Corrosion.....	6-2
6.1.3 Galvanic Corrosion	6-3
6.2 STEELS AND ALLOYS.....	6-4
6.2.1 Stainless Steel	6-7
6.2.2 Steel Containing Neutron Absorbers	6-15

CONTENTS (Continued)

	Page
6.2.3 Carbon Steel Type A516.....	6-20
6.2.4 Aluminum Alloys.....	6-24
6.2.5 Zircaloy (2 and 4).....	6-29
6.2.6 Alloy N06464.....	6-29
6.2.7 Inconel Alloys.....	6-31
6.2.8 Alloy 22	6-32
6.3 MISCELLANEOUS MATERIALS	6-33
6.3.1 Silicon Carbide (SiC) Oxidation.....	6-33
6.3.2 Pyrolytic Carbon and Graphite Oxidation	6-34
6.3.3 Gadolinium Phosphate (GdPO ₄) Dissolution.....	6-34
6.4 SPENT FUELS AND WASTE FORMS	6-35
6.4.1 DOE Spent Nuclear Fuel	6-35
6.4.2 Commercial Spent Nuclear Fuel.....	6-35
6.4.3 Defense High-Level Waste Glass	6-35
6.5 TITANIUM GRADES 7 AND 24	6-38
6.5.1 Titanium Grade 7	6-38
6.5.2 Titanium Grade 24	6-39
7. CONCLUSIONS.....	7-1
7.1 STEELS AND ALLOYS.....	7-1
7.2 MISCELLANEOUS MATERIALS	7-3
7.3 GLASS FRACTURE FACTOR	7-3
7.4 YUCCA MOUNTAIN REVIEW PLAN ACCEPTANCE CRITERIA	7-4
8. INPUTS AND REFERENCES.....	8-1
8.1 DOCUMENTS CITED.....	8-1
8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES.....	8-10
8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER	8-12
8.4 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER	8-12
APPENDIX I LISTING OF FILES ON CD.....	I-1
APPENDIX II ATTACHED CD-ROM	II-1
APPENDIX III QUALIFICATION OF DATA THAT SUPPORTS AQUEOUS CORROSION RATES FOR WASTE PACKAGES MATERIALS (ANL-DSD-MD-000001)	III-1

FIGURES

	Page
6-1. ECDF for Stainless Steel Types 302/304/304L in All Water Types Investigated.....	6-9
6-2. ECDF for Stainless Steel Types 302/304/304L Showing Detail for Slower Rates	6-9
6-3. ECDF for Stainless Steel Types 316/316L/AM-350 in Freshwater	6-11
6-4. ECDF for Stainless Steel Types 316/316L/AM-350 in Saltwater	6-11
6-5. ECDF for Stainless Steel Types 316/316L/AM-350 in Saltwater Showing More Detail for Corrosion Rates Below 2.5 $\mu\text{m}/\text{yr}$	6-12
6-6. Experimental Results of Boil-Down Tests	6-13
6-7. Corrosion Rate of Stainless Steel Type 304L as a Function of H_2O_2 from Radiolysis .	6-14
6-8. ECDF for Neutronit (Using Stainless Steel Type 321 Surrogate) in Freshwater	6-16
6-9. ECDF for Neutronit (Using Stainless Steel Type 321 Surrogate) in Saltwater	6-17
6-10. ECDF for 0.3 Percent Borated Stainless Steel Type 304 in All Water Types Investigated	6-18
6-11. ECDF for 1.5 Percent Borated Stainless Steel Type 304 in All Water Types Investigated	6-19
6-12. Corrosion Rates versus Temperature for Mild Steel.....	6-22
6-13. ECDF for Carbon Steel Type A516 in All Water Types Investigated (Time ≥ 1 Year)	6-23
6-14. ECDF for Aluminum Alloy	6-26
6-15. ECDF for Aluminum Alloy For $F_n(x)$ Less than 0.50	6-27
6-16. ECDF for Aluminum Alloy For $F_n(x)$ Between 0.50 and 0.85.....	6-28
6-17. ECDF for Aluminum Alloy For $F_n(x)$ Between 1.0 and 0.85.....	6-29
6-18. Corrosion of Alloy N06464	6-30
6-19. ECDF for Alloy N06464 in Freshwater at Time ≤ 0.8 Years	6-31
6-20. ECDF for Inconel Alloys in All Water Types Investigated.....	6-32
6-21. Titanium Grade 7 Weight-Loss Corrosion Rates after 2.5 Years	6-39
6-22. Corrosion Rates of Titanium Grades 2, 5, 7, 16, and 24 in Boiling HCl.....	6-40
6-23. ECDF for Titanium Grade 24 in All Water Types Investigated	6-41

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TABLES

	Page
3-1. Computer Software Used in this Analysis	3-1
3-2. Computers Used in Analysis	3-1
4-1. Summary of Waste Package Materials	4-3
4-2. Stainless Steel Types 302/304/304L Corrosion in Freshwater	4-6
4-3. Stainless Steel Types 316/316L Corrosion in Freshwater	4-10
4-4. Stainless Steel Types 302/304/304L Corrosion in Seawater	4-12
4-5. Stainless Steel Types 316/316L Corrosion in Seawater	4-15
4-6. Corrosion of Stainless Steel Type 304L in Boil-Down Tests	4-17
4-7. Corrosion Rates of Stainless Steel Type 304L in Solution Containing Radiolysis Products (H_2O_2)	4-18
4-8. Neutronit-Corrosion Rates (Using Stainless Steel Type 321 Surrogate) in Freshwater	4-19
4-9. Neutronit Corrosion Rates (Using Stainless Steel Type 321 Surrogate) in Seawater ...	4-20
4-10. Corrosion of Borated Stainless Steel Type 304L for Use as “Freshwater” Rates	4-21
4-11. Corrosion of Borated Stainless Steel Type 304L for Use as “Saltwater” Rates	4-22
4-12. Corrosion Rates of Gadolinium-Alloyed Steel	4-25
4-13. Carbon Steel Corrosion at 1 Year in Freshwater at 90°C	4-26
4-14. Carbon Steel Corrosion at 1 Year in Saltwater at 90°C	4-27
4-15. Carbon Steel Corrosion at 1 Year in Freshwater at 60°C	4-28
4-16. Carbon Steel Corrosion at 1 Year in Saltwater at 60°C	4-29
4-17. Carbon Steel Corrosion at 0.53 Years in Freshwater at 90°C	4-30
4-18. Carbon Steel Corrosion at 0.5 Years in Saltwater at 90°C	4-31
4-19. Carbon Steel Corrosion at 0.52 Years in Freshwater at 60°C	4-32
4-20. Carbon Steel Corrosion at 0.50 Years in Saltwater at 60°C	4-33
4-21. Corrosion Rates of Aluminum in Seawater	4-34
4-22. Corrosion Rates of Aluminum in Freshwater	4-37
4-23. Corrosion Rates of Alloy N06464 in J-13 Water	4-39
4-24. Corrosion Rates of Inconel Alloys in Freshwater	4-40
4-25. Corrosion Rates of Inconel Alloys in Acidified Water	4-40
4-26. Corrosion Rates of Inconel Alloys in Saltwater	4-42
4-27. Material Densities	4-43
4-28. Corrosion Behavior of Sintered Carbon Materials	4-44
4-29. High Temperature Values for SiC Oxidation	4-44
4-30. Miscellaneous Constants Used in Conversions	4-45
4-31. Titanium Grade 7 Weight-Loss Corrosion Rates in Aqueous Media (2.5-Year Data) ..	4-46
6-1. Major Bi-Metallic Couples Located Within Waste Packages	6-4
6-2. Composition (wt%) of Steel and Alloys	6-5
6-3. Halide Content of Several Waters from Yucca Mountain Strata Compared to J-13 Well Water	6-8
6-4. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Stainless Steel Types 302/304/304L	6-10

6-5.	Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Stainless Steel Types 316/316L/AM-350	6-12
6-6.	Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Neutronit (Using Stainless Steel Type 321 Surrogate)	6-16
6-7.	Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Borated Stainless Steel Type 304	6-19
6-8.	Comparison of Minimum, Maximum, Mean, and Median Corrosion Rates of Gadolinium-Alloyed and Non Gadolinium-Alloyed Stainless Steel Type 304L	6-20
6-9.	Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Carbon Steel Type A516	6-23
6-10.	Pitting in Aluminum Alloys.....	6-25
6-11.	Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Aluminum Alloy	6-28
6-12.	Minimum, Maximum, Mean, and Median Corrosion Rates of Alloy N06464 in Solution	6-30
6-13.	Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Inconel Alloys.....	6-32
6-14.	Approximate Values of Oxidation for Graphite and Pyrolytic Carbon	6-34
6-15.	Probability of Loading Damaged Glass Pour Canisters into Waste Packages.	6-36
6-16.	Fracture Factor Probabilities (Fracture Factor Averaged Over 5 Glass Pour Canisters) for High Level Waste Glass Based on Loading Damaged Glass Pour Canisters into Waste Packages.....	6-37
6-17.	True Fracture Factors for High Level Waste Glass in One Glass Pour Canister.....	6-38
6-18.	Minimum, Maximum, Mean, and Median Corrosion Rates of Titanium Alloy Grade 24 in Solution	6-41
7-1.	Summary of Statistical Values of Corrosion for Waste Package Metals.....	7-1
7-2.	Comparison of Minimum, Maximum, Mean, and Median Corrosion Rates of Gadolinium-Alloyed and Non Gadolinium-Alloyed Stainless Steel Type 304.....	7-2
7-3.	Summary of Corrosion Behavior and Rates for Graphite, SiC, and Gadolinium Phosphate	7-3
7-4.	Fracture Factor Probabilities (Fracture Factor Averaged Over 5 Glass Pour Canisters) for High-Level Waste Glass Based on Loading Damaged Glass Pour Canisters into Waste Packages.....	7-4
7-5.	True Fracture Factors for High-Level Waste Glass in One Damaged Glass Pour Canister	7-4

ACRONYMS AND ABBREVIATIONS

ANL	Argonne National Laboratory
ATWT	atomic weight
BSC	Bechtel SAIC Company
BWR	boiling water reactor
CDF	cumulative distribution function
CRWMS	Civilian Radioactive Waste Management System
CSNF	commercial spent nuclear fuel
DHLW	defense high-level waste
DOE	U.S. Department of Energy
DTN	data tracking number
ECDF	empirical cumulative distribution function
EPRI	Electric Power Research Institute
FFTF	Fast Flux Test Facility
FSVR	Fort Saint Vrain Reactor
LA	License Application
LWBR	light water breeder reactor
LLNL	Lawrence Livermore National Laboratory
LTCTF	Long Term Corrosion Test Facility
μm	micron or micrometer, or 10 ⁻⁶ meter
mil	1/1,000 th of an inch, or 25.4 μm
M&O	Management and Operating Contractor
MCO	multi-canister overpack
MOX	mixed oxide
MR	model report
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
SAW	simulated acidified well
SCW	simulated concentrated well
SDW	simulated dilute well
SKB	Swedish Nuclear Fuel and Waste Management Company
SNF	spent nuclear fuel
TRIGA	Training, Research, Isotopes, General Atomics
TSPA	Total System Performance Assessment
TSPA-LA	Total System Performance Assessment License Application

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1. PURPOSE

The purpose of this analysis, as directed by *Technical Work Plan for: Regulatory Integration Modeling and Analysis of the Waste Form and Waste Package* (BSC 2004 [DIRS 171583]), is to compile applicable corrosion data from the literature (journal articles, engineering documents, materials handbooks, or standards, and national laboratory reports), evaluate the quality of these data, and use these to perform statistical analyses and distributions for aqueous corrosion rates of waste package materials. The purpose of this report is not to describe the performance of engineered barriers for the TSPA-LA. Instead, the analysis provides simple statistics on aqueous corrosion rates of steels and alloys.

These rates are limited by various aqueous parameters such as temperature (up to 100°C), water type (i.e., fresh versus saline), and pH. Corrosion data of materials at pH extremes (below 4 and above 9) are not included in this analysis, as materials commonly display different corrosion behaviors under these conditions. The exception is highly corrosion-resistant materials (Inconel Alloys) for which rate data from corrosion tests at a pH of approximately 3 were included. The waste package materials investigated are those from the long and short 5-DHLW waste packages, 2-MCO/2-DHLW waste package, and the 21-PWR commercial waste package. This analysis also contains rate data for some of the materials present inside the fuel canisters for the following fuel types: U-Mo (Fermi U-10%Mo), MOX (FFTF), Thorium Carbide and Th/U Carbide (Fort Saint Vrain [FSVR]), Th/U Oxide (Shippingport LWBR), U-metal (N Reactor), Intact U-Oxide (Shippingport PWR, Commercial), aluminum-based, and U-Zr-H (TRIGA).

Analysis of corrosion rates for Alloy 22, spent nuclear fuel, defense high level waste (DHLW) glass, and Titanium Grade 7 can be found in other analysis or model reports (See Sections 6.2.8, 6.4, and 6.5.1).

This analysis supports risk and criticality calculations or analyses, but will not be used directly in the TSPA-LA. Output from this analysis will be used to support calculations or analyses using the EQ6 computer code for reaction-path modeling of aqueous geochemical systems (Wolery and Daveler 1992 [DIRS 100097]). The following downstream criticality documents use this analysis or its output data as input: *Impacts of Updated Design and Rates on EQ6 Calculations for Chemical Degradation of Fermi and TRIGA Codisposal Waste Packages*, *EQ6 Calculations for Chemical Degradation of ATR Aluminum-Based DOE SNF in a Waste Package*, *Screening Analysis of Criticality Features, Events, and Processes for License Application*, *Boron Loss from CSNF Waste Packages*, *Probability of External Criticality for Codisposal Waste Packages*, and *Configuration Generator Model for In-Package Criticality*. This analysis supports the determination of the probability of criticality for DOE SNF codisposal waste packages by providing, where appropriate: 1) minimum, maximum, mean, and median values of corrosion rates with the corresponding standard deviations; and 2) empirical cumulative distribution functions (ECDFs) of the corrosion rates of materials.

Output from this report is limited to general corrosion rates of waste package materials. A statistical analysis of galvanic and localized corrosion rates is not provided in this analysis.

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2. QUALITY ASSURANCE

The preparation of this analysis and the supporting activities are subject to *Quality Assurance Requirements and Description* (DOE 2004 [DIRS 171539]), as stated in the technical work plan (BSC 2004 [DIRS 171583]). This analysis was prepared in accordance with AP-SIII.9Q, *Technical Reports*, and reviewed in accordance AP-2.14Q, *Document Review*. It does not investigate any items in *Q-List* (BSC 2004 [DIRS 168361]).

The control of the electronic management of information was evaluated in accordance with AP-SV.1Q, *Control of the Electronic Management of Information*. Methods used for electronic information control, as specified in the technical work plan (BSC 2004 [DIRS 171583]) include:

- Records submitted in accordance with AP-17.1Q, *Records Management*, and AP-6.1Q, *Document Control*, are retrievable through the records processing center.
- Engineering technical information stored on writeable CD-ROMs that are not rewriteable. Conditions, location, retention time, and access are controlled through the records center following submittal in accordance with AP-17.1Q, *Records Management*, and AP-6.1Q, *Document Control*.
- Media identified in accordance with AP-17.1Q, *Records Management*, and AP-SIII.9Q, *Technical Reports*.

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3. USE OF SOFTWARE

3.1 QUALIFIED SOFTWARE

No software that requires project or application-specific qualification or validation in accordance with LP-SI.11Q-BSC, *Software Management*, was used in this analysis.

3.2 EXEMPT SOFTWARE

This section describes the computer software used to carry out the calculations in Section 4 and the regression analysis in Section 6. Table 3-1 lists computer software used in this analysis.

Table 3-1. Computer Software Used in this Analysis

Software Name	Version	Software Tracking Number (Qualification Status)	Description and Components Used	Input and Output Files (Included in Appendix II)
Microsoft Excel	Versions 97 SR-2, 9.0.4402 SR-1	Commercial off-the-shelf software	Used in this document for graphical representation and arithmetical manipulations	output: *.xls

Microsoft Excel for Windows 97 (Versions SR-1 and SR-2) is used in calculations and analyses to manipulate the inputs using standard mathematical expressions and operations. It is also used to tabulate and chart results. The user-defined formulas, inputs, and results are documented in sufficient detail to allow an independent repetition of computations. Thus, Microsoft Excel is used only as a worksheet, not as a software routine; therefore, in accordance with LP-SI.11Q-BSC, *Software Management*, it is not required to be qualified or documented.

Microsoft Excel was run on standard personal computers listed in Table 3-2.

Table 3-2. Computers Used in Analysis

Computer Make	CPU #	Operating System	Software Used
Dell Optiplex GX300	CRWMS-M&O Tag # 117728	Windows 95	Microsoft Excel (97 SR-2)
Dell Latitude C/Port II APR	Framatome ANP Inc. Service Tag # H22MT11	Windows 2000	Microsoft Excel (9.0.4402 SR-1)
Dell Optiplex GX260	CRWMS-M&O Tag # 152393	Windows 2000	Microsoft Excel (97 SR-2)

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4. INPUTS

4.1 DIRECT INPUTS

This section includes the types of materials used within the waste packages, as well as the corrosion rate data of those materials. Section 4.1.1 lists the components of waste packages analyzed in this report and identifies the materials of which these are made. Input data and information necessary to perform the analyses for these materials are provided in Sections 4.1.2 through 4.1.5. Section 4.1.6 includes input data and information for drip shield materials.

4.1.1 Waste Package Materials

There are four basic waste package designs used in geochemistry calculations for DOE and commercial SNF. These include 5-DHLW long and short, 2-MCO/2-DHLW, and commercial 21-PWR waste packages. The major components of these waste package types and the materials of which these are made are provided in the following sections. A synopsis of waste package materials is presented in Table 4-1.

4.1.1.1 Components Common to All DOE Waste Packages

The following components are common to all DOE waste packages:

- The outer shell, constructed of Alloy 22 (BSC 2004 [DIRS 169472])
- The inner vessel (also called liner) constructed of Stainless Steel Type 316 (BSC 2004 [DIRS 169472])
- A Carbon Steel Type A516 structural basket (divider plate assembly or fuel divider assembly). For 5-DHLW packages (BSC 2004 [DIRS 166860]; BSC 2004 [DIRS 166861]) per *D&E / PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 169480]), the structural basket is designed to hold the high-level waste glass pour canisters in place. For the 2-MCO/2-DHLW packages (BSC 2004 [DIRS 166862]) per *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 169480]), the basket consists of perpendicularly aligned A-plates designed to hold the glass pour canisters and multicanister overpacks (MCOs) in place.
- The glass pour canisters, consisting of Stainless Steel Type 304L canisters (Baxter 1988 [DIRS 106164]), are filled with solidified high-level waste glass.

4.1.1.2 Components of the 5-DHLW Long and Short Waste Packages

The major fuel types that will potentially be stored in these waste packages include Shippingport PWR, Shippingport LWBR, Fort Saint Vrain, FFTF, aluminum-based, Fermi, and TRIGA. It is convenient to consider the 5-DHLW waste packages as several structural components:

- Centrally located Stainless Steel Type 316 DOE SNF canister (sometimes called the “18-inch canister”) with internal Carbon Steel Type A516 impact plates (DOE 1999 [DIRS 140225]).
- Individual DOE SNF canister internals, including:
 - *Shippingport PWR* – borated Stainless Steel Type 304L, chrome plating, Inconel X spacer rings, Zircaloy-4 fuel cluster structure, Zircaloy-2 spacers, and UO₂-CaO-ZrO₂ alloy fuel wafers (DOE 1999 [DIRS 104940])
 - *Shippingport LWBR* – Stainless Steel Type 316L basket and spacers, AM-350 stainless steel grid, Aluminum Alloy Type 6061-T6 fill material with 1% added gadolinium, Zircaloy-4 cladding and support shell, Inconel X-750 Wire Compression Spring, Inconel 600 base plates, ThO₂, and UO₂-ThO₂ SNF (DOE 1999 [DIRS 105007])
 - *Fort Saint Vrain* - fuel elements (graphite blocks that hold the fuel compacts). The fuel compacts contain the fuel kernels. Fuel kernels are composed of a Thorium Carbide or Th/U carbide core surrounded by four protective coatings of SiC and pyrolytic carbon (Taylor 2001 [DIRS 154726])
 - *FFTF* – (“driver assembly”) Stainless Steel Type 316 cladding, wire, and spacers, Inconel 600 reflectors, Stainless Steel Type 316L pins, Stainless Steel Type 316L basket doped with 2.75 wt% GdPO₄, Stainless Steel Type 302 spring, MOX (UO₂ and PuO₂) fuel, and UO₂ fuel (INEEL 2002 [DIRS 158820])
 - *Aluminum-Based Fuels* – Fuel assemblies composed of aluminum-based fuels, Aluminum Alloy Types 1100 or 6061-T6 cladding and frame, Aluminum Alloy Type 6061-T6 side plates, comb, and pin (Paige 1969 [DIRS 167978]). Basket composed of Alloy N06464 and Stainless Steel Type 304L
 - *Enrico-Fermi (Fermi)* – Stainless Steel Type 316L basket, Carbon Steel Type A516 and GdPO₄ shot (filler material), U-Mo fuel meat metallurgically bonded to a zirconium cladding tube (DOE 1999 [DIRS 104110])
 - *TRIGA* – Graphite reflectors, Zr rods, Stainless Steel Type 304L cladding, and U-Zr hydride fuel (DOE 1999 [DIRS 103891]).

4.1.1.3 Components of the 2-MCO/2-DHLW Waste Package

The following components are found in the 2-MCO/2-DHLW waste packages:

- Two MCO stands composed of Carbon Steel Type A516 (DOE 2000 [DIRS 150095])
- Two Stainless Steel Type 304L MCOs (DOE 2000 [DIRS 150095])
- MCO internals - Stainless Steel Type 304L baskets, aluminum (Aluminum Alloy Type 1100) spacers, N Reactor (U-metal) SNF rods (DOE 2000 [DIRS 150095]).

4.1.1.4 CSNF Waste Package

The CSNF waste package also contains the Alloy 22 outer shell and Stainless Steel Type 316 inner vessel. The fuel basket assembly, which is located inside the Stainless Steel Type 316 liner, is made up of the following components:

- Four Fuel Plate Assemblies constructed of plates of Alloy N06464 and Aluminum Alloy Type 6061 (BSC 2004 [DIRS 171319]; BSC 2004 [DIRS 171320]) (former design used Neutronit, BSC 2004 [DIRS 169472])
- Four Side/Corner-Guide/Stiffeners constructed of Carbon Steel Type A516 (BSC 2004 [DIRS 169472])
- 21 Fuel Basket Tubes constructed of Carbon Steel Type A516 (BSC 2004 [DIRS 169472])
- 21-PWR Fuel Assemblies constructed of zircaloy cladding and PWR fuel (BSC 2003 [DIRS 169110]; Punatar 2001 [DIRS 155635]).

Table 4-1. Summary of Waste Package Materials

Fuel Types/Waste Forms ^a	Steels	Alloys	Miscellaneous Materials
U-metal	Stainless Steel Type 302	Zircaloy-2	GdPO ₄
U-Mo	Stainless Steel Type 304L	Zircaloy-4	SiC
Aluminum-Based SNF	Stainless Steel Types 316/316L	Alloy 22 ^c	Graphite
MOX	Carbon Steel Type A516	Aluminum Alloy Type 1100	
UO ₂	Stainless Steel Type AM-350	Aluminum Alloy Type 6061-T6	
U-Th/Th Oxide	Gd-Doped Stainless Steel Type 316L ^b	Gd-doped Aluminum Alloy Type 6061 ^b	
U-Th/Th Carbide	Borated Stainless Steel Type 304L	Inconel X-750	
Ca-U-Zr Oxide	Neutronit	Inconel 600	
U-Zr Hydride		Alloy N06464	
Commercial UO ₂		Chrome plating ^d	
DHLW Glass			

NOTES: ^a See Section 4.1.2.

^b No rate data was available for these materials and they are not analyzed further in this document.

^c See Section 4.1.3.6.

^d See Section 4.1.3.9.

This table summarizes Sections 4.1.1.1 through 4.1.1.4.

4.1.1.5 Drip Shield Material

The drip shield is not a waste package component. However, its proximity and position relative to the waste package warrants investigation of corrosion rates for drip shield materials. According to *D&E / PA/C IED Interlocking Drip Shield and Emplacement Pallet* (BSC 2004 [DIRS 169220]), the primary components of the drip shield are composed of Titanium Grades 7 (SB-265 R52400) and 24 (SB-265 R56405).

4.1.2 Spent Fuels and Waste Forms

Since analysis of degradation and dissolution rates for DOE fuels and waste forms, including high-level waste glass and commercial SNF, can be found in other sources (Section 6.4), no further analysis of this information is provided in this document.

4.1.3 Steels and Alloys

4.1.3.1 Stainless Steel (Types 302/304/304L and 316/316L/AM-350)

The corrosion rates for different types of stainless steel are presented in Sections 4.1.3.1.1 through 4.1.3.1.5. These sections are divided into various environmental conditions to correlate with Section 6.2 as properties of the aqueous solution determine the rate of corrosion for stainless steels (Section 6.2). Discussions of corrosion rates for Stainless Steel Type 304L also apply to Stainless Steel Types 304 and 302 (Section 5.1.2). Discussions of corrosion rates for Stainless Steel Type 316L also apply to Stainless Steel Types 316 and AM-350 (Section 5.1.1).

For this analysis, all values for corrosion of stainless steels were converted to the same units of $\mu\text{m}/\text{yr}$. When only a value in $\mu\text{m}/\text{yr}$ is provided in tables, the rates were already in those units in the reference. When values for the corrosion rate are presented in any other units in the tables, these are the units presented in the reference, which are then converted to a rate in $\mu\text{m}/\text{yr}$ and indicated with an asterisk. These converted rates are calculated in spreadsheets in Appendix II. These calculated rates are presented in Section 4 along with the rates from the original source for transparency and traceability. When a value of zero corrosion was reported in the reference, the detection limit of the measurement equipment was used (and recorded in the tables) as the weight loss.

4.1.3.1.1 Corrosion of Stainless Steel in Fresh/Dilute Waters

Corrosion rates for Stainless Steel Types 304L and 316L, used in this analysis for fresh or dilute waters (similar to J-13 well water, DTN: MO0006J13WTRCM.000 [DIRS 151029]), can be found in Table 4-2 and Table 4-3. Further explanation on the use of these rates can be found in Sections 6.2.1.1 and 6.2.1.2.

4.1.3.1.2 Corrosion of Stainless Steel in Saltwater

General corrosion rates for Stainless Steel Types 304L and 316L in saltwater are found in Table 4-4 and Table 4-5. Further explanation on the use of these rates can be found in Sections 6.2.1.1 and 6.2.1.2.

4.1.3.1.3 Boil-Down Tests

The results from 80-week boil-down tests are located in Table 4-6. Section 6.2.1.3 provides further explanation on the use of these rates.

4.1.3.1.4 Radiolysis

The results of experiments simulating the effects of radiolysis products on corrosion can be found in Table 4-7. Section 6.2.1.4 further explains the use of these rates.

4.1.3.1.5 Sensitization of Stainless Steel

This section does not report any data on corrosion of sensitized stainless steel. The rationale for this can be found in Section 6.2.1.5.

4.1.3.2 Steels Containing Neutron Absorbers (Boron and Gadolinium)

Neutronit corrosion rates are based on the corrosion of Stainless Steel Type 321 (Section 6.2.2.1) and can be found in Tables 4-8 and 4-9. The corrosion rates of borated Stainless Steel Type 304L and gadolinium-alloyed stainless steel are also presented below in Table 4-10 through Table 4-12. Further explanation on the use of these rates can be found in Sections 6.2.2.2 and 6.2.2.3. All rates for corrosion of stainless steel were converted to the same units of $\mu\text{m/yr}$. These converted rates are presented in this section along with their values in the original units taken directly from the sources. These converted rates are determined in spreadsheets in Appendix II.

Table 4-2. Stainless Steel Types 302/304/304L Corrosion in Freshwater

See Note	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m/yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
a	1.00	N/A	0.0811	28	WL	304L	7	Irradiated J-13 Well Water Containing Crushed Tuff	Average of 6 Stainless Steel Type 304L Coupons in Set
a	1.00	N/A	0.151	28	WL	304L	7	Irradiated J-13 Well Water	Average of 6 Stainless Steel Type 304L Coupons in Set
a	1.00	N/A	0.123	28	WL	304L	7	Irradiated J-13 Well Water Containing Crushed Tuff	Average of 6 Stainless Steel Type 304L Coupons in Set, Heat-Treated, 650°C for 1 Hour
a	1.00	N/A	0.116	28	WL	304L	7	Irradiated J-13 Well Water	Average of 6 Stainless Steel Type 304L Coupons in Set, Heat-Treated, 650°C for 1 Hour
a	1.00	N/A	0.242	28	WL	304L	7	Nonirradiated J-13 Well Water Containing Crushed Tuff	Average of 6 Stainless Steel Type 304L Coupons in Set
a	1.00	N/A	0.285	28	WL	304L	7	Nonirradiated J-13 Well Water	Average of 6 Stainless Steel Type 304L Coupons in Set
a	1.00	N/A	0.249	28	WL	304L	7	Nonirradiated J-13 Well Water Containing Crushed Tuff	Average of 6 Stainless Steel Type 304L Coupons in Set, Heat-Treated, 650°C for 1 Hour
a	1.00	N/A	0.283	28	WL	304L	7	Nonirradiated J-13 Well Water	Average of 6 Stainless Steel Type 304L Coupons in Set, Heat-Treated, 650°C for 1 Hour
a	1.31	N/A	0.133	50	WL	304L	6	Freshwater	Average of 3 Specimens
a	1.26	N/A	0.085	80	WL	304L	6	Freshwater	Average of 3 Specimens
a	1.18	N/A	0.072	100	WL	304L	6	Freshwater	Average of 3 Specimens
		Detection Limit (g)^h							
b	1	0.01	0.0113*	29.5°C	WL	302	2	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test
b	2	0.01	0.0057*	29.5°C	WL	302	2	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test
b	4	0.01	0.0028*	29.5°C	WL	302	2	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test
b	8	0.01	0.0014*	29.5°C	WL	302	2	Freshwater	Gatun Lake, Panama Canal Zone, immersion Test

Table 4-2. Stainless Steel Types 302/304/304L Corrosion in Freshwater (Continued)

See Note	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
d	16	0.01	0.0007*	29.5 $^{\circ}\text{C}$	WL	302	4	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test
d	1	0.01	0.0478*	29.5 $^{\circ}\text{C}$	WL	302	6	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test, 302/302 Couple
		mils							
d	8	0.1	0.3175*	29.5 $^{\circ}\text{C}$	WL	302	6	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test, 302/302 Couple
d	16	0.1	0.1588*	29.5 $^{\circ}\text{C}$	WL	302	6	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test, 302/302 Couple
		Detection Limit (g)^h							
d	1	0.01	0.0113*	29.5 $^{\circ}\text{C}$	WL	302	6	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test, 302/302 Couple
d	8	0.01	0.0014*	29.5 $^{\circ}\text{C}$	WL	302	6	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test, 302/302 Couple
d	16	0.01	0.0007*	29.5 $^{\circ}\text{C}$	WL	302	6	Freshwater	Gatun Lake, Panama Canal Zone, Immersion Test, 302/302 Couple
		mpy							
e	0.40	0.001	0.0254*	50	WL	304L	4	J-13 Well Water	
e	0.57	0.009	0.2286*	50	WL	304L	4	J-13 Well Water	
e	0.40	0.008	0.2032*	70	WL	304L	4	J-13 Well Water	
e	0.57	0.008	0.2032*	70	WL	304L	4	J-13 Well Water	
e	0.40	0.008	0.2032*	80	WL	304L	4	J-13 Well Water	
e	0.57	0.009	0.2286*	80	WL	304L	4	J-13 Well Water	
e	0.40	0.006	0.1524*	90	WL	304L	4	J-13 Well Water	
e	0.57	0.006	0.1524*	90	WL	304L	4	J-13 Well Water	
e	0.40	0.004	0.1016*	100	WL	304L	4	J-13 Well Water	
e	0.57	0.005	0.127*	100	WL	304L	4	J-13 Well Water	
f	0.003	N/A	0.37	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.003	N/A	1.06	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.02	N/A	0.49	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.02	N/A	0.12	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825

Table 4-2. Stainless Steel Types 302/304/304L Corrosion in Freshwater (Continued)

See Note	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
f	0.04	N/A	0.46	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.04	N/A	0.09	90	EM	304L	4.8	Simulated J-13 well water	Galvanic Couple of 304L and 825
f	0.06	N/A	0.47	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.06	N/A	0.09	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.07	N/A	0.68	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.07	N/A	0.08	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.09	N/A	1.12	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.09	N/A	0.15	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.11	N/A	0.26	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.11	N/A	No data presented	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.12	N/A	0.07	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.12	N/A	1.29	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.13	N/A	0.07	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.13	N/A	0.21	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.16	N/A	0.06	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.16	N/A	0.15	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.17	N/A	0.05	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.17	N/A	0.25	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.19	N/A	0.04	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.19	N/A	0.04	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.21	N/A	0.05	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.21	N/A	0.04	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.23	N/A	0.05	90	EM	304L	4.8	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.23	N/A	0.11	90	EM	304L	4.9	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
f	0.23	N/A	0.57	90	WL	304L	4.10	Simulated J-13 Well Water	Galvanic Couple of 304L and 825
f	0.23	N/A	1.57	90	WL	304L	4.10	Solution 10, Table 2.5	Galvanic Couple of 304L and 825
g	0.02	N/A	0.14	90	EM	304L	4.2	Aerated Simulated J-13 Well Water	
g	0.04	N/A	0.02	90	EM	304L	4.2	Aerated Simulated J-13 Well Water	

Table 4-2. Stainless Steel Types 302/304/304L Corrosion in Freshwater (Continued)

See Note	Time (years)	Corrosion Rate	Corrosion Rate (µm/yr)	Temp (°C)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
g	0.06	N/A	0.02	90	EM	304L	4.2	Aerated Simulated J-13 Well Water	
g	0.17	N/A	0.13	90	EM	304L	4.2	Aerated Simulated J-13 Well Water	
g	0.12	N/A	0.04	90	EM	304L	4.2	Aerated Simulated J-13 Well Water	
g	0.23	N/A	0.06	90	EM	304L	4.2	Aerated Simulated J-13 Well Water	
g	0.11	N/A	0.13	100	WL	304L	7.1	Tuff Conditioned Water and Steam	Reported as "Nil," Which is Less Than the Weight-Loss Detection Limit of 0.13. Given Value for Detection Limit
g	0.11	N/A	0.25	100	WL	304L	7.1	Tuff Conditioned Water and Steam	
g	0.11	N/A	0.13	100	WL	304L	7.1	Tuff Conditioned Water and Steam	Reported as "Nil," Which is Less Than the Weight-Loss Detection Limit of 0.13. Given Value for Detection Limit

Sources: ^aMcCright et al. 1987 [DIRS 159336].

^bAlexander et al. 1961 [DIRS 162265].

^cForgeson et al. 1958 [DIRS 159343] (Average temperature of Gatun Lake, Panama is approximately 85°F. This reference is Part 1 of a 5-part series and indicates the temperatures for corrosion studies presented by Alexander et al. 1961 [DIRS 162265] (Table 2) and Southwell et al. 1976 [DIRS 100927]).

^dSouthwell et al. 1976 [DIRS 100927].

^eGlass et al. 1984 [DIRS 159340].

^fBeavers et al. 1992 [DIRS 159339].

^gBeavers and Durr 1991 [DIRS 159341].

^hWhen the reported corrosion rate is zero, it was set to the detection limit (Southwell et al. 1976 [DIRS 100927]).

NOTE: Values marked with an asterisk (*) calculated in *aqueous-304L.xls* in Appendix II.

WL = weight loss, EM = electrochemical measurement, 1 mil =25.4 µm.

Table 4-3. Stainless Steel Types 316/316L Corrosion in Freshwater

See NOTES	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m/yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
		Detection Limit (g) ⁹							
a	1	0.01	0.0113*	29.5 ^c	WL	316	2	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test
a	2	0.01	0.0056*	29.5 ^c	WL	316	2	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test
a	4	0.01	0.0028*	29.5 ^c	WL	316	2	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test
a	8	0.01	0.0014*	29.5 ^c	WL	316	2	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test
b	16	0.01	0.0007*	29.5 ^c	WL	316	4	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test
b	1	0.01	0.0113*	29.5 ^c	WL	316	6	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test, Stainless Steel Type 316/316 Couple
b	8	0.01	0.0014*	29.5 ^c	WL	316	6	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test, Stainless Steel Type 316/316 Couple
b	16	0.01	0.0007*	29.5 ^c	WL	316	6	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test, Stainless Steel Type 316/316 Couple
b	1	0.01	0.0475*	29.5 ^c	WL	316	6	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test, Stainless Steel Type 316/316 Couple
b	8	0.01	0.0059*	29.5 ^c	WL	316	6	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test, Stainless Steel Type 316/316 Couple
b	16	0.01	0.0030*	29.5 ^c	WL	316	6	Gatun Lake (freshwater)	Panama Canal Zone, Immersion Test, Stainless Steel Type 316/316 Couple
		mpy							
d	0.40	0.009	0.229*	50	WL	316L	4	J-13 Well Water	
d	0.57	0.004	0.102*	50	WL	316L	4	J-13 Well Water	
d	0.40	0.01	0.254*	70	WL	316L	4	J-13 Well Water	

Table 4-3. Stainless Steel Types 316/316L Corrosion in Freshwater (Continued)

See NOTES	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
d	0.57	0.009	0.229*	70	WL	316L	4	J-13 Well Water	
d	0.40	0.011	0.279*	80	WL	316L	4	J-13 Well Water	
d	0.57	0.01	0.254*	80	WL	316L	4	J-13 Well Water	
d	0.40	0.006	0.152*	90	WL	316L	4	J-13 Well Water	
d	0.57	0.01	0.254*	90	WL	316L	4	J-13 Well Water	
d	0.40	0.007	0.178*	100	WL	316L	4	J-13 Well Water	
d	0.57	0.008	0.203*	100	WL	316L	4	J-13 Well Water	
e	1.31	N/A	0.154	50	WL	316L	6	J-13 Well Water	Average
e	1.26	N/A	0.109	80	WL	316L	6	J-13 Well Water	Average
e	1.18	N/A	0.037	100	WL	316L	6	J-13 Well Water	Average
f	0.11	N/A	0.51	100	EM	316L	7.1	Tuff Conditioned Water and Steam	
f	0.11	N/A	0.51	100	EM	316L	7.1	Tuff Conditioned Water and Steam	
f	0.11	N/A	0.51	100	EM	316L	7.1	Tuff Conditioned Water and Steam	

Sources: ^aAlexander et al. 1961 [DIRS 162265], Table 2.

^bSouthwell et al. 1976 [DIRS 100927].

^cForgeson et al. 1958 [DIRS 159343] (Average temperature of Gatun Lake, Panama is approximately 85°F. This reference is Part 1 of a 5-part series and indicates the temperatures for corrosion studies presented by Alexander et al. 1961 [DIRS 162265] and Southwell et al. 1976 [DIRS 100927]).

^dGlass et al. 1984 [DIRS 159340].

^eMcCright et al. 1987 [DIRS 159336].

^fBeavers and Durr 1991 [DIRS 159341].

^gWhen the detection limit (Southwell et al. 1976 [DIRS 100927]) is listed for the weight loss, the original corrosion rate was listed as zero.

NOTE: Values marked with an asterisk (*) calculated in *aqueous-316L.xls* in Appendix II.
WL = weight loss, EM = electrochemical measurement.

Table 4-4. Stainless Steel Types 302/304/304L Corrosion in Seawater

See NOTES	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m/yr}$)	Temp (C)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
a	0.022	N/A	1.11	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.041	N/A	0.66	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.060	N/A	1.36	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.080	N/A	1.15	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.099	N/A	1.65	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.117	N/A	2.03	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.136	N/A	4.75	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.155	N/A	8.2	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and C1010 Carbon Steel
a	0.196	N/A	15.9	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010

Table 4-4. Stainless Steel Types 302/304/304L Corrosion in Seawater (Continued)

See NOTES	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp (C)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
a	0.214	N/A	14.84	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and Carbon Steel Type C1010
a	0.232	N/A	12.33	90	EM	304L	4.7	J-13 Well Water with 1,000 ppm Chloride	Galvanic Couple of Stainless Steel Type 304L and C1010
		(g/dm ²)							
b	1	2.93	36.90*	26.7 ^c	WL	302	2	Seawater	Seawater Immersion
b	1	0.36	4.53*	26.7 ^c	WL	302	2	Seawater	Mean Tide
b	2	4.43	27.90*	26.7 ^c	WL	302	2	Seawater	Seawater Immersion
b	2	0.55	3.46*	26.7 ^c	WL	302	2	Seawater	Mean Tide
b	4	7.06	22.23*	26.7 ^c	WL	302	2	Seawater	Seawater Immersion
b	4	0.99	3.12*	26.7 ^c	WL	302	2	Seawater	Mean Tide
b	8	10.99	17.30*	26.7 ^c	WL	302	2	Seawater	Seawater Immersion
b	8	1.76	2.77*	26.7 ^c	WL	302	2	Seawater	Mean Tide
		g/m ²							
d	16	1870	14.72*	26.7 ^c	WL	302	4	Seawater	Seawater Immersion
d	16	330	2.60*	26.7 ^c	WL	302	4	Seawater	Mean Tide
		mils							
d	1	0.1	2.54*	26.7 ^c	WL	302	6	Seawater	Seawater Immersion, Stainless Steel Type 302/302 Couple
d	8	5.7	18.10*	26.7 ^c	WL	302	6	Seawater	Seawater Immersion, Stainless Steel Type 302/302 Couple
d	16	8.2	13.02*	26.7 ^c	WL	302	6	Seawater	Seawater Immersion, Stainless Steel Type 302/302 Couple
d	1	0.2	5.08*	26.7 ^c	WL	302	6	Seawater	Mean Tide, Stainless Steel Type 302/302 Couple
d	8	0.5	1.59*	26.7 ^c	WL	302	6	Seawater	Mean Tide, Stainless Steel Type 302/302 Couple
d	16	1.3	2.06*	26.7 ^c	WL	302	6	Seawater	Mean Tide, Stainless Steel Type 302/302 Couple

Table 4-4. Stainless Steel Types 302/304/304L Corrosion in Seawater (Continued)

See NOTES	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m/yr}$)	Temp (C)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
d	1	0.3	7.62*	26.7 ^c	WL	302	6	Seawater	Seawater Immersion, Stainless Steel Type 302/302 Couple
d	8	4.5	14.29*	26.7 ^c	WL	302	6	Seawater	Seawater Immersion, Stainless Steel Type 302/302 Couple
d	16	7.6	12.07*	26.7 ^c	WL	302	6	Seawater	Seawater Immersion, Stainless Steel Type 302/302 Couple
d	1	0.1	2.54*	26.7 ^c	WL	302	6	Seawater	Mean Tide, Stainless Steel Type 302/302 Couple
d	8	0.7	2.22*	26.7 ^c	WL	302	6	Seawater	Mean Tide, Stainless Steel Type 302/302 Couple
d	16	1.2	1.91*	26.7 ^c	WL	302	6	Seawater	Mean Tide, Stainless Steel Type 302/302 Couple
		mpy							
e	1.32	0.08	2.032*		WL	302	III	Flowing Seawater	Flow = 3 ft/sec in Trough, Kure Beach, NC
e	4.5	0.088	2.235*		WL	302	III	Flowing Seawater	Flow = 3 ft/sec in Trough, Kure Beach, NC
e	1.31	0.146	3.708*		WL	302	IV	Quiet Seawater	Kure Beach, NC
		(mg/dm²/day)							
f	0.337	5.91	27.19*	2.78	WL	304	III	Seawater	Immersion, 5,640 feet
f	2.056	8.51	39.15*	2.39	WL	304	III	Seawater	Immersion, 5,640 feet
f	2.913	5.31	24.43*	2.50	WL	304	III	Seawater	Immersion, 5,300 feet
f	1.057	3.15	14.49*	17.61	WL	304	III	Seawater	Immersion, Surface

Sources: ^a Beavers et al. 1992 [DIRS 159339].

^b Alexander et al. 1961 [DIRS 162265].

^c Forgeson et al. 1958 [DIRS 159343] (Average temperature of Pacific Ocean around canal zone, Panama is approximately 80°F. This reference is Part 1 of a 5-part series and indicates the temperatures for corrosion studies presented by Alexander et al. 1961 [DIRS 162265] and Southwell et al. 1976 [DIRS 100927]).

^d Southwell et al. 1976 [DIRS 100927].

^e Bomberger et al. 1954 [DIRS 163699].

^f Wheatfall 1967 [DIRS 164934].

NOTE: Values marked with an asterisk (*) calculated in *aqueous-304L.xls* in Appendix II.

WL = weight loss, EM = electrochemical measurement, 1 mil = 25.4 μm .

Table 4-5. Stainless Steel Types 316/316L Corrosion in Seawater

See NOTES	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m/yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
		mpy							
a	1.32	0.16	4.064*		WL	316	III	Seawater	Kure Beach, NC
a	4.5	0.061	1.549*		WL	316	III	Seawater	Kure Beach, NC
a	1.31	0.24	6.096*		WL	316	IV	Seawater	Kure Beach, NC
		($\text{g/dm}^2/\text{yr}$)							
b	1	1.18	14.79*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Immersion
b	2	0.65	4.07*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Immersion
b	4	0.54	1.69*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Immersion
b	8	4.08	6.39*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Immersion
b	1	0.13	1.63*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Mean Tide
b	2	0.1	0.63*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Mean Tide
b	4	0.27	0.85*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Mean Tide
b	8	0.39	0.61*	26.7 $^{\circ}\text{C}$	WL	316	2	Seawater	Canal Zone, Mean Tide
		g/m^2							
d	16	160	1.25*	26.7 $^{\circ}\text{C}$	WL	316	4	Seawater	Canal Zone, Immersion
d	16	20	0.16*	26.7 $^{\circ}\text{C}$	WL	316	4	Seawater	Canal Zone, Mean Tide
		mils							
d	8	0.3	0.9525*	26.7 $^{\circ}\text{C}$	WL	316	6	Seawater	Canal Zone, Immersion, Stainless Steel Type 316/316 Couple
d	16	3.1	4.92125*	26.7 $^{\circ}\text{C}$	WL	316	6	Seawater	Canal Zone, Immersion, Stainless Steel Type 316/316 Couple
d	8	0.1	0.3175*	26.7 $^{\circ}\text{C}$	WL	316	6	Seawater	Canal Zone, Mean Tide, Stainless Steel Type 316/316 Couple
d	16	0.1	0.15875*	26.7 $^{\circ}\text{C}$	WL	316	6	Seawater	Canal Zone, Mean Tide, Stainless Steel Type 316/316 Couple
d	8	0.6	1.905*	26.7 $^{\circ}\text{C}$	WL	316	6	Seawater	Canal Zone, Immersion, Stainless Steel Type 316/316 Couple
d	16	1.3	2.06375*	26.7 $^{\circ}\text{C}$	WL	316	6	Seawater	Canal Zone, Immersion, Stainless Steel Type 316/316 Couple
d	16	0.1	0.15875*	26.7 $^{\circ}\text{C}$	WL	316	6	Seawater	Canal Zone, Mean Tide, Stainless Steel Type 316/316 Couple

Table 4-5. Stainless Steel Types 316/316L Corrosion in Seawater (Continued)

See NOTES	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
		g (detection limit) ^e							
d	1	0.01	0.05*	26.7 ^c	WL	316	6	Seawater	Canal Zone, Immersion, Stainless Steel Type 316/316 Couple
d	1	0.01	0.05*	26.7 ^c	WL	316	6	Seawater	Canal Zone, Mean Tide, Stainless Steel Type 316/316 Couple
d	1	0.01	0.01*	26.7 ^c	WL	316	6	Seawater	Canal Zone, Immersion, Stainless Steel Type 316/316 Couple
d	1	0.01	0.01*	26.7 ^c	WL	316	6	Seawater	Canal Zone, Mean Tide, Stainless Steel Type 316/316 Couple
d	8	0.01	0.001*	26.7 ^c	WL	316	6	Seawater	Canal Zone, Mean Tide, Stainless Steel Type 316/316 Couple
f	0.11	N/A	0.51	100	EM	316L	7.1	Tuff Conditioned Water and Steam	
f	0.11	N/A	0.51	100	EM	316L	7.1	Tuff Conditioned Water and Steam	

Sources: ^a Bomberger et al. 1954 [DIRS 163699].

^b Alexander et al. 1961 [DIRS 162265].

^c Forgeson et al. 1958 [DIRS 159343] (Average temperature of pacific ocean around canal zone, Panama is approximately 80°F. This reference is Part 1 of a 5-part series and indicates the temperatures for corrosion studies presented in Alexander et al. 1961 [DIRS 162265] and Southwell et al. 1976 [DIRS 100927]).

^d Southwell et al. 1976 [DIRS 100927].

^e When the reported corrosion rate is zero, it was set to the detection limit (Southwell et al. 1976 [DIRS 100927]).

^f Beavers and Durr 1991 [DIRS 159341].

NOTE: Values marked with an asterisk (*) are calculated in *aqueous-304L.xls* in Appendix II.

WL = weight loss, EM = electrochemical measurement, 1 mil = 25.4 μm .

Table 4-6. Corrosion of Stainless Steel Type 304L in Boil-Down Tests

Time (years)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type
0.04	0.1	90	EM	304L	5.4	Aerated J-13 Well Water
0.08	0.09	90	EM	304L	5.4	Aerated J-13 Well Water
0.17	0.26	90	EM	304L	5.4	Aerated J-13 Well Water
0.23	0.13	90	EM	304L	5.4	Aerated J-13 Well Water
0.31	1.08	90	EM	304L	5.4	Aerated J-13 Well Water
0.38	1.28	90	EM	304L	5.4	Aerated J-13 Well Water
0.46	0.6	90	EM	304L	5.4	Aerated J-13 Well Water
0.54	11.8	90	EM	304L	5.4	Aerated J-13 Well Water
0.61	0.78	90	EM	304L	5.4	Aerated J-13 Well Water
0.71	7.71	90	EM	304L	5.4	Aerated J-13 Well Water
0.77	4.49	90	EM	304L	5.4	Aerated J-13 Well Water
0.84	8.76	90	EM	304L	5.4	Aerated J-13 Well Water
0.92	3.34	90	EM	304L	5.4	Aerated J-13 Well Water
1.00	2.25	90	EM	304L	5.4	Aerated J-13 Well Water
1.07	2.13	90	EM	304L	5.4	Aerated J-13 Well Water
1.15	3.36	90	EM	304L	5.4	Aerated J-13 Well Water
1.23	3.14	90	EM	304L	5.4	Aerated J-13 Well Water
1.32	3.54	90	EM	304L	5.4	Aerated J-13 Well Water
1.38	1.93	90	EM	304L	5.4	Aerated J-13 Well Water
1.48	2.31	90	EM	304L	5.4	Aerated J-13 Well Water
1.53	2.32	90	EM	304L	5.4	Aerated J-13 Well Water

Source: Beavers et al. 1992 [DIRS 159339].

NOTE: EM = electrochemical measurement.

Table 4-7. Corrosion Rates of Stainless Steel Type 304L in Solution Containing Radiolysis Products (H_2O_2)

Time (years)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Steel Type	Table in Source	Fluid Type	Other Comments
0.29	0.04	90	EM	304L	5.5	Solution 20 (Main Components = 200 ppm F^- , 1,000 ppm Cl^- , 200 ppm NO_2^- , and 408 ppm K^+)	0 ppm H_2O_2
0.29	0.18	90	EM	304L	5.5		200 ppm H_2O_2
0.30	0.6	90	EM	304L	5.5		400 ppm H_2O_2
0.30	0.88	90	EM	304L	5.5		600 ppm H_2O_2
0.31	1.16	90	EM	304L	5.5		1,200 ppm H_2O_2
0.31	3.44	90	EM	304L	5.5		2,400 ppm H_2O_2
0.32	6.58	90	EM	304L	5.5		4,800 ppm H_2O_2

Source: Beavers and Durr 1991 [DIRS 159341].

NOTE: EM = electrochemical measurement.

Table 4-8. Neutronit-Corrosion Rates (Using Stainless Steel Type 321 Surrogate) in Freshwater

See Note	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Table From Reference	Steel Type	Fluid Type
		Detection Limit (g) ^e						
a	2	0.01	0.006*	29.5 ^d	WL	2	321	Gatun Lake, Panama Canal Zone, Freshwater Lake
a	4	0.01	0.003*	29.5 ^d	WL	2	321	Gatun Lake, Panama Canal Zone, Freshwater Lake
a	1	0.01	0.01*	29.5 ^d	WL	2	321	Gatun Lake, Panama Canal Zone, Freshwater Lake
b	8	0.01	0.001*	29.5 ^d	WL	2	321	Gatun Lake, Panama Canal Zone, Freshwater Lake
b	16	0.01	0.0007*	29.5 ^d	WL	4	321	Gatun Lake, Panama Canal Zone, Freshwater Lake
		mils/yr						
c	0.405	0.007	0.2*	50	WL	4	321	J-13 Well Water
c	0.570	0.005	0.1*	50	WL	4	321	J-13 Well Water
c	0.405	0.012	0.30*	70	WL	4	321	J-13 Well Water
c	0.570	0.011	0.28*	70	WL	4	321	J-13 Well Water
c	0.405	0.008	0.2*	80	WL	4	321	J-13 Well Water
c	0.570	0.008	0.2*	80	WL	4	321	J-13 Well Water
c	0.405	0.008	0.2*	90	WL	4	321	J-13 Well Water
c	0.570	0.013	0.33*	90	WL	4	321	J-13 Well Water
c	0.405	0.008	0.2*	100	WL	4	321	J-13 Well Water
c	0.570	0.001	0.03*	100	WL	4	321	J-13 Well Water

Sources: ^a Alexander et al. 1961 [DIRS 162265].^b Southwell et al. 1976 [DIRS 100927].^c Glass et al. 1984 [DIRS 159340].^d Forgeson et al. 1958 [DIRS 159343].^e When the reported corrosion rate is zero, it was set to the detection limit (Southwell et al. 1976 [DIRS 100927]).NOTE: Values marked with an asterisk (*) calculated in *aqueous-B-Gd-steels.xls* in Appendix II. WL = weight loss, 1 mil = 25.4 μm .

Table 4-9. Neutronit Corrosion Rates (Using Stainless Steel Type 321 Surrogate) in Seawater

See Note	Time (years)	Corrosion Rate	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Type of Analysis	Table From Reference	Steel Type	Fluid Type
		g/m^2						
a	16	1,460	11.49*	26.7 ^c	WL	4	321	Seawater, Panama Canal Zone/Immersion
a	16	230	1.81*	26.7 ^c	WL	4	321	Seawater, Panama Canal Zone/Mean Tide
		g/dm^2						
b	1	2.32	29.2*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Immersion
b	2	3.44	21.7*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Immersion
b	4	6.55	20.6*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Immersion
b	8	10.02	15.77*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Immersion
b	1	0.26	3.3*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Mean Tide
b	2	0.4	3*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Mean Tide
b	4	0.67	2.1*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Mean Tide
b	8	1.34	2.11*	26.7 ^c	WL	2	321	Seawater, Panama Canal Zone/Mean Tide

Sources: ^aSouthwell et al. 1976 [DIRS 100927].^bAlexander et al. 1961 [DIRS 162265].^cForgeson et al. 1958 [DIRS 159343].NOTE: Values marked with an asterisk (*) calculated in *aqueous-B-Gd-steels.xls* in Appendix II.

WL = weight loss, EM = electrochemical measurement.

Table 4-10. Corrosion of Borated Stainless Steel Type 304L for Use as “Freshwater” Rates

Corrosion Rate (mils/month)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Wt.% B	Steel Type	Solution Type	Table in Source	Other Comments
0.67	200*	Boiling	1.5	304	6	VII	
0.72	220*	Boiling	1.5	304	6	VII	
0.62	190*	Boiling	1.5	304	6	VII	With Chemically Sacrificial Zirconium
0.53	160*	Boiling	1.5	304	6	VII	With Chemically Sacrificial Zirconium
2.36	719*	Ambient	1.5	304	11	VIII	
2.53	771*	Ambient	1.5	304	11	VIII	
0.77	230*	Ambient	1.5	304	11	VIII	With Chemically Sacrificial Zirconium
0.83	250*	Ambient	1.5	304	11	VIII	With Chemically Sacrificial Zirconium
0.01	3*	50	0.3	304	11	VIII	
0.01	3*	50	0.3	304	11	VIII	
0.04	10*	50	0.3	304	11	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.06	20*	50	0.3	304	11	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.09	30*	50	0.3	304	11	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.07	20*	50	0.3	304	11	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.04	10*	Boiling	0.3	304	6	VII	
0.03	9*	Boiling	0.3	304	6	VII	
0.07	20*	Boiling	0.3	304	6	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.05	20*	Boiling	0.3	304	6	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.08	20*	Boiling	0.3	304	6	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 With ER-310 Rod
0.07	20*	Boiling	0.3	304	6	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 With ER-310 Rod
0.01	3*	Ambient	0.3	304	11	VIII	
0.01	3*	Ambient	0.3	304	11	VIII	
0.01	3*	Ambient	0.3	304	11	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.02	6*	Ambient	0.3	304	11	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.04	10*	Ambient	0.3	304	11	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.03	10*	Ambient	0.3	304	11	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod

Source: Cole 1976 [DIRS 159369].

NOTES: For more information on the solution type, see *aqueous-B-Gd-steels.xls* in Appendix II.Values marked with an asterisk (*) calculated in *aqueous-B-Gd-steels.xls* in Appendix II.

Table 4-11. Corrosion of Borated Stainless Steel Type 304L for Use as "Saltwater" Rates

Corrosion Rate (mils/month)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Wt. % B	Steel Type	Solution Type	Table in Source	Other Comments
1.95	573*	100	1.5	304	2	VII	
1.51	444*	100	1.5	304	2	VII	
2.54	747*	100	1.5	304	3	VII	
1.91	562*	100	1.5	304	3	VII	
6.04	1,780*	100	1.5	304	5	VII	
6.44	1,890*	100	1.5	304	5	VII	
0.92	270*	100	1.5	304	9	VII	
1.03	303*	100	1.5	304	9	VII	
0.58	170*	100	1.5	304	2	VII	With Chemically Sacrificial Zirconium
0.72	210*	100	1.5	304	2	VII	With Chemically Sacrificial Zirconium
0.57	170*	100	1.5	304	3	VII	With Chemically Sacrificial Zirconium
0.56	160*	100	1.5	304	3	VII	With Chemically Sacrificial Zirconium
0.84	250*	100	1.5	304	5	VII	With Chemically Sacrificial Zirconium
0.86	250*	100	1.5	304	5	VII	With Chemically Sacrificial Zirconium
1.19	350*	100	1.5	304	9	VII	With Chemically Sacrificial Zirconium
1.26	370*	100	1.5	304	9	VII	With Chemically Sacrificial Zirconium
6.14	1,810*	Ambient	1.5	304	13	VIII	
5.99	1,760*	Ambient	1.5	304	13	VIII	
2.34	688*	Ambient	1.5	304	13	VIII	With Chemically Sacrificial Zirconium
2.21	650*	Ambient	1.5	304	13	VIII	With Chemically Sacrificial Zirconium
3.6	*1,100	50	1.5	304	10	VIII	With Chemically Sacrificial Zirconium
3.19	938*	50	1.5	304	10	VIII	With Chemically Sacrificial Zirconium
0.09	30*	100	0.3	304	2	VII	
0.1	30*	100	0.3	304	2	VII	
0.05	10*	100	0.3	304	3	VII	
0.06	20*	100	0.3	304	3	VII	
0.12	35*	100	0.3	304	5	VII	
0.11	32*	100	0.3	304	5	VII	
0.08	20*	100	0.3	304	9	VII	
0.06	20*	100	0.3	304	9	VII	
0.2	60*	100	0.3	304	2	VII	Stainless Steel Type 304 Welded with ER- 310 Rod
0.18	53*	100	0.3	304	2	VII	Stainless Steel Type 304 Welded with ER- 310 Rod

Table 4-11. Corrosion of Borated Stainless Steel Type 304L for Use as "Saltwater" Rates (Continued)

Corrosion Rate (mils/month)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Wt. % B	Steel Type	Solution Type	Table in Source	Other Comments
0.06	20*	100	0.3	304	3	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.08	20*	100	0.3	304	3	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.09	30*	100	0.3	304	5	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.1	*30	100	0.3	304	5	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.11	32*	100	0.3	304	9	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.09	30*	100	0.3	304	9	VII	Stainless Steel Type 304 Welded with ER-310 Rod
0.12	35*	100	0.3	304	2	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.13	38*	100	0.3	304	2	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.04	10*	100	0.3	304	3	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.05	10*	100	0.3	304	3	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.19	56*	100	0.3	304	5	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.12	35*	100	0.3	304	5	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.09	26.46*	100	0.3	304	9	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.11	32.34*	100	0.3	304	9	VII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.01	3*	Ambient	0.3	304	10	VIII	
0.01	3*	Ambient	0.3	304	10	VIII	
0.02	6*	Ambient	0.3	304	13	VIII	
0.07	20*	Ambient	0.3	304	13	VIII	

Table 4-11. Corrosion of Borated Stainless Steel Type 304L for Use as "Saltwater" Rates (Continued)

Corrosion Rate (mils/month)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	Wt. % B	Steel Type	Solution Type	Table in Source	Other Comments
0.09	30*	Ambient	0.3	304	10	VIII	Stainless Steel Type 304 Welded with Stainless Steel Type ER-310 Rod
0.08	20*	Ambient	0.3	304	10	VIII	Stainless Steel Type 304 Welded with Stainless Steel Type ER-310 Rod
0.08	20*	Ambient	0.3	304	13	VIII	Stainless Steel Type 304 Welded with Stainless Steel Type ER-310 Rod
0.06	20*	Ambient	0.3	304	13	VIII	Stainless Steel Type 304 Welded with Stainless Steel Type ER-310 Rod
0.09	30*	Ambient	0.3	304	10	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.07	20*	Ambient	0.3	304	10	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.33	97*	50	0.3	304	10	VIII	
0.22	65*	50	0.3	304	10	VIII	
0.14	41*	50	0.3	304	13	VIII	
0.13	38*	50	0.3	304	13	VIII	
0.47	140*	50	0.3	304	10	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.46	140*	50	0.3	304	10	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.27	79*	50	0.3	304	13	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.22	65*	50	0.3	304	13	VIII	Stainless Steel Type 304 Welded with ER-310 Rod
0.48	140*	50	0.3	304	10	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod
0.5	100*	50	0.3	304	10	VIII	Stainless Steel Type 304 Welded to Stainless Steel Type 304 with ER-310 Rod

Source: Cole 1976 [DIRS 159369].

NOTE: For more information on the solution type, see *aqueous-B-Gd-steels.xls* in Appendix II.
 Values marked with an asterisk (*) calculated in *aqueous-B-Gd-steels.xls* in Appendix II.
 1 mil = 25.4 μm .

Table 4-12. Corrosion Rates of Gadolinium-Alloyed Steel

Corrosion Rate (mils/month)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Temp ($^{\circ}\text{C}$)	% Gd	Steel Type	Solution Type	Table in Source
"Freshwater"						
0.03	9*	100	0.3	304	6	VII
0.03	9*	100	0.3	304	6	VII
0.01	3*	Ambient	0.3	304	11	VIII
0.01	3*	Ambient	0.3	304	11	VIII
0.05	20*	50	0.3	304	11	VIII
0.01	3*	50	0.3	304	11	VIII
"Harshwater"						
0.03	9	100	0.3	304	2	VII
0.04	10	100	0.3	304	2	VII
0.02	6	100	0.3	304	3	VII
0.02	6	100	0.3	304	3	VII
0.07	20	100	0.3	304	5	VII
0.08	20	100	0.3	304	5	VII
0.02	6	100	0.3	304	9	VII
0.02	6	100	0.3	304	9	VII
0.01	3	Ambient	0.3	304	10	VIII
0.01	3	Ambient	0.3	304	10	VIII
0.01	3	Ambient	0.3	304	13	VIII
0.01	3	Ambient	0.3	304	13	VIII
1.04	306	50	0.3	304	10	VIII
1.02	300	50	0.3	304	10	VIII
0.26	76	50	0.3	304	13	VIII
0.31	91	50	0.3	304	13	VIII

Source: Cole 1976 [DIRS 159369]

NOTES: For more information on the solution type, see *aqueous-B-Gd-steels.xls* in Appendix II. Values marked with an asterisk (*) calculated in *aqueous-B-Gd-steels.xls* in Appendix II. 1 mil = 25.4 μm .

4.1.3.3 Carbon Steel Type A516

The rates used to describe the corrosion of Carbon Steel Type A516 for long-term studies (>1 year) are found in Table 4-13 through Table 4-16. Further explanation on the use of these rates can be found in Section 6.2.3.

The rates used to describe the corrosion of Carbon Steel Type A516 for short-term studies (≤ 0.53 years) are found in Table 4-17 through Table 4-20. Further explanation on the use of these rates can be found in Section 6.2.3.

Table 4-13. Carbon Steel Corrosion at 1 Year in Freshwater at 90°C

Corrosion Rate ($\mu\text{m/yr}$)	Steel Type	Table in Source	Type of Analysis	Fluid Type
43.65	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SDW J-13 Well Water
45.19	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SDW J-13 Well Water
48.30	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SDW J-13 Well Water
55.97	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
63.58	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
50.17	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
42.42	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
45.91	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
29.53	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
65.04	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
65.73	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
88.68	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SDW J-13 Well Water
46.79	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SDW J-13 Well Water
68.91	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SDW J-13 Well Water
46.72	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SDW J-13 Well Water
46.31	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
36.38	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
65.88	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
58.48	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
35.87	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
50.14	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
49.10	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water
53.98	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water
40.46	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SDW = simulated dilute well.

Table 4-14. Carbon Steel Corrosion at 1 Year in Saltwater at 90°C

Corrosion Rate (µm/yr)	Steel Type	Table in Source	Type of Analysis	Fluid Type
6.96	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
5.75	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SCW J-13 Well Water
3.69	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SCW J-13 Well Water
9.35	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
6.46	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
6.85	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
7.69	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
6.53	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
5.16	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
6.64	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
6.01	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
6.25	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
6.51	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
7.13	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
5.32	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
6.13	A27	Sec. 2.2.6, Sup. 1, p. 2.2-45	WL	SCW J-13 Well Water
5.91	A27	Sec. 2.2.6, Sup. 1, p. 2.2-45	WL	SCW J-13 Well Water
8.20	A27	Sec. 2.2.6, Sup. 1, p. 2.2-45	WL	SCW J-13 Well Water
8.40	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
7.84	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
8.24	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
7.87	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
8.04	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
7.32	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SCW = simulated concentrated well.

Table 4-15. Carbon Steel Corrosion at 1 Year in Freshwater at 60°C

Corrosion Rate (µm/yr)	Steel Type	Table in Source	Type of Analysis	Fluid Type
80.00	A516	Sec. 2.2.6, Sup. 1, p. 2.2-39	WL	SDW J-13 Well Water
66.75	A516	Sec. 2.2.6, Sup. 1, p. 2.2-39	WL	SDW J-13 Well Water
77.31	A516	Sec. 2.2.6, Sup. 1, p. 2.2-39	WL	SDW J-13 Well Water
69.84	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
83.74	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
79.29	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
71.25	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
65.77	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
70.00	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
72.64	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
72.89	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
106.93	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
90.97	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
83.26	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
74.29	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
72.87	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
73.47	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
83.66	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
74.51	A27	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SDW J-13 Well Water
74.60	A27	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SDW J-13 Well Water
75.41	A27	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SDW J-13 Well Water
72.21	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water
80.87	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water
85.68	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SDW = simulated dilute well.

Table 4-16. Carbon Steel Corrosion at 1 Year in Saltwater at 60°C

Corrosion Rate (µm/yr)	Steel Type	Table in Source	Type of Analysis	Fluid Type
7.93	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
11.19	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
8.03	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
9.45	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SCW J-13 Well Water
11.05	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
9.1	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
6.77	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
10.07	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
11.72	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
12.2	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
12.9	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
12.99	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
10.67	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
10.00	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
7.42	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
8.09	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SCW J-13 Well Water
10.32	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SCW J-13 Well Water
10.83	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SCW J-13 Well Water
12.09	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
14.36	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
12.21	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
11.94	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
12.62	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SCW = simulated concentrated well.

Table 4-17. Carbon Steel Corrosion at 0.53 Years in Freshwater at 90°C

Corrosion Rate ($\mu\text{m}/\text{yr}$)	Steel Type	Table in Source	Type of Analysis	Fluid Type
89.41	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SDW J-13 Well Water
68.90	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SDW J-13 Well Water
84.02	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SDW J-13 Well Water
87.65	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
107.46	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
130.02	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
76.96	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
70.45	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
74.29	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
180.42	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
58.08	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
66.27	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
71.97	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
79.61	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
97.43	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
75.50	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
67.99	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
89.88	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SDW J-13 Well Water
78.85	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
85.06	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
79.56	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
74.56	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water
75.23	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water
77.05	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SDW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SDW = simulated dilute well.

Table 4-18. Carbon Steel Corrosion at 0.5 Years in Saltwater at 90°C

Corrosion Rate (µm/yr)	Steel Type	Table in Source	Type of Analysis	Fluid Type
12.81	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
13.88	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
10.92	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
19.08	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
14.01	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
16.2	A516	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SCW J-13 Well Water
12.24	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
8.05	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
8.66	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SCW J-13 Well Water
7.39	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
9.12	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
9.02	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
11.48	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
13.67	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
9.03	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
16.84	A27	Sec. 2.2.6, Sup. 1, p. 2.2-45	WL	SCW J-13 Well Water
22.06	A27	Sec. 2.2.6, Sup. 1, p. 2.2-45	WL	SCW J-13 Well Water
18.06	A27	Sec. 2.2.6, Sup. 1, p. 2.2-45	WL	SCW J-13 Well Water
14.78	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
15.03	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
12.60	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
9.74	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
10.46	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
11.47	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SCW = simulated concentrated well.

Table 4-19. Carbon Steel Corrosion at 0.52 Years in Freshwater at 60°C

Corrosion Rate (µm/yr)	Steel Type	Table in Source	Type of Analysis	Fluid Type
101.01	A516	Sec. 2.2.6, Sup. 1, p. 2.2-39	WL	SDW J-13 Well Water
108.43	A516	Sec. 2.2.6, Sup. 1, p. 2.2-39	WL	SDW J-13 Well Water
105.33	A516	Sec. 2.2.6, Sup. 1, p. 2.2-39	WL	SDW J-13 Well Water
88.15	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
101.95	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
117.92	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SDW J-13 Well Water
87.80	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
88.29	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
78.71	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SDW J-13 Well Water
112.46	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
103.18	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
99.73	A516	Sec. 2.2.6, Sup. 2, p. 2.2-97	WL	SDW J-13 Well Water
116.72	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
41.31	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
95.78	A27	Sec. 2.2.6, Sup. 1, p. 2.2-42	WL	SDW J-13 Well Water
100.69	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SDW J-13 Well Water
88.62	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SDW J-13 Well Water
109.93	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SDW J-13 Well Water
102.33	A27	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SDW J-13 Well Water
101.74	A27	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SDW J-13 Well Water
130.70	A27	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SDW J-13 Well Water
108.44	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
92.90	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water
121.60	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SDW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SDW = simulated dilute well.

Table 4-20. Carbon Steel Corrosion at 0.50 Years in Saltwater at 60°C

Corrosion Rate (µm/yr)	Steel Type	Table in Source	Type of Analysis	Fluid Type
54.59	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
54.97	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
50.25	A516	Sec. 2.2.6, Sup. 1, p. 2.2-40	WL	SCW J-13 Well Water
68.58	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SCW J-13 Well Water
85.21	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SCW J-13 Well Water
91.55	A516	Sec. 2.2.6, Sup. 1, p. 2.2-41	WL	SCW J-13 Well Water
65.19	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SCW J-13 Well Water
65.32	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SCW J-13 Well Water
63.02	A516	Sec. 2.2.6, Sup. 2, p. 2.2-96	WL	SCW J-13 Well Water
58.03	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
60.17	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
62.52	A516	Sec. 2.2.6, Sup. 2, p. 2.2-98	WL	SCW J-13 Well Water
73.05	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
78.39	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
70.84	A27	Sec. 2.2.6, Sup. 1, p. 2.2-43	WL	SCW J-13 Well Water
53.66	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SCW J-13 Well Water
57.72	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SCW J-13 Well Water
55.38	A27	Sec. 2.2.6, Sup. 1, p. 2.2-44	WL	SCW J-13 Well Water
61.67	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
60.87	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
62.14	A27	Sec. 2.2.6, Sup. 2, p. 2.2-99	WL	SCW J-13 Well Water
88.01	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
104.20	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water
88.57	A27	Sec. 2.2.6, Sup. 2, p. 2.2-100	WL	SCW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: WL = weight loss; SCW = simulated concentrated well.

4.1.3.4 Aluminum Alloys

The corrosion rates of aluminum can be found in Table 4-21 through Table 4-22. Further explanation on the use of these rates can be found in Section 6.2.4. All aluminum alloy corrosion rates were converted to the same units of µm/yr (Appendix II, *aluminum.xls*). These converted rates are presented in this section along with their original values taken directly from the sources.

Table 4-21. Corrosion Rates of Aluminum in Seawater

Type ^a	Weight Loss (g) ^a				Corrosion Rate (μm/yr)			
	1 year	2 years	5 years	10 years	1 year	2 years	5 years	10 years
1100-H14	4.4	5.4	10.3	11.1	8.4	5.1	3.92	2.11
3003-H14	4.1	6.4	9.3	11.2	7.8	6.0	3.5	2.12
5052-H34	4.5	6.5	9.0	14.9	8.7	6.3	3.5	2.87
6051-T4	3.7	4.9	9.9	12.3	7.1	4.7	3.8	2.35
6051-T6	4.4	5.7	10.3	13.1	8.4	5.4	3.94	2.50
6061-T4	4.8	6.6	12.4	18.6	9.2	6.3	4.74	3.56
6061-T6	5.5	7.7	14	21.5	11	7.4	5.4	4.11
7072	—	—	—	10.2	—	—	—	1.87
7075-T6	—	—	—	149	—	—	—	27.4
5083	2.5	3.7	—	7.3	4.9	3.6	—	1.4
5083	4.7	3.4	5.7	8.1	9.1	3.3	2.2	1.6
5056	3.7	4.7	6.0	9.2	7.1	4.5	2.3	1.8
5056	4.5	5.2	—	16.7	8.6	5.0	—	3.22
6051-T4	3.9	4.2	12.1	9.1	7.5	4.0	4.6	1.7
6051-T6	4.1	4.5	7.7	10.6	7.8	4.3	2.9	2.03
6053-T6	4.1	4.5	6.6	9.7	7.8	4.3	2.5	1.9
6061-T6	7.6	13.4	29.4	51.6	15	13	11.2	9.86
6061-T6	5.5	6.5	15.4	34.2	11	6.2	5.89	6.54
Al-7 Mg	4.1	4.1	6.5	9.4	7.8	3.9	2.5	1.8
5154	2.8	5.2	6.0	—	5.4	5.0	2.3	—
5083	3.5	4.6	6.0	—	6.8	4.5	2.3	—
6053-T6	3.8	6.6	25.9	—	7.3	6.3	9.90	—
7075-T6	60.4	49.3	74.8	—	111	45.3	27.5	—
3003, alclad	4.3	12	—	—	8.1	11	—	—
6061, alclad	4.3	3.9	5.7	—	8.2	3.7	2.2	—
7075, alclad	4.4	5.2	6.1	—	8.1	4.8	2.2	—
1100-H14	1.9	3.5	5.3	12.7	3.6	3.3	2.0	2.42
3003-H14	0.0	3.3	4.6	7.5	—	3.1	1.7	1.4
5052-H34	2.8	3.3	—	14.2	5.4	3.2	—	2.73

Table 4-21. Corrosion Rates of Aluminum in Seawater (Continued)

Type ^a	Weight Loss (g) ^a				Corrosion Rate (μm/yr)			
	1 year	2 years	5 years	10 years	1 year	2 years	5 years	10 years
6051-T4	0.0	0.7	3.5	8	—	0.7	1.3	2
6051-T6	2.1	5.5	6.1	19.5	4.0	5.3	2.3	3.73
6061-T4	4.4	6.0	8.0	15.6	8.4	5.7	3.1	2.98
6061-T6	4.3	7.3	12.7	22.8	8.2	7.0	4.85	4.36
7072	—	—	—	15.9	—	—	—	2.92
7075-T6	—	—	—	242.6	—	—	—	44.55
5083	2.8	0.0	6.1	8.5	5.4	—	2.4	1.6
5083	2.6	3.2	5.2	7.5	5.0	3.1	2.0	1.5
5056	2.5	3.3	5.7	10.4	4.8	3.2	2.2	2.00
5056	4.0	4.1	5.5	11.1	7.7	3.9	2.1	2.14
6051-T4	3.6	3.1	5.5	9.2	6.9	3.0	2.1	1.8
6051-T6	5.3	4.1	8.4	18.6	10	3.9	3.2	3.56
6053-T6	3.0	3.3	5.6	14.8	5.7	3.2	2.1	2.83
6061-T6	9.8	11.2	33.2	48.5	19	10.7	12.7	9.27
6061-T6	10.0	9.4	19.1	54.1	19.1	9.0	7.30	10.3
Al-7 Mg	2.4	2.4	4.6	8.0	4.6	2.3	1.8	1.5
5154	2.4	2.6	3.8	—	4.7	2.5	1.5	—
5083	2.0	2.8	3.6	—	3.9	2.7	1.4	—
6053-T6	19.3	29.2	4.7	—	36.9	27.9	1.8	—
7075-T6	44.8	66.1	116.0	—	82.3	60.70	42.60	—
3003, alclad	1.6	2.3	—	—	3.0	2.2	—	—
6061, alclad	8.4	3.3	6.5	—	16	3.2	2.5	—
7075, alclad	2.8	3.6	6.8	—	5.1	3.3	2.5	—
1100-H14	0.0	2.4	1.3	2.3	—	2.3	0.50	0.44
3003-H14	0.0	0.0	3.0	2.2	—	—	1.1	0.42
5052-H34	1.7	0.0	0.0	0.6	3.3	—	—	0.1
6051-T4	1.9	7.8	19.0	14.6	3.6	7.5	7.26	2.79
6051-T6	22.5	13.8	19.9	27.3	43.0	13.2	7.61	5.22
6061-T4	0.9	2.3	28.2	62	2	2.2	10.8	12

Table 4-21. Corrosion Rates of Aluminum in Seawater (Continued)

Type ^a	Weight Loss (g) ^a				Corrosion Rate (μm/yr)			
	1 year	2 years	5 years	10 years	1 year	2 years	5 years	10 years
6061-T6	6.7	7.1	11.1	44.3	13	6.8	4.24	8.47
7072	—	—	—	3.1	—	—	—	0.59
7075-T6	—	—	—	246.5	—	—	—	47.11
5083	1.3	1.9	2.7	3.3	2.5	1.8	1.0	0.64
5083	15.3	16.3	36.3	31.1	29.7	15.8	14.1	6.03
5056	10.7	16.5	19.5	28.9	20.6	15.9	7.51	5.56
5056	7.0	6.0	11.0	11.4	13	5.8	4.24	2.20
6051-T4	9.1	18.8	15.3	51.0	17	18.0	5.85	9.75
6051-T6	17.2	23.3	30.6	33.5	32.9	22.3	11.7	6.40
6053-T6	15.7	25.1	19.3	25.8	30.0	24.0	7.38	4.93
6061-T6	12.3	26.8	48.7	48.0	23.5	25.6	18.6	9.17
6061-T6	7.3	7.0	21.3	18.6	14	6.7	8.14	3.56
Al-7 Mg	1.6	2.9	2.1	3.3	3.0	2.8	0.80	0.63
5154	1.4	2.1	2.6	—	2.7	2.0	1.0	—
5083	0.2	2.2	2.8	—	0.39	2.1	1.1	—
6053-T6	45.6	80.4	86.0	—	87.1	76.8	32.9	—
7075-T6	50.9	71.3	153.5	—	93.5	65.5	56.38	—
3003, alclad	—	1.9	—	—	—	1.8	—	—
6061, alclad	20.8	15.8	34.3	—	39.8	15.1	13.1	—
7075, alclad	8.5	14.5	16.6	—	16	13.3	6.10	—

Source: ^aHollingsworth and Hunsicker 1987 [DIRS 150403].

NOTE: Average temperature (15.6°C) estimated from Figure 17 by Sedriks 1982 [DIRS 164923]. Temperature at Halifax, N.S., Esquimalt, B.C., and Kure Beach, NC are assumed similar.

Table 4-22. Corrosion Rates of Aluminum in Freshwater

See NOTES	Table in Source	Aluminum Type	Time (years)	Loss	Weight Loss (g)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Comments	Temp ($^{\circ}\text{C}$)	Water
				Weight Loss (g/m^2)					
a, b	2 ^b	1100	1	30	N/A	11	—	29.5 ^a	Gatun lake, Panama Canal Zone
a, b	7 ^a	1100	4	96	N/A	8.9	—	29.5 ^a	Gatun lake, Panama Canal Zone
a, b	7+2 ^{a, b}	1100	8	160	N/A	7.38	Heavily pitted	29.5 ^a	Gatun lake, Panama Canal Zone
a, b	2 ^b	1100	16	350	N/A	8.07	Heavily pitted	29.5 ^a	Gatun lake, Panama Canal Zone
a, b	2 ^b	6061T	1	<10	N/A	3.7	—	29.5 ^a	Gatun lake, Panama Canal Zone
a, b	2 ^b	6061T	8	50	N/A	2.3	Heavily pitted	29.5 ^a	Gatun lake, Panama Canal Zone
a, b	2 ^b	6061T	16	100	N/A	2.31	Heavily pitted	29.5 ^a	Gatun lake, Panama Canal Zone
c	II	3S-1/2H	0.417	N/A	0.01	0.51	—	Ambient air	"High sulfide"-bearing water (Cl = 7,477 ppm, sulfate = 4,300 ppm)
c	II	Alclad 3S-1/2H	0.417	N/A	0.04	2	—	Ambient air	"High sulfide"-bearing water (Cl = 7,477 ppm, sulfate = 4,300 ppm)
c	II	52S-1/2H	0.417	N/A	0.05	2	—	Ambient air	"High sulfide"-bearing water (Cl = 7,477 ppm, sulfate = 4,300 ppm)
c	II	61S-T	0.417	N/A	0.08	3	—	Ambient air	"High sulfide"-bearing water (Cl = 7,477 ppm, sulfate = 4,300 ppm)
				Corrosion Rate ($\text{mg}/\text{dm}^2/\text{d}$)					
d	10	3003	1	0.03	N/A	0.4	—	—	Tap Water, Youngstown, OH
d	10	3003	1	0.86	N/A	12	—	—	Tap Water, Dallas, TX
d	10	3003	1	0.06	N/A	0.8	—	—	Tap Water, Oklahoma City, OK.
d	10	3003	1	0.71	N/A	9.5	—	—	Tap Water, New Orleans, LA
d	10	3003	1	0.98	N/A	13	—	—	Tap Water, Columbus, OH
d	10	3003	1	1.32	N/A	17.7	—	—	Tap Water, New York, NY
d	10	3003	1	2.51	N/A	33.6	—	—	Tap Water, Toledo, OH
d	10	3003	1	1.58	N/A	21.1	—	—	Tap Water, Syracuse, NY
d	10	3003	1	0.18	N/A	2.4	—	—	Tap Water, Miami, FL
d	10	3003	1	1.93	N/A	25.8	—	—	Tap Water, Richmond, VA
d	10	3003	1	0.21	N/A	2.8	—	—	Tap Water, Charlotte, NC

Table 4-22. Corrosion Rates of Aluminum in Freshwater (Continued)

See NOTES	Table in Source	Aluminum Type	Time (years)	Loss	Weight Loss (g)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Comments	Temp ($^{\circ}\text{C}$)	Water
^d	10	3003	1	1.01	N/A	13.5	—	—	Tap Water, Little Rock, AR
^d	10	3003	1	0.40	N/A	5.4	—	—	Tap Water, Atlanta, GA
—	10	3003	1	0.33	N/A	4.4	—	—	Tap Water, Portland, OR
—	10	3003	1	1.92	N/A	25.7	—	—	Tap Water, Hartford, CT
—	10	3003	1	2.58	N/A	34.5	—	—	Tap Water, Saginaw, MI
—	10	3003	1	0.04	N/A	0.5	—	—	Tap Water, Minneapolis, MN
—	10	3003	1	1.77	N/A	23.7	—	—	Tap Water, Boston, MA
—	10	3003	1	0.33	N/A	4.4	—	—	Tap Water, Wichita, KS
—	10	3003	1	1.70	N/A	22.7	—	—	Tap Water, Corpus Christi, TX
—	10	3003	1	0.38	N/A	5.1	—	—	Tap Water, Birmingham, AL
—	10	3003	1	2.36	N/A	31.6	—	—	Tap Water, Salt Lake City, UT
—	10	3003	1	1.95	N/A	26.1	—	—	Tap Water, Milwaukee, WI
—	10	3003	1	2.76	N/A	36.9	—	—	Tap Water, Philadelphia, PA
—	10	3003	1	1.52	N/A	20.3	—	—	Tap Water, Nashville, TN
—	10	3003	1	1.78	N/A	23.8	—	—	Tap Water, Los Angeles, CA
—	10	3003	1	0.47	N/A	6.3	—	—	Tap Water, Chicago, IL
—	10	3003	1	0.23	N/A	3.1	—	—	Tap Water, Pittsburgh, PA
—	10	3003	1	1.46	N/A	19.5	—	—	Tap Water, Kansas City, MO
—	10	3003	1	1.21	N/A	16.2	—	—	Tap Water, Washington, D.C.
—	10	3003	1	0.85	N/A	11	—	—	Tap Water, Omaha, NE
—	10	3003	1	1.70	N/A	22.7	—	—	Tap Water, Houston, TX
—	10	3003	1	2.06	N/A	27.6	—	—	Tap Water, San Francisco, CA
—	10	3003	1	0.59	N/A	7.9	—	—	Tap Water, Phoenix, AZ

Sources: ^a Forgeson et al. 1958 [DIRS 159343].^b Southwell et al. 1976 [DIRS 100927].^c Sawyer and Brown 1947 [DIRS 164921].^d Ailor 1969 [DIRS 164907], Table 10.

4.1.3.5 Zircaloy (2 and 4)

Most information on the corrosion of zircaloy comes from high temperature experiments in which the weight gain over time is measured (i.e., Hillner et al. (1998 [DIRS 100455]) and Rothman 1984 [DIRS 100417]). Hillner et al. (1998 [DIRS 100455]) conclude that oxide growth in the Yucca Mountain repository over a period of one million years would be extremely small (0.3 mils, 1 mil = 25.4 μm).

4.1.3.6 Alloy 22

Since analysis of degradation rates for Alloy 22 can be found in other sources, no further analysis of this information will be provided in this analysis. This is discussed further in Section 6.2.8.

4.1.3.7 Alloy N06464

Corrosion data for a Ni-Cr-Mo-Gd alloy (UNS N06464, Table 6-2), is presented in Table 4-23.

Table 4-23. Corrosion Rates of Alloy N06464 in J-13 Water

Time (years)	Corrosion Rate (nm/yr)	Fluid Type
0.03	415.8	J-13
0.08	55.7	J-13
0.20	62.1	J-13
0.27	48.5	J-13
0.39	77.4	J-13
0.77	20.1	J-13
0.62	88.9	J-13 50×

Source: DOE 2004 [DIRS 168434] Table 16.

4.1.3.8 Inconel Alloys

The corrosion rates of Inconel alloys can be found in Table 4-24 through Table 4-26 below. Further explanation on the use of these rates can be found in Section 6.2.7. Inconel Alloy 625 is used in corrosion tests, which is assumed to have the same degradation rate as the Inconel alloys within the waste packages (Inconel Alloy Types 600 and X-750) (Section 5.2.1).

Table 4-24. Corrosion Rates of Inconel Alloys in Freshwater

Time (years)	Corrosion Rate (µm/yr)	Table in Source	Temp (°C)	Type of Analysis	Fluid Type
0.51	0.05	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SDW J-13 Well Water
0.51	0.02	Sec.2.2.6, Sup.1, p.2.2-47	60	WL	SDW J-13 Well Water
0.51	0.01	Sec.2.2.6, Sup.1, p.2.2-101	60	WL	SDW J-13 Well Water
0.51	0.03	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SDW J-13 Well Water
0.51	0.04	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SDW J-13 Well Water
0.51	0.04	Sec.2.2.6, Sup.2, p.2.2-103	60	WL	SDW J-13 Well Water
0.51	0.01	Sec.2.2.6, Sup.2, p.2.2-103	60	WL	SDW J-13 Well Water
0.51	0.00	Sec.2.2.6, Sup.2, p.2.2-103	60	WL	SDW J-13 Well Water
0.50	0.10	Sec.2.2.6, Sup.1, p.2.2-46	90	WL	SDW J-13 Well Water
0.50	0.03	Sec.2.2.6, Sup.1, p.2.2-47	90	WL	SDW J-13 Well Water
0.50	0.01	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SDW J-13 Well Water
0.50	0.06	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SDW J-13 Well Water
0.50	0.03	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SDW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.2, p.2.2-103	90	WL	SDW J-13 Well Water
0.50	0.02	Sec.2.2.6, Sup.2, p.2.2-103	90	WL	SDW J-13 Well Water
0.50	0.07	Sec.2.2.6, Sup.2, p.2.2-103	90	WL	SDW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: Negative corrosion values reported as zero in table.
WL = weight loss; SDW = simulated dilute well.

Table 4-25. Corrosion Rates of Inconel Alloys in Acidified Water

Time (years)	Corrosion Rate (µm/yr)	Table in Source	Temp (°C)	Type of Analysis	Fluid Type
0.49	0.00	Sec.2.2.6, Sup.1, p.2.2-45	60	WL	SAW J-13 Well Water
0.49	0.00	Sec.2.2.6, Sup.1, p.2.2-45	60	WL	SAW J-13 Well Water
0.49	0.00	Sec.2.2.6, Sup.1, p.2.2-45	60	WL	SAW J-13 Well Water
0.96	0.00	Sec.2.2.6, Sup.1, p.2.2-45	60	WL	SAW J-13 Well Water
0.96	0.00	Sec.2.2.6, Sup.1, p.2.2-45	60	WL	SAW J-13 Well Water
0.96	0.00	Sec.2.2.6, Sup.1, p.2.2-45	60	WL	SAW J-13 Well Water
0.49	0.00	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SAW J-13 Well Water
0.49	0.03	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SAW J-13 Well Water
0.49	0.00	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SAW J-13 Well Water
0.96	0.00	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SAW J-13 Well Water
0.96	0.01	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SAW J-13 Well Water
0.96	0.00	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SAW J-13 Well Water
0.49	0.08	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SAW J-13 Well Water
0.49	0.03	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SAW J-13 Well Water
0.49	0.03	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SAW J-13 Well Water
0.96	0.03	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SAW J-13 Well Water
0.96	0.03	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SAW J-13 Well Water
0.96	0.02	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SAW J-13 Well Water
0.49	0.03	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SAW J-13 Well Water

Table 4-25. Corrosion Rates of Inconel Alloys in Acidified Water (Continued)

Time (years)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Table in Source	Temp ($^{\circ}\text{C}$)	Type of Analysis	Fluid Type
0.49	0.05	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SAW J-13 Well Water
0.49	0.08	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SAW J-13 Well Water
0.96	0.04	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SAW J-13 Well Water
0.96	0.06	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SAW J-13 Well Water
0.96	0.05	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SAW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.1, p.2.2-45	90	WL	SAW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.1, p.2.2-45	90	WL	SAW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.1, p.2.2-45	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.1, p.2.2-45	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.1, p.2.2-45	90	WL	SAW J-13 Well Water
1.00	0.02	Sec.2.2.6, Sup.1, p.2.2-45	90	WL	SAW J-13 Well Water
0.50	0.09	Sec.2.2.6, Sup.1, p.2.2-46	90	WL	SAW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.1, p.2.2-46	90	WL	SAW J-13 Well Water
0.50	0.01	Sec.2.2.6, Sup.1, p.2.2-46	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.1, p.2.2-47	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.1, p.2.2-47	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.1, p.2.2-47	90	WL	SAW J-13 Well Water
0.50	0.01	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SAW J-13 Well Water
0.50	0.02	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SAW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SAW J-13 Well Water
0.50	0.03	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SAW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SAW J-13 Well Water
0.50	0.00	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SAW J-13 Well Water
1.00	0.00	Sec.2.2.6, Sup.2, p.2.2-102	90	WL	SAW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: Negative corrosion values reported as zero in table.
WL = weight loss; SAW = simulated acidified well.

Table 4-26. Corrosion Rates of Inconel Alloys in Saltwater

Time (years)	Corrosion Rate ($\mu\text{m}/\text{yr}$)	Table in Source	Temp ($^{\circ}\text{C}$)	Type of Analysis	Fluid Type
0.50	0.08	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SCW J-13 Well Water
0.50	0.05	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SCW J-13 Well Water
0.50	0.10	Sec.2.2.6, Sup.1, p.2.2-46	60	WL	SCW J-13 Well Water
0.50	0.10	Sec.2.2.6, Sup.1, p.2.2-47	60	WL	SCW J-13 Well Water
0.50	0.09	Sec.2.2.6, Sup.1, p.2.2-47	60	WL	SCW J-13 Well Water
0.50	0.06	Sec.2.2.6, Sup.1, p.2.2-47	60	WL	SCW J-13 Well Water
0.50	0.07	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SCW J-13 Well Water
0.50	0.05	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SCW J-13 Well Water
0.50	0.08	Sec.2.2.6, Sup.2, p.2.2-101	60	WL	SCW J-13 Well Water
0.50	0.08	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SCW J-13 Well Water
0.50	0.06	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SCW J-13 Well Water
0.50	0.10	Sec.2.2.6, Sup.2, p.2.2-102	60	WL	SCW J-13 Well Water
0.51	0.05	Sec.2.2.6, Sup.1, p.2.2-46	90	WL	SCW J-13 Well Water
0.51	0.07	Sec.2.2.6, Sup.1, p.2.2-46	90	WL	SCW J-13 Well Water
0.51	0.04	Sec.2.2.6, Sup.1, p.2.2-46	90	WL	SCW J-13 Well Water
0.51	0.04	Sec.2.2.6, Sup.1, p.2.2-47	90	WL	SCW J-13 Well Water
0.51	0.04	Sec.2.2.6, Sup.1, p.2.2-47	90	WL	SCW J-13 Well Water
0.51	0.03	Sec.2.2.6, Sup.1, p.2.2-47	90	WL	SCW J-13 Well Water
0.51	0.11	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SCW J-13 Well Water
0.51	0.10	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SCW J-13 Well Water
0.51	0.24	Sec.2.2.6, Sup.2, p.2.2-101	90	WL	SCW J-13 Well Water
0.51	0.06	Sec.2.2.6, Sup.2, p.2.2-103	90	WL	SCW J-13 Well Water
0.51	0.07	Sec.2.2.6, Sup.2, p.2.2-103	90	WL	SCW J-13 Well Water
0.51	0.12	Sec.2.2.6, Sup.2, p.2.2-103	90	WL	SCW J-13 Well Water

Source: McCright 1998 [DIRS 114637].

NOTE: Negative corrosion values reported as zero in table.
WL = weight loss; SCW = simulated concentrated well.

4.1.3.9 Chrome Plating

Due to the extremely limited use of chrome plating in waste packages (chrome plating of borated Stainless Steel Type 304L poison wafers in Shippingport PWR assemblies—Section 4.1.1.2), the corrosion of chrome plating will not be investigated in this analysis.

4.1.3.10 Densities of Steels and Alloys

In several cases, conversion of rates from referenced sources to $\mu\text{m}/\text{yr}$ was necessary to obtain a consistent unit of measure of corrosion for this analysis. This was required when the corrosion rate was given as a mass loss per time. To complete the conversions (Appendix II), the densities of the materials (Table 4-27) had to be used.

Table 4-27. Material Densities

Aluminum Alloys			
Type	Density (g/cm ³)	Type	Density (g/cm ³)
1100	2.71	5154	2.66
3003	2.73	6061	2.70
5052	2.68	7075	2.81
5083	2.66		
Stainless Steels			
Type	Density (g/cm ³)	Type	Density (g/cm ³)
302	7.94	316	7.98
304	7.94	316L	7.98
304L	7.94	321	7.94

Source: ASTM G 1-90 [DIRS 103515].

4.1.4 Miscellaneous Materials

Miscellaneous materials, as defined in this analysis, are waste package component materials that do not fit neatly into one of the three categories specified above (i.e., fuel types or waste forms, steels, or alloys). These materials are presented below.

4.1.4.1 Sintered Compounds

The sintered compounds here are those contained within the Fort Saint Vrain fuel elements. The fuel elements are graphite blocks that hold the fuel compacts, which contain the fuel kernels. Fuel kernels are composed of a thorium carbide or Th/U carbide core surrounded by four protective coatings of SiC and pyrolytic carbon. These kernels are mixed with a carbonaceous binder material and “baked” to create the fuel compacts (Taylor 2001 [DIRS 154726]). This section is concerned with fuel element materials that do not contain fissile material (graphite, pyrolytic carbon, and SiC).

4.1.4.1.1 Graphite and Pyrolytic Carbon

The oxidation data for graphite and pyrolytic carbon are found in Table 4-28.

Table 4-28. Corrosion Behavior of Sintered Carbon Materials

Reference	Corrosion/Oxidation Rate/Behavior
Lide 2002 [DIRS 160832], p. 4-50	Insoluble in H ₂ O
Lewis 1990 [DIRS 130543], p. 188	For Industrial graphite: Excellent corrosion resistance
Lotts et al. 1992 [DIRS 164916], Appendix C	Report air oxidation of graphite: at 150°C = 1.05×10^{-17} g/cm ² /s; at 100°C = 4.5×10^{-20} g/cm ² /s. Corrosion by water is known to be slower than that in air (Propp 1998 [DIRS 149395]). Therefore, at 25°C in H ₂ O, the graphite can be assumed insoluble.
Morgan 1981 [DIRS 164920], p. 18	Insoluble at "ordinary temperatures"
Gurwell 1981 [DIRS 164911]	Reacts very slowly in deionized water (250°C = 10^{-7} g/cm ² /day, extrapolated to 99°C = 10^{-10} g/cm ² /day)
Shreir et al. 1998 [DIRS 164925], Chapter 18	Generally unreactive at low temperatures. Table 18.2 shows that it is completely resistant to a great number of highly corrosive environments.
Propp 1998 [DIRS 149395], p. 21	Air oxidation of graphite at 400°C = 1 mg/cm ² in 1.9 years and at 200°C = 1 mg/cm ² in 190,000 years

4.1.4.1.2 Silicon Carbide (SiC)

Most information on the oxidation of SiC comes from high temperature data in humid atmospheres, many times with the temperatures exceeding 1,000°C. Those data are located in Table 4-29. In Section 6.3.1, these high temperature data are used to approximate an oxidation rate of SiC at 25°C. Lide (2002 [DIRS 160832]) indicates that SiC is insoluble in water at 25°C.

Table 4-29. High Temperature Values for SiC Oxidation

Temperature (°C)	Condition	Rate (mg/cm ² ·h)
1,100	10%vol H ₂ O/O ₂	2.96×10^{-3}
1,100	25%vol H ₂ O/O ₂	6.52×10^{-3}
1,100	50%vol H ₂ O/O ₂	4.34×10^{-3}
1,100	70%vol H ₂ O/O ₂	3.32×10^{-3}
1,100	90%vol H ₂ O/O ₂	2.83×10^{-3}
1,100	14 vol% H ₂ O/Argon	1.85×10^{-3}
1,100	32 vol% H ₂ O/Argon	3.65×10^{-3}
1,100	59 vol% H ₂ O/Argon	4.45×10^{-3}
1,100	93 vol% H ₂ O/Argon	4.46×10^{-3}
1,200	10%vol H ₂ O/O ₂	3.05×10^{-2}
1,200	50%vol H ₂ O/O ₂	1.27×10^{-2}
1,200	70%vol H ₂ O/O ₂	2.11×10^{-2}
1,200	90%vol H ₂ O/O ₂	9.06×10^{-2}

Source: Temperature data from Opila 1999 [DIRS 155502], Table II.

4.1.4.2 Gadolinium Phosphate (GdPO₄)

In this analysis, the mineral monazite, a mixed lanthanide orthophosphate, is assumed to be a natural analog for GdPO₄ (Section 5.3.1). Natural mineral deposits of monazite have been reported to be over 2 billion years old and alluvial deposits indicate that the mineral has survived multiple sedimentation and metamorphic cycles occurring over several hundred million years

(Boatner and Sales 1988 [DIRS 164908]). This indicates that the mineral (in its natural form) is extremely resistant to corrosion.

Tests on synthetic monazite indicate that $<0.001 \text{ g/m}^2\cdot\text{day}$ of the lanthanide was released from the material and that the monazite matrix had a corrosion rate of less than $0.002 \text{ g/m}^2\cdot\text{d}$ in water at 90°C (Boatner and Sales 1988 [DIRS 164908], Figure 23 and Section 8.2). However, this was not a pure form of the substance, but was combined with 20 wt% Savannah River defense waste. Therefore, corrosion of pure monazite is expected to be much lower, since mineral impurities usually cause crystal structure defects or stress, which leads to increased mineral solubility.

4.1.5 Miscellaneous Handbook Data

Table 4-30 contains various constants used in the spreadsheet analyses for conversions and calculating values of corrosion rates.

Table 4-30. Miscellaneous Constants Used in Conversions

Constants (Lide 2002 [DIRS 160832])					
Term		Value		Source	
Gas Constant (R)		8.314510 Pa m ³ K ⁻¹ mol ⁻¹		p. 1-54	
Kelvin (K)		°C + 273.15		p. 1-46	
Celsius (°C)		(5/9) × (°F–32)		p. 1-46	
SiC density		3.16 g/cm ³		p. 4-82	
Graphite density		2.2 g/cm ³		p. 4-50	
Atomic weight of elements (Parrington et al. 1996 [DIRS 103896])					
Element	ATWT (grams/mole)	Element	ATWT (grams/mole)	Element	ATWT (grams/mole)
Gd	157.25	P	30.973761	O	15.9994
Cl	35.4527	F	18.9984032		

4.1.6 Titanium Grades 7 and 24

4.1.6.1 Titanium Grade 7

Since analysis of corrosion rates for Titanium Grade 7 can be found in other sources, this data will not be analyzed in this document. Information about other sources for this data is provided in Section 6.5.1.

4.1.6.2 Titanium Grade 24

Titanium Grade 24, an alloy with $\sim 6 \text{ wt } \%$ Al and $4 \text{ wt } \%$ V with and ~ 0.04 to $0.08 \text{ wt } \%$ Pd, is used as the structural material in the design of the drip shield. An experimentally obtained corrosion rate for Titanium Grade 24 under repository conditions is not available at this time. However, the comparative corrosion behavior of Titanium Grade 24 can be estimated based on available data for Titanium Grade 7 (See Section 6.5.2).

The LTCTF (Long Term Corrosion Test Facility) has obtained corrosion rate data for Titanium Grade 7 exposed in both vapor and liquid phases of SAW, SCW and SDW at 60°C and 90°C for

two and a half (2.5) years with weight-loss specimens (DTN: LL030410012251.056 [DIRS 169583]). The 2.5-year Titanium Grade 7 aqueous corrosion rate data are shown in Table 4-31 and are used to calculate the corrosion rate for Titanium Grade 24 (Section 6.5.2).

Table 4-31. Titanium Grade 7 Weight-Loss Corrosion Rates in Aqueous Media (2.5-Year Data)

Corrosion Rate (nm/yr)	Temp (°C)	Type of Analysis	Fluid Type
0.00	60	WL	Aqueous Phase SAW
0.00	60	WL	Aqueous Phase SAW
0.00	60	WL	Aqueous Phase SAW
0.00	90	WL	Aqueous Phase SAW
2.91	90	WL	Aqueous Phase SAW
14.59	90	WL	Aqueous Phase SAW
23.37	90	WL	Aqueous Phase SCW
2.92	90	WL	Aqueous Phase SCW
26.30	90	WL	Aqueous Phase SCW
43.57	90	WL	Aqueous Phase SCW
43.63	90	WL	Aqueous Phase SCW
46.29	90	WL	Aqueous Phase SCW
2.89	60	WL	Aqueous Phase SDW
5.77	60	WL	Aqueous Phase SDW
2.89	60	WL	Aqueous Phase SDW
0.00	90	WL	Aqueous Phase SDW
0.00	90	WL	Aqueous Phase SDW
0.00	90	WL	Aqueous Phase SDW
0.00	60	WL	Aqueous Phase SAW
0.00	60	WL	Aqueous Phase SAW
2.95	60	WL	Aqueous Phase SAW
17.64	90	WL	Aqueous Phase SAW
2.94	90	WL	Aqueous Phase SAW
2.94	90	WL	Aqueous Phase SAW
11.83	90	WL	Aqueous Phase SCW
14.83	90	WL	Aqueous Phase SCW
17.64	90	WL	Aqueous Phase SCW
43.75	90	WL	Aqueous Phase SCW
49.70	90	WL	Aqueous Phase SCW
49.46	90	WL	Aqueous Phase SCW
0.00	60	WL	Aqueous Phase SDW
0.00	60	WL	Aqueous Phase SDW
0.00	60	WL	Aqueous Phase SDW
0.00	90	WL	Aqueous Phase SDW
0.00	90	WL	Aqueous Phase SDW
2.92	90	WL	Aqueous Phase SDW

4.2 CRITERIA

The technical work plan for this activity (BSC 2004 [DIRS 171583], Table 3-1) has identified the following acceptance criteria (AC) based on the requirements mentioned in *Project Requirements Document* (PRD) (Canori and Leitner 2003 [DIRS 166275]) and *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]):

System Description and Demonstration of Multiple Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-014, PRD-002/T-016)

Specific requirements involve identifying multiple barriers (natural and engineered), describing the capabilities of these barriers to isolate waste, and providing technical bases for capabilities descriptions consistent with the postclosure performance objectives. To comply with these requirements, the following acceptance criteria are identified in the technical work plan (BSC 2004 [DIRS 171583], Table 3-1):

- AC1: Identification of Barriers is Adequate
- AC2: Description of Barrier Capability to Isolate Waste is Acceptable
- AC3: Technical Basis for Barrier Capability is Adequately Presented.

Degradation of Engineered Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.3.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-015)

Specific requirements include describing deterioration or degradation of engineered barriers and modeling degradation processes using data for performance assessment, including total system performance assessment (TSPA). Consideration of uncertainties and variabilities in model parameters and alternative conceptual models are also required. To fulfill these requirements, the following acceptance criteria are identified in the technical work plan (BSC 2004 [DIRS 171583], Table 3-1):

- AC1: System Description and Model Integration are Adequate
- AC2: Data are Sufficient for Model Justification
- AC3: Data Uncertainty is Characterized and Propagated Through the Model Abstraction
- AC4: Model Uncertainty is Characterized and Propagated Through the Model Abstraction
- AC5: Model Abstraction Output is Supported by Objective Comparisons.

4.3 CODES, STANDARDS, AND REGULATIONS

The following standards and regulations were used in Sections 4 and 6 and Appendix II of this analysis:

- ASTM A 240/A 240M-03b. 2003. *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications*

- ASTM A 276-03. 2003. *Standard Specification for Stainless Steel Bars and Shapes*
- ASTM A 516/A 516M-01. 2001. *Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service*
- ASTM A 887-89 (Reapproved 2000). 2000. *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application*
- ASTM B 209-96. 1996. *Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate*
- ASTM B 265-02. 2002. *Standard Specification for Titanium and Titanium Alloy Strip, Sheet, and Plate*
- ASTM B 932-04. 2004. *Standard Specification for Low-Carbon Nickel-Chromium-Molybdenum-Gadolinium Alloy Plate, Sheet, and Strip*
- ASTM G 1-90 (Reapproved 1999). 1999. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*
- 10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada
- 48 FR 28194. 10 CFR Part 60 Disposal of High-Level Radioactive Wastes in Geologic Repositories Technical Criteria.

5. ASSUMPTIONS

5.1 ASSUMPTIONS CONCERNING STEEL TYPES INVESTIGATED IN THIS ANALYSIS

5.1.1 AM-350 Corrosion Rate

Assumption: Published degradation rates were not found for Stainless Steel Type AM-350. For this analysis, the degradation rate is assumed to be the same as the degradation rate of Stainless Steel Type 316/316L.

Rationale: These stainless steels are very similar compositionally (Table 6-2) and are, therefore, likely to have similar degradation rates.

Confirmation Status: Information by Hudson and Stanners (1955 [DIRS 159334]), Scarberry et al. (1967 [DIRS 159335]), and Wallen and Olsson (1977 [DIRS 164948]) indicate the strong dependence of corrosion on metal composition, especially alloying elements. This indicates that compositionally similar metals will corrode at similar rates. Therefore, no further confirmation is required.

Use in the Analysis: This assumption is used in Section 6.2.1.2 in which the rates for Stainless Steel Types 316, 316L, and AM-350 are considered to have the same corrosion rates as presented in Table 6-5 and Figure 6-3 through Figure 6-5.

5.1.2 Use of Corrosion of Stainless Steel Type 302

Assumption: Published degradation rates for Stainless Steel Type 302 can be used for the corrosion of Stainless Steel Type 304 and 304L.

Rationale: The basis for this assumption is that these stainless steels are very similar compositionally (Table 6-2) and are, therefore, likely to have similar degradation rates.

Confirmation Status: Information in Hudson and Stanners (1955 [DIRS 159334]), Scarberry et al. (1967 [DIRS 159335]), and Wallen and Olsson (1977 [DIRS 164948]) indicate the strong dependence of corrosion to metal composition, especially alloying elements. This indicates that compositionally similar metals will corrode at similar rates. Therefore, no further confirmation is required.

Use in the Analysis: This assumption is used in Appendix II (*ECDF_metals.xls*) in which the corrosion rates for Stainless Steel Types 304, 304L, and 302 were combined to create the statistical information for these three steel types for use in Section 6.2.1.

5.2 ASSUMPTIONS CONCERNING ALLOYS INVESTIGATED IN THIS ANALYSIS

5.2.1 Corrosion of Inconel Alloys 600 and X-750

Assumption: Published degradation rates were not found for Inconel Alloys 600 and X-750. For this analysis, the degradation rate was assumed the same as the Inconel Alloy 625 degradation rate.

Rationale: The basis for this assumption is that these alloys are similar compositionally (Table 6-2) and are, therefore, likely to have similar degradation rates.

Confirmation Status: Information provided by Hudson and Stanners (1955 [DIRS 159334]), Scarberry et al. (1967 [DIRS 159335]), and Wallen and Olsson (1977 [DIRS 164948]) indicates the strong dependence of corrosion on metal composition, especially alloying elements. This indicates that compositionally similar metals will corrode at similar rates. Therefore, no further confirmation is required.

Use in the Analysis: This assumption is used in Appendix II (*aqueous Inconel-Alloy.xls*) in which these alloys are referred to only as Inconel alloy. These rates were then used for all the statistical information presented in Section 6.2.6.

5.2.2 Density of Aluminum Alloys

Assumption: Published density values were not found for several aluminum alloys. The density for Aluminum Alloy Type 5056 is assumed the same as Aluminum Alloy Type 5052; Aluminum Alloy Types 6051 and 6053 (all tempers) are assumed the same as Aluminum Alloy Type 6061; and Aluminum Alloy Type 7072 was assumed the same as Aluminum Alloy Type 7075. For alloys for which there is a core material surrounded by a different “clad” alloy, the density of the core was taken as the density of the sample.

Rationale: For single metal specimens, the basis for this assumption is that the alloys are similar compositionally (Table 6-2), and are, therefore, likely to have similar densities. For clad material, since the metal core comprises the majority of the volume of the specimen, it is logical that the density of the specimen would be similar to that of the core material.

Confirmation Status: As shown in Table 6-2, aluminum alloys range in density from 2.81 to 2.68 g/cm³. In addition, it can be seen from this table that compositionally similar metals have the same density (i.e., Aluminum Alloy Types 5052 and 5056). Because of this similarity, no further confirmation is required.

Use in the Analysis: This assumption is used in Appendix II (*aluminum.xls*) to calculate the corrosion rate from g to µm/yr for use in the statistical analysis presented in *ECDF_metals.xls* and Section 6.2.4.

5.3 ASSUMPTIONS CONCERNING MISCELLANEOUS MATERIALS

5.3.1 GdPO₄ Mineralogy

Assumption: The general properties and density of GdPO₄ were taken to be the same as those of the mineral monazite ((Ce,La,Nd,Th)PO₄).

Rationale: The rationale is that since gadolinium is a lanthanide and will have similar properties to the actinide and lanthanides occurring in monazite, monazite properties can be used to bound characteristics of GdPO₄.

Confirmation Status: This assumption is considered realistic. Therefore, no further confirmation is required.

Use in the Analysis: This assumption is used in Appendix II (*Misc_Materials.xls*) to calculate a rate in units of $\mu\text{m/yr}$ for use in Section 6.3.3. It is also used in Section 6.3.3 for verification of the durability of GdPO_4 .

5.4 ASSUMPTIONS CONCERNING GLASS FRACTURING

5.4.1 Cooling Fractures

Assumption: The fracture factor corresponding to glass cooling is assumed to be 12.5.

Rationale: The rationale is that a fracture factor range for typical cooling rates of DHLW glass is 10 to 15 (CRWMS M&O 1998 [DIRS 100362], p. 6-79). The average of this is 12.5, which also corresponds to a fracture factor for free air convection cooled glass (CRWMS M&O 1998 [DIRS 100362], Figure 6-32).

Confirmation status: This assumption is considered to be realistic. Therefore, no further confirmation is required.

Use in the analysis: This assumption is used in Appendix II (*glass-fracturefac.xls*) to calculate the fracture factor of high-level waste glass as presented in Table 6-16 and Table 6-17 in Section 6.4.3.1.

5.4.2 Fractures Due to a Drop

Assumption: The fracture factor corresponding to fractures created in a situation where the glass pour canisters are dropped is 5.

Rationale: Smith and Ross (1975 [DIRS 102088], pp. 12 to 14 and Figure 41) indicate that if a drop occurred, facilities under consideration would have a usual drop distance of 10 feet. A 30-foot drop would be near the upper limit of the drop distance and also matches the transportation packing requirements. Therefore, the upper limit of 30 feet was used for this analysis to derive the fractional increase in surface area for dropped canisters. Figure 41 of *Impact Testing of Vitreous Simulated High-Level Waste in Canisters* (Smith and Ross 1975 [DIRS 102088]) shows that at the velocity the package would be traveling when impact occurred from 30 feet (44 feet per second, (Smith and Ross 1975 [DIRS 102088], Table 1) the corresponding fractional increase in surface area (from best estimate curve) would be approximately 4. A value of 5 (4 plus 1 for the geometric surface area) is therefore used here.

Confirmation status: This assumption is considered to be realistic. Therefore, no further confirmation is required.

Use in the analysis: This assumption is used in Appendix II (*glass-fracturefac.xls*) to calculate the fracture factor of high-level waste glass as presented in Table 6-16 and Table 6-17 in Section 6.4.3.1.

5.4.3 Availability of Cooling Fractures

Assumption: Fractures created during glass cooling will not add to the degradation rate of the high level waste glass in a glass pour canister that has not been dropped.

Rationale: Most references dealing with fractures discuss how surface area increases. To obtain a fracture factor, more information in the form of availability of fracture surfaces and reactivity of fracture surfaces must be taken into account. Since references do not take these additional parameters into account, surface area measurements represent a total surface area instead of an effective surface area. The rationale for this assumption is that cracks created during cooling would be small, on the order of several tens of microns in width (Smith and Baxter 1981 [DIRS 102089], p. 15). It has been shown (Perez and Westsik 1981 [DIRS 111044]) that, even though total surface area may increase, fractures of this size have no appreciable contribution to the degradation rate of glass.

Confirmation status: This assumption is considered to be realistic. Therefore, no further confirmation is required.

Use in the analysis: This assumption is used in Appendix II (*glass-fracturefac.xls*) to calculate the fracture factor of high-level waste glass as presented in Table 6-16 and Table 6-17 in Section 6.4.3.1.

5.4.4 Reactivity of Glass Fractures

Assumption: It is also assumed that the reactivity of surfaces within fractures would be $\frac{1}{2}$ of the reactivity of unrestricted glass surfaces.

Rationale: Studies have shown that for highly fractured material (such as glass in a dropped canister), fractures display lower degradation rates than the outer surface area of the material. The degradation rate only increases slightly because fluid in the fractures will presumably not flow very freely and degradation will slow due to back reactions or precipitation. To be consistent with glass fracture reactivity used by *Defense HLW Glass Degradation Model* (BSC 2004 [DIRS 167619], Section 6.5.6), this analysis also uses $\frac{1}{2}$ for the glass fracture reactivity.

Confirmation status: This assumption is considered to be realistic. Therefore, no further confirmation is required.

Use in the analysis: This assumption is used in Appendix II (*glass-fracturefac.xls*) to calculate the fracture factor of high-level waste glass as presented in Table 6-16 and Table 6-17 in Section 6.4.3.1.

6. SCIENTIFIC ANALYSIS DISCUSSION

Where possible, the empirical cumulative distribution function (ECDF) is used to describe the corrosion data. Given the limited number of data points for corrosion of materials, the underlying distribution is not obvious and, therefore, the ECDF is considered appropriate for use. D'Agostino and Stephens (1986 [DIRS 160320], Chapter 2) define ECDF for any random sample as:

$$F_n(x) = \frac{\#(X_j \leq x)}{n}, -\infty < x < \infty \quad (\text{Eq. 1})$$

where the numerator is read as the number of samples (X_j) less than or equal to x (for this analysis, the corrosion value) with n equaling the number of samples. The ECDF is a step function that estimates the population distribution function. Thus, for $F_n(x)$, as x increases it takes a step up of height $1/n$ as each sample observation is reached. The ECDF [$F_n(x)$] differs from the CDF [$F(x)$] in that it records the proportion of observations less than or equal to x while the CDF represents the probability of an observation less than or equal to x . $F_n(x)$ can be used to estimate $F(x)$, and is a consistent estimator of $F(x)$ as n approaches infinity.

The use of the ECDF plot does not depend upon assumptions concerning the underlying distribution and has several advantages over other statistical devices such as:

- It is invariant under monotone transformations with regard to quantities (however, the appearance may change)
- Its complexity is independent of the number of observations
- It supplies immediate and direct information regarding the shape of underlying distribution (i.e., skewness and bimodality)
- It is an effective indicator of peculiarities such as outliers
- It supplies robust information on location and dispersion
- It does not involve grouping difficulties such as would arise in a histogram.

One of the disadvantages to the use of the ECDF is that they can be sensitive to random occurrences in the data, especially when the data set is small. Another limitation encountered with the use of the ECDF is that if the user is interested in any value outside of the range of values used to create the ECDF, the probability is zero. However, all inputs used to create the ECDF plots in this analysis are presented in Section 4 and are archived in output DTN: MO0409SPAACRWP.000 and may be used to obtain a probability curve by the user.

Due to limited information or the nature of some data or populations, there are several materials for which the ECDF could not be used. The distributions for these cases are described in the following sections as they arise.

The developed statistical parameters and ECDFs for aqueous degradation rates affecting waste package materials degradation will encompass various aqueous parameters such as temperature (up to 100°C), water type (i.e., fresh versus saline), and pH. Corrosion of materials at pH extremes (below 4 and above 10) is not included in this analysis since this is a special condition for which materials commonly display different corrosion behaviors. The output from this analysis is to be used in corrosion analysis to determine likelihood of corrosion scenarios and most likely corrosion rates for waste package materials to be used in corrosion studies.

The output from this analysis will support the determination of the probability of criticality for DOE SNF codisposal waste packages. Outputs can also be used for corrosion analyses to determine realistic (most probable) values of corrosion for various materials in waste packages.

6.1 TYPES OF CORROSION

The purpose of this report is not to describe the performance of engineered barriers for the TSPA-LA. Instead, the analysis provides simple statistics on aqueous corrosion rates of steels and alloys. In the EQ6 cases used to characterize corrosion of DOE waste packages, the rate is represented as a general corrosion over the entire surface of the material. For example, localized corrosion weight loss rates for aluminum are converted to general corrosion rates in $\mu\text{m}/\text{yr}$ for use in EQ6 calculations (BSC 2001 [DIRS 157640]; BSC 2002 [DIRS 158828]). Since the purpose of this analysis is to support EQ6 reaction path calculations and analyses, it will also focus on general corrosion rates. However, for some materials (such as aluminum), the primary corrosion behavior is a form of localized corrosion called pitting. In addition, galvanic coupling of materials in proximity to each other can have a strong effect on the rates of corrosion. Therefore, some data from specimens exhibiting localized or galvanic corrosion weight loss have been converted to general corrosion rates in $\mu\text{m}/\text{yr}$ and included in the rates presented in Section 6.2. This section presents a short overview of these corrosion types.

6.1.1 General Corrosion

General corrosion describes the process by which the entire surface of the metal is attacked uniformly.

6.1.2 Localized Corrosion

Localized corrosion of passive metals includes various phenomena such as pitting, crevice corrosion, intergranular attack, and stress corrosion cracking.

Crevice corrosion is a form of localized corrosion that can occur within crevices or shielded surfaces in which a solution can stagnate. Crevices can form from 1) the geometry of a structure (riveted plates, threaded joints, etc.), 2) Contact of the metal with nonmetallic solids (plastics, rubber, or glass associated with rivets, bolts, gaskets, welds, etc.), and 3) Deposits of sand, dirt, or corrosion products, or microbial growths on the metal surface (Shreir et al. 1998 [DIRS 100891], Section 1.6; Sedriks 1996 [DIRS 164036], Section 5). This corrosion can range from small pits to extensive corrosion over the whole surface.

Pitting corrosion includes the formation of cavities within the passivated area. With this type of corrosion, the metal may be fully penetrated despite having a low general corrosion rate. Pitting may also range from a few deep holes in the metal to the metal surface being completely covered with pits of differing depth (Sedriks 1996 [DIRS 164036], Section 4).

Crevice and pitting corrosion depend on the stability of the passive film, the metal, the aqueous environment, and temperature. As a general rule, increasing temperature and halide content of the corrosive medium increase localized attack. As with general corrosion, the elements chromium, nickel, and molybdenum help decrease the corrosion rate during localized corrosion. Stainless steel is usually quite resistant to localized attack. Sedriks (1996 [DIRS 164036], p. 214) cites 300 ppm as a safe chloride level for Stainless Steel Type 316, but other experiments indicate that halide levels can be much higher before localized corrosion becomes a problem. Carbon steel, lacking the alloying elements, is more susceptible. Aluminum alloys are very susceptible to pitting and usually display this behavior over long periods of exposure, in conditions causing the oxide film to break down. Rates for localized corrosion and depth of attack have been recorded by Gdowski and Bullen (1988 [DIRS 100860]), Sedriks (1996 [DIRS 164036]), Aziz (1956 [DIRS 159379]), and Kain et al. (1984 [DIRS 159385]).

6.1.3 Galvanic Corrosion

In a bimetallic couple, one metal (the anodic metal) corrodes sacrificially, protecting the cathode from corrosion. In most cases, this causes the corrosion rate of the anode to increase and the corrosion rate of the cathode to decrease or for corrosion to halt. Factors affecting the galvanic corrosion of a bimetallic couple include (Zhang 2000 [DIRS 164938], Figure 1):

- Reversible electrode potentials
- Reactions: dissolution, oxygen reduction, and hydrogen evolution
- Metallurgical factors: alloying, heat treatment, and mechanical working
- Surface conditions: surface treatment, passive film, and corrosion products
- Geometric factors: area; distance, position, shape, and orientation
- Environmental effects: forms of moisture, cyclic wet-dry, solar radiation, climate, and seasonal variations
- Electrolyte properties: ionic species, pH, conductivity, temperature, volume, and flow rate.

Possible bimetallic partners inside waste packages and their relation to each other can be found in Table 6-1.

Table 6-1. Major Bi-Metallic Couples Located Within Waste Packages

Metal	Coupled With	Couple Anodic Member	Effect on Anode
Aluminum	Carbon Steel	Aluminum ^a	Slight to marked increase in corrosion
Aluminum	Stainless Steel	Aluminum ^a	Slight to marked increase in corrosion
Aluminum	Aluminum	N/A ^a	none
Aluminum	Zircaloy	Aluminum ^c	Increase in corrosion
Carbon Steel	Stainless Steel	Carbon Steel ^a	Marked increase in corrosion
Carbon Steel	Carbon Steel	N/A ^a	none
Carbon Steel	Zircaloy	Zircaloy ^b	Increase in corrosion
Stainless Steel	Stainless Steel	N/A ^a	none
Stainless Steel	Zircaloy	Zircaloy ^b	Increase in corrosion
Stainless Steel	Alloy 22	Stainless Steel ^d	Increase in corrosion ^d

Sources: ^aShreir et al. 1998, Table 1.25 [DIRS 100891].

^bCole 1976 [DIRS 159369] and Smith 1987 [DIRS 159375]; Zr degrades sacrificially in the presence of stainless steel and ferric iron.

^cYau and Webster 1987 [DIRS 165063].

NOTE: ^dA typical galvanic series indicates that the stainless steels are less noble than Hastalloy Alloy C, which is similar to Alloy 22.

6.2 Steels and Alloys

As presented in Section 4.1.3, corrosion data of steels and alloys is divided according to the type of corroding medium and, where appropriate, temperature. The freshwater rates are representative of those solutions, which are dilute, such as lake water and J-13 well water. The saltwater in this case is ocean water with an average chloride content of 17,115 to 17,357 ppm (Forgeson et al. 1958 [DIRS 159343]) to simulate natural waters that have been concentrated by evaporation or contact with engineered materials. Any additions or modification to these definitions will be discussed below with the specific materials.

For solutions indicated by SDW, SCW, and SAW, this is indicative of Simulated Dilute Well Water, Simulated Concentrated Well Water, and Simulated Acidified Well Water (McCright 1998 [DIRS 114637]). The SDW simulates J-13 well water at 10× concentration to account for minor effects of water evaporation and boiling, while SCW simulates J-13 well water concentrated 1,000× to account for long-term water evaporation and boiling in the repository environment. The SAW represents J-13 well water that has been acidified and concentrated to simulate microbial metabolic products. Further information on these simulated solutions can be found in *Corrosion Data and Modeling, Update for Viability Assessment* (McCright 1998 [DIRS 114637], Section 2.2.4).

Compositions of alloys used in the analysis of corrosion rates are located in Table 6-2.

Table 6-2. Composition (wt %) of Steel and Alloys

Density (g/cm ³)	Material	C	Mn	P	Cu	S	Fe	Si	Cr	Ni	N	Al	Mo	Mg	Zn	Ti	Other	Total
304L = 7.94 ^b	302 ^a	0.15	2.00	0.045	—	0.030	Bal	1.00	17.0 to 19.0	8 to 10	0.1	—	—	—	—	—	—	—
304L = 7.94 ^b	304 ^a	0.08	2.00	0.045	—	0.030	Bal	1.00	18.0 to 20.0	8 to 11	—	—	—	—	—	—	—	—
304L = 7.94 ^b	304L ^a	0.030	2.00	0.045	—	0.030	Bal	1.00	18.0 to 20.0	8 to 12	—	—	—	—	—	—	—	—
N/A	B-304L Poison ^c	0.030	1.95	0.04	—	0.03	Bal	0.73	18.56	9.77	0.10	—	—	—	—	—	2.33B	—
N/A	825 ^d	0.02	0.37	—	1.90	0.004	Bal	0.08	22.70	43.98	—	0.06	2.92	—	—	1.07	—	—
316L = 7.98 ^b	316 ^a	0.08	2.00	0.045	—	0.030	Bal	1.00	16.0 to 18.0	10 to 14	—	—	2.00 to 3.00	—	—	—	—	—
316L = 7.98 ^b	316L ^a	0.030	2.00	0.045	—	0.030	Bal	1.00	16.0 to 18.0	10 to 14	—	—	2.00 to 3.00	—	—	—	—	—
316L = 7.98 ^b	316NG ⁿ	0.020	2.00	0.045	—	0.030	Bal	1.00	16.0 to 18.0	10 to 14	0.06 to 0.10	—	2.00 to 3.00	—	—	—	—	—
7.76 ^e	Neutronit (A978) ^f	0.04	—	—	—	—	Bal	—	18.5	13	—	—	2.2	—	—	—	0.20 Co / 1.245 B	—
7.94 ^b	321 ^a	0.08	2.00	0.045	—	0.0300	Bal	1.00	17.0 to 19.0	9 to 12	—	—	—	—	—	5X(C+N)-0.70	—	—
7.90	AM-350 ^o	0.07 to 0.11	0.5 to 1.25	0.04	—	0.03	Bal	0.50	16.0 to 17.0	4.0 to 5.0	0.07 to 0.13	—	2.5 to 3.25	—	—	—	—	—
N/A	A516 ^m	0.28	0.85 to 1.20	0.035	—	0.035	Bal	0.15 to 0.40	—	—	—	—	—	—	—	—	—	—
N/A	Alloy N06464 ^p	0.010 max	0.5 max	0.005 max	—	0.005 max	1.0 max	0.08 max	14.5 to 17.1	Bal.	0.010 max	—	13.1 to 16.0	—	—	—	2.0 max Co 1.9 to 2.1 Gd 0.005 O	—
N/A	24S-T3 ^g	—	0.58	—	4.54	—	0.30	0.15	—	—	—	Bal	—	1.46	—	—	—	—
N/A	Alclad 24S-T3 Coating ^g	—	0.01	—	0.27	—	0.13	0.07	—	—	—	Bal	—	0.13	—	—	—	—
N/A	Alclad 24S-T3 Core ^g	—	0.56	—	4.19	—	0.28	0.11	—	—	—	Bal	—	1.39	—	—	—	—
N/A	52S-1/2H ^g	—	0.05	—	0.02	—	0.15	0.12	0.21	—	—	Bal	—	2.53	—	—	—	—
N/A	Alclad 75S-T6 Coating ^g	—	0.01	—	0.09	—	0.36	0.07		—	—	Bal	—	0.15	1.31	—	—	—
N/A	Alclad 75S-T6 Core ^g	—	0.12	—	1.58	—	0.15	0.08	0.24	—	—	Bal	—	2.61	5.9	0.05	—	—
N/A	3S-1/2H ^h	—	1.2	—	—	—	—	—	—	—	—	Bal	—	—	—	—	—	—
N/A	Alclad 3S-1/2H	Unavailable																
N/A	61S-T ^h	—	—	—	0.25	—	—	0.6	0.25	—	—	Bal	—	1.0	—	—	—	—
2.71 ^b	1100-H14 ⁱ	—	0.05	—	0.05 to 0.20	—	0.95 (Fe + Si)		—	—	—	—	—	—	0.10	—	0.05	0.15
2.73 ^b	3003-H14 ⁱ	—	1.0 to 1.5	—	0.05 to 0.20	—	0.7	0.6	—	—	—	Bal	—	—	0.10	—	0.05	0.15
2.68 ^b	5052-H34 ⁱ	—	0.10	—	0.10	—	0.4	0.25	0.15 to 0.35	—	—	Bal	—	2.2 to 2.8	0.10	—	0.05	0.15
2.68 ^f	5056 ^j	—	0.05 to 0.20	—	0.10	—	0.4	0.3	0.05 to 0.20	—	—	Bal	—	4.5 to 5.6	0.10	—	0.05	0.15
2.66 ^b	5083 ⁱ	—	0.40 to 1.0	—	0.1	—	0.4	0.4	0.05 to 0.25	—	—	Bal	—	4.0 to 4.9	0.25	0.15	0.05	0.15
2.66 ^b	5154 ⁱ	—	0.10	—	0.10	—	0.4	0.25	0.15 to 0.35	—	—	Bal	—	3.1 to 3.9	0.20	0.20	0.05	0.15
2.70 ^s	6051-T4	Unavailable																
2.70 ^s	6051-T6	Unavailable																
2.70 ^s	6053-T6	Unavailable																
2.70 ^b	6061-T4 ⁱ	—	0.15	—	0.15 to 0.40	—	0.7	0.40 to 0.8	0.04 to 0.35	—	—	Bal	—	0.8 to 1.2	0.25	0.15	0.05	0.15
2.70 ^b	6061-T6 ⁱ	—	0.15	—	0.15 to 0.40	—	0.7	0.40 to 0.8	0.04 to 0.35	—	—	Bal	—	0.8 to 1.2	0.25	0.15	0.05	0.15
2.81 ⁱ	7072 ⁱ	—	0.10	—	0.10	—	0.7 (Fe + Si)	—	—	—		Bal	—	0.10	0.8 to 1.3	—	0.05	0.15
2.81 ^b	7075-T6 ⁱ	—	0.30	—	1.2 to 2.0	—	0.50	0.40	0.18 to 0.28	—	—	Bal	—	2.1 to 2.9	5.1 to 6.1	0.20	0.05	0.15
2.73 ^u	3003-Alclad ⁱ	Aluminum Alloy Type 3003 clad with Aluminum Alloy Type 7072																
2.70 ^u	6061-Alclad ⁱ	Aluminum Alloy Type 6061 clad with Aluminum Alloy Type 7072																
2.81 ^u	7075-Alclad ⁱ	Aluminum Alloy Type 7075 clad with Aluminum Alloy Type 7072																

Table 6-2. Composition (wt %) of Steel and Alloys (Continued)

Density (g/cm ³)	Material	C	Mn	P	Cu	S	Fe	Si	Cr	Ni	N	Al	Mo	Mg	Zn	Ti	Other	Total
2.71 ^q	Alcan 2S-O ^k	—	0.01	—	0.01	—	0.36	0.22	No data	—	—	Bal	—	No data	—	0.01	—	—
N/A	Inconel 600 ^l	0.15	1.0	—	0.5	0.015	6.0 to 10.0	0.5	14.0 to 17.0	72 min	—	—	—	—	—	—	—	—
N/A	Inconel 625 ^l	0.1	0.50	0.015	—	0.015	5.0	0.5	20.0 to 23.0	58.0 min	—	0.40	8.0 to 10.0	—	—	0.40	3.15 to 4.15 Nb+Ta and 1.0 Co	
N/A	Inconel X-750 ^l	0.08	1.00	—	0.50	0.01	5.0 to 9.0	0.50	14.0 to 17.0	70.0 min	—	0.4 to 1.00	—	—	—	2.25 to 2.75	0.70 to 1.20 Nb, 1.00 Co	
N/A	Titanium Grade 7 ^v	0.08 max	—	—	—	—	0.30 max	—	—	—	0.03 max	—	—	—	—	Bal	0.015 max H, 0.25 max O, and 0.12 to 0.25 Pd	
N/A	Titanium Grade 24 ^v	0.08 max	—	—	—	—	0.40 max	—	—	—	0.05 max	5.5 to 6.75	—	—	—	Bal	0.015 max H, 0.20 max O, 3.5 to 4.5 V, and 0.04 to 0.08 Pd	

Sources: ^aASTM A 276-03 [DIRS 165006].
^bASTM G 1-90 [DIRS 103515].
^cASTM A 240/A 240M-03b [DIRS 165003] Stainless Steel Type 304L composition; CRWMS M&O 1999 [DIRS 127351] accommodating 2.33% boron.
^dBeavers et al. 1992 [DIRS 159339].
^eDTN: MO0109RIB00049.001 [DIRS 155964].
^fDTN: MO0109RIB00049.001 [DIRS 155964]; ASTM A 887-89 [DIRS 154062], Table 1, S30463, S30464, and S30466 for boron content.
^gBomberger et al. 1954 [DIRS 163699].
^hSawyer and Brown 1947 [DIRS 164921].
ⁱASTM B 209-96 [DIRS 144744].
^jAilor 1969 [DIRS 164907], Table 11.
^kAziz 1956 [DIRS 159379].
^lInco Alloys International 1988 [DIRS 130835].
^mASTM A516/A 516M-01 2001 [DIRS 162723] (Table 1, 2" to 4" thickness, Grade 65).
ⁿDanko 1987 [DIRS 154395], p. 931 – Stainless Steel Type 316 base with difference in N and C content.
^oBauccio 1993 [DIRS 131480], pp. 359 and 360.
^pASTM B 932-04 2004 [DIRS 168403].
^vASTM B 265-02 2002 [DIRS 162726].

NOTES: ^qAssumed the same as Aluminum Alloy 1100 (Section 5.2.2).
^rAssumed the same as Aluminum Alloy 5052 (Section 5.2.2).
^sAssumed the same as Aluminum Alloy 6061 (Section 5.2.2).
^tAssumed the same as Aluminum Alloy 7075 (Section 5.2.2).
^uAssumed same density as aluminum-alloy comprising core (Section 5.2.2).

6.2.1 Stainless Steel

The extent to which corrosion proceeds is highly dependent on the elemental composition of the material. Hudson and Stanners (1955 [DIRS 159334]) show that even small amounts of chromium will slow damage to steel. Even in highly oxidizing environments, chromium lends strong resistance to attack (Scarberry et al. 1967 [DIRS 159335]). The addition of nickel further fortifies the steel, as it is effective in reducing corrosion in reducing conditions and in neutral salt solutions and alkalies (Scarberry et al. 1967 [DIRS 159335]). The introduction of molybdenum to stainless steel is done to aid in corrosion resistance, but specifically, to add resistance to localized corrosion (Scarberry et al. 1967 [DIRS 159335]). However, the addition of molybdenum can have a negative effect in highly oxidizing conditions (Wallen and Olsson 1977 [DIRS 164948]).

Stainless steels planned for use in the waste packages (Stainless Steel Type 304 series and 316 series) contain significant amounts of chromium, nickel, and molybdenum (ASTM A 240/A 240M-03b [DIRS 165003], ASTM A 276-03 [DIRS 165006], and Bauccio 1993 [DIRS 131480]). These three elements have been shown to significantly decrease the corrosion of stainless steel in aqueous environments ranging from mild freshwaters to caustic saltwater. This is accomplished through the formation of a passive layer (film). The passive films of stainless steels are very thin hydrous oxides enriched in chromium, silicon, and molybdenum. At high temperatures a more stable chromium-nickel spinel structure can form. By solid-state diffusion through the passive film, continuous dissolution and precipitation of the film occurs (Wallen and Olsson 1977 [DIRS 164948]; McCright et al. 1987 [DIRS 159336]) providing a protective barrier to attack from the surrounding media. Passive film formation causes the continual decrease of the degradation rate seen in many studies (i.e., Gdowski and Bullen 1988 [DIRS 100860]; Larrabee 1953 [DIRS 159337]). As time passes, unless otherwise disturbed, the passive film stabilizes and sometimes (in the case of freshwater corrosion) can halt corrosion of the steel completely.

Breakdown of the passive film can occur in highly oxidizing or reducing environments, in the presence of chloride or sulfates, and harsh, localized environments caused by physical properties such as galvanic coupling, surface blemishes on the material, and the growth of bacterial colonies. These effects usually contribute to forms of corrosion other than the general corrosion discussed here (discussion of localized and galvanic corrosion is in Sections 6.1.2 and 6.1.3).

As shown in the tables in Section 4.1.3, most of the corrosion data is from short-term experiments ranging from a few weeks to sixteen years. It has been generally shown that there is a continual decrease of the degradation rate over time (Gdowski and Bullen 1988 [DIRS 100860]; Larrabee 1953 [DIRS 159337]; and Southwell et al. 1976 [DIRS 100927]). Therefore, the rates may eventually reach a steady state in which the overall corrosion approaches 0 $\mu\text{m}/\text{yr}$. Since corrosion rates over longer periods have not been measured, the data from short-term experiments will be used here to describe the corrosion of materials. Given the information above, the rates are expected to be low. The corrosion rates for Stainless Steel Types 304L and 316L in fresh or dilute waters expected at the repository can be found in Table 4-2 and Table 4-3.

Another factor affecting stainless steel corrosion is the concentration of halides in the corroding medium. The chloride (Cl⁻) and fluoride (F⁻) content of several water types is presented in Table 6-3.

Table 6-3. Halide Content of Several Waters from Yucca Mountain Strata Compared to J-13 Well Water

Water Type	J-13 Well Water ^a	Tptpll Crown Seepage ^b	Evaporated Tptpmn Crown Seepage Water ^c	Tptpll Crown Seepage / Grout Leachate ^c	Evaporated Perched Water / Grout Leachate ^d
Cl ⁻ (ppm)	7.14	117	7,587	117	1,858
F ⁻ (ppm)	2.18	5.81	6.63	5.97	None Reported

Sources: ^aDTN:MO0006J13WTRCM.000 [DIRS 151029].

^bBSC 2001 [DIRS 155859], Transition to ambient temperature, Table 11.

^cBSC 2001 [DIRS 156183], Transition to ambient temperature, Tables 6.1-6 and 6.2-10.

^dBSC 2001 [DIRS 156183], Ambient temperature, Table 6.2-16.

NOTE: All values converted to ppm in *ppm_.xls* on Appendix II.

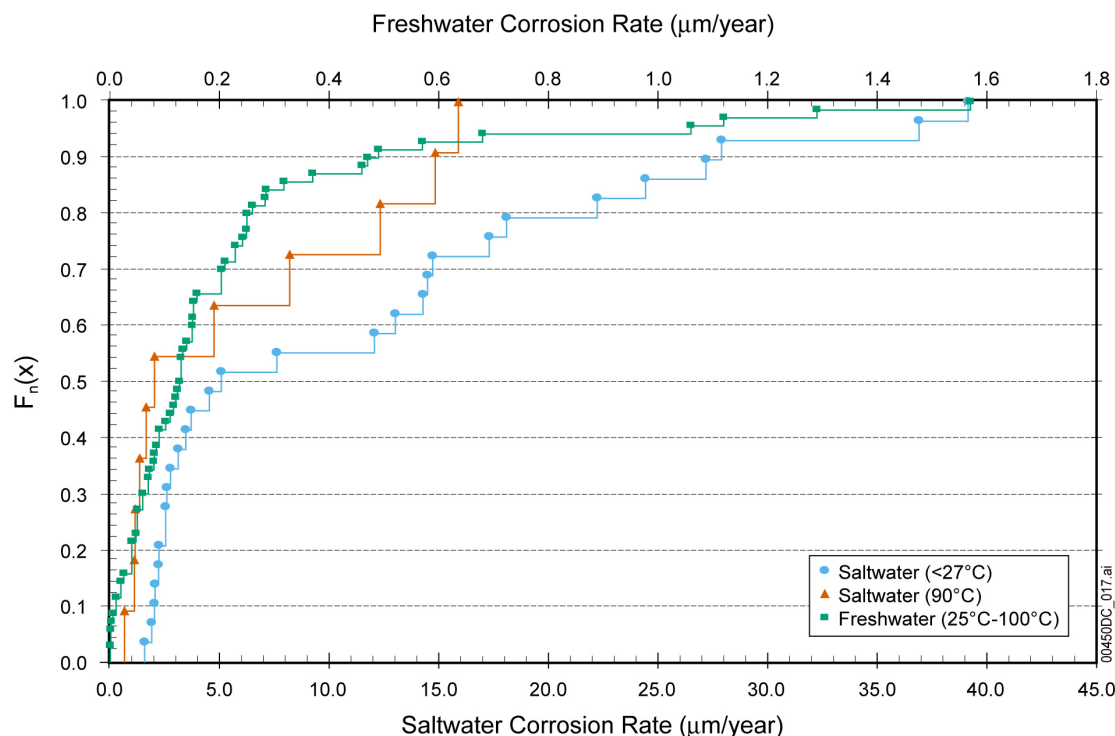
For comparison, an example of the Cl⁻ concentration in seawater at the Panama Canal Zone lies between 17,357 and 17,415 ppm (Forgeson et al. 1958 [DIRS 159343]). These components inside the corroding medium are important because they interfere with the maintenance of the passive film (Wallen and Olsson 1977 [DIRS 164948]; Davison et al. 1987 [DIRS 162971]) and accelerate localized corrosion of the metal. General corrosion rates for Stainless Steel Types 304L and 316L in saltwater used for this analysis are found in Table 4-4 and Table 4-5.

As indicated in Section 4.1.3, the corrosion resistance of stainless steels in freshwater and saltwater differs quite markedly. Therefore, they have been analyzed separately here.

6.2.1.1 Stainless Steel Types 302/304/304L

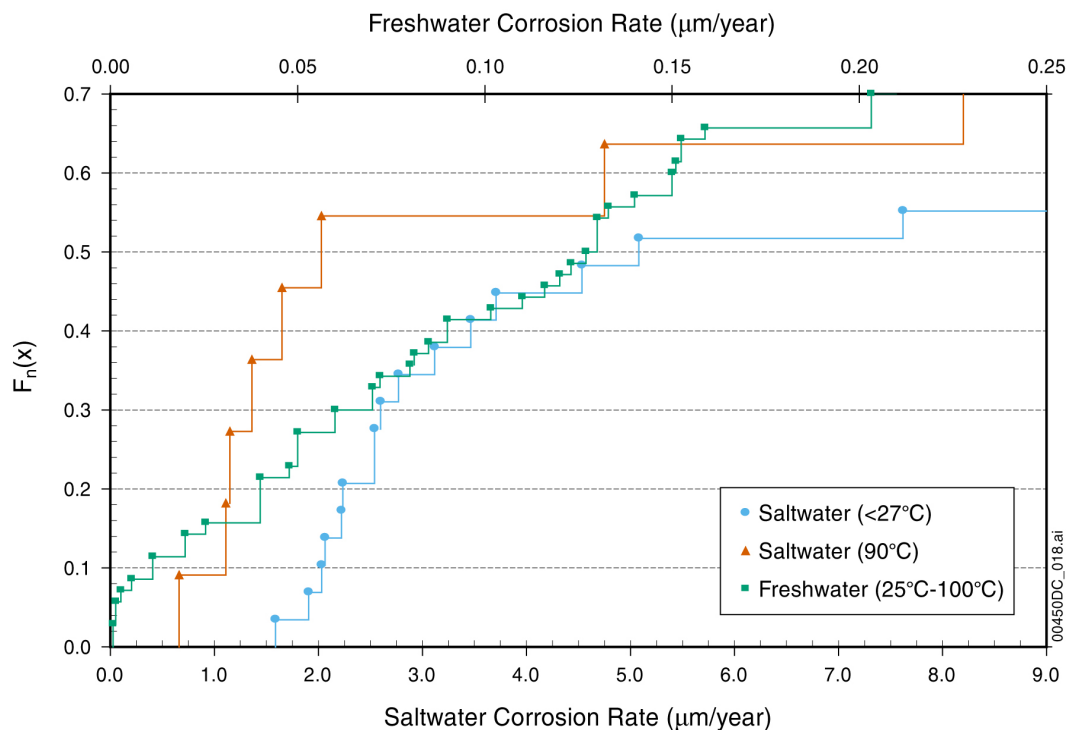
Probabilities for general corrosion rates of Stainless Steel Type 304L are presented in *Degradation of Stainless Steel Structural Material* (BSC 2001 [DIRS 156356]). However, these rates come primarily from data on the corrosion of stainless steel in seawater. As the waters entering the drift at Yucca Mountain will be dilute solutions (similar to J-13 well water, DTN: MO0006J13WTRCM.000 [DIRS 151029]), it is not expected that the corrosion rates of waste package materials will be as fast as those occurring in sea water. For this reason, the full suite of information of corrosion in fresh and saltwater, including time duration, and environmental conditions of experiments is presented in Section 4.1.3.1.

The statistical information on the corrosion of Stainless Steel Type 304L is located in Table 6-4 and Figure 6-1 and Figure 6-2.



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-2, Table 4-2, and Table 4-4. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-1. ECDF for Stainless Steel Types 302/304/304L in All Water Types Investigated



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-2 and Table 4-4. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-2. ECDF for Stainless Steel Types 302/304/304L Showing Detail for Slower Rates

Table 6-4. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Stainless Steel Types 302/304/304L

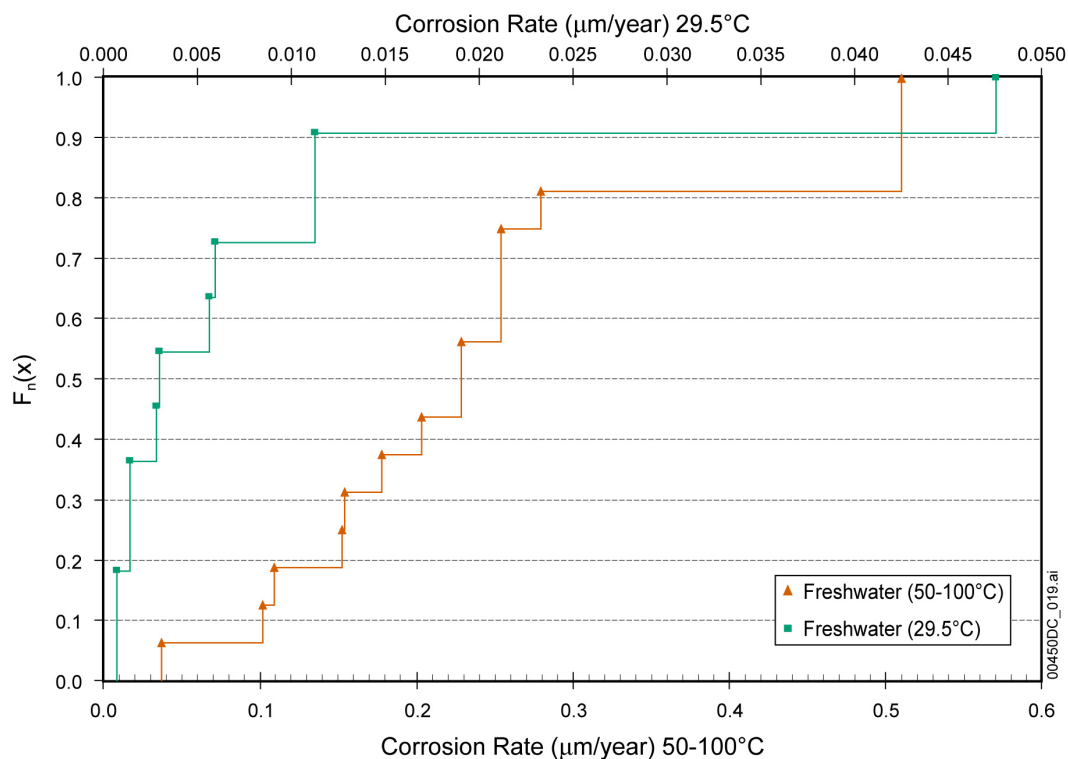
Environment	Corrosion Rate ($\mu\text{m}/\text{yr}$)				Standard Deviation
	Minimum	Maximum	Median	Mean	
Freshwater (25°C to 100°C)	0.001	1.570	0.1285	0.214	0.298
Saltwater (26.7°C)	1.588	39.147	5.08	11.441	11.134
Saltwater (90°C)	0.660	15.900	2.03	5.816	5.953

NOTE: Calculated in *aqueous-304L.xls* in Appendix II from values in Table 4-2 and Table 4-4. Archived in output DTN: MO0409SPAACRWP.000.

6.2.1.2 Stainless Steel Types 316/316L/AM-350

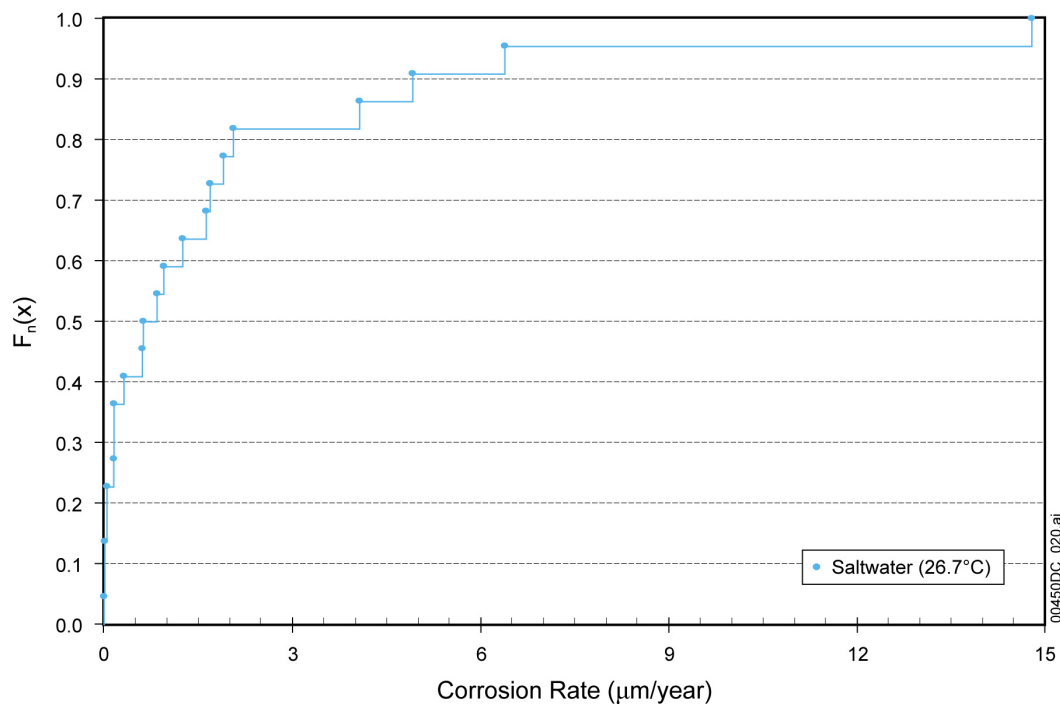
Probabilities for general corrosion rates of Stainless Steel Type 316L are also presented in *Degradation of Stainless Steel Structural Material* (BSC 2001 [DIRS 156356]). However, as for Stainless Steel Type 304L, these rates come primarily from data on the corrosion of stainless steel in seawater. As the waters entering the drift at Yucca Mountain will be dilute solutions (similar to J-13 well water, DTN: MO0006J13WTRCM.000 [DIRS 151029]), it is not expected that the corrosion rates of waste package materials will be as fast as those occurring in sea water. For this reason, the full suite of information of corrosion in fresh and saltwater, including time duration, and environmental conditions of experiments is presented Section 4.1.3.1.

The statistical information on the corrosion of Stainless Steel Type 316L is located in Table 6-5 and Figure 6-3 through Figure 6-5.



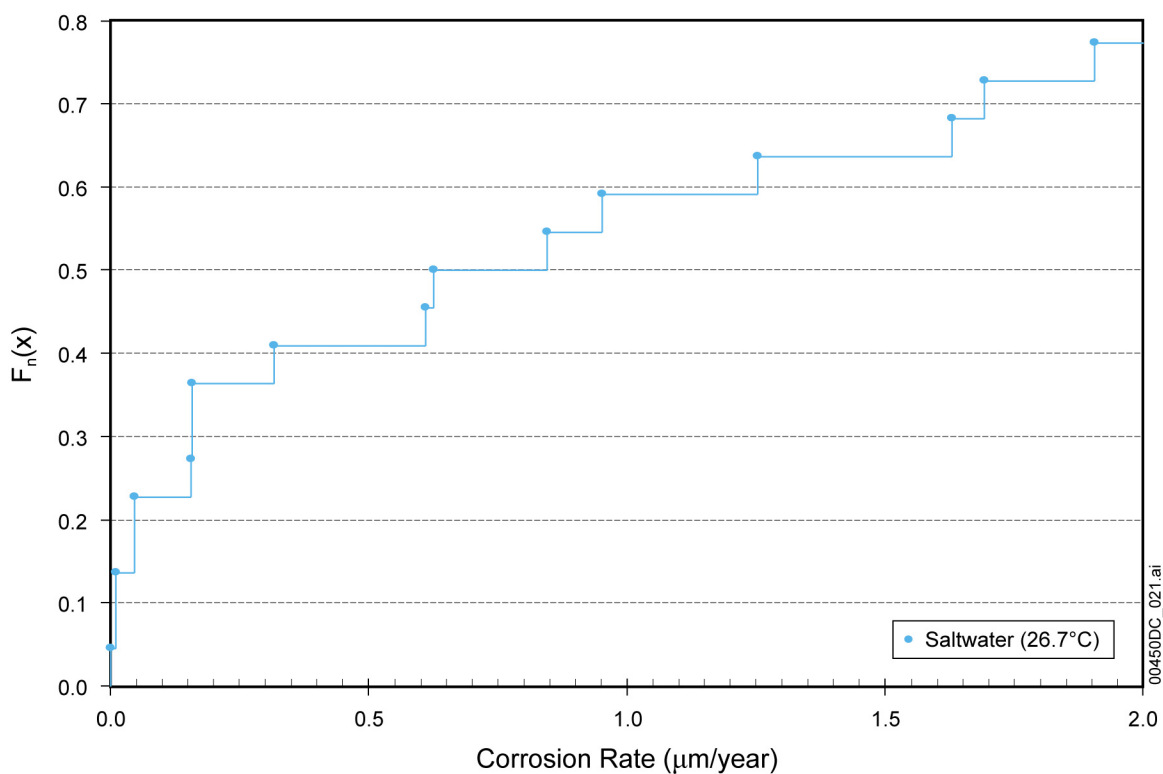
NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-3. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-3. ECDF for Stainless Steel Types 316/316L/AM-350 in Freshwater



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-5. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-4. ECDF for Stainless Steel Types 316/316L/AM-350 in Saltwater



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-5. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-5. ECDF for Stainless Steel Types 316/316L/AM-350 in Saltwater Showing More Detail for Corrosion Rates Below 2.5 $\mu\text{m}/\text{yr}$

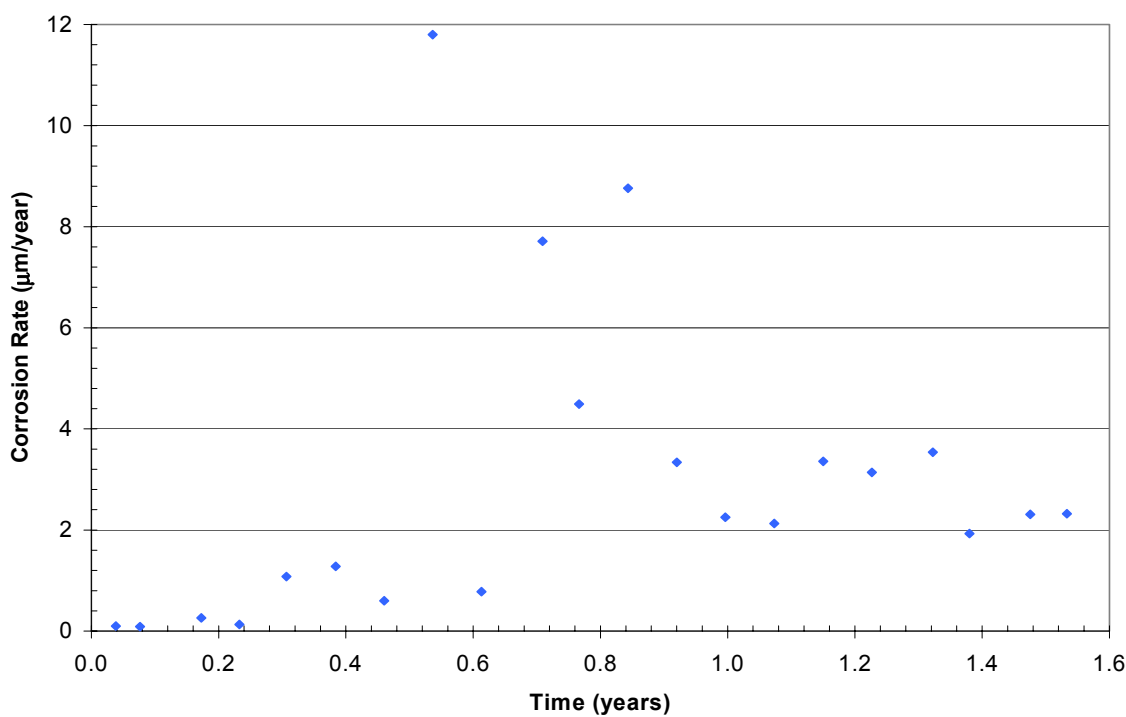
Table 6-5. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Stainless Steel Types 316/316L/AM-350

Environment	Corrosion Rate ($\mu\text{m}/\text{yr}$)				Standard Deviation
	Minimum	Maximum	Median	Mean	
Freshwater (29.5°C)	0.0007	0.0475	0.003	0.0083	0.0136
Freshwater (50°C to 100°C)	0.037	0.51	0.229	0.248	0.146
Saltwater (26.7°C)	0.0014	14.787	0.7362	1.939	3.346

NOTE: Calculated in *aqueous-316L.xls* in Appendix II from values in Table 4-3 and Table 4-5. Archived in output DTN: MO0409SPAACRWP.000.

6.2.1.3 Boil-Down Tests

The results from 80-week boil-down tests are located in Table 4-6. These results are included as they show the trend of Stainless Steel Type 304L corrosion as the test solution is gradually concentrated by evaporation. The data on the corrosion of Stainless Steel Type 304L in a boil-down environment is located in Figure 6-6. As there are no published data on the solution chemistry of these tests, other than that the solution was slowly concentrated through evaporation, no statistical analysis was done for this set of corrosion values. However, Figure 6-6 below shows that after approximately one year, the rate of corrosion levels off at around 3 $\mu\text{m}/\text{yr}$.



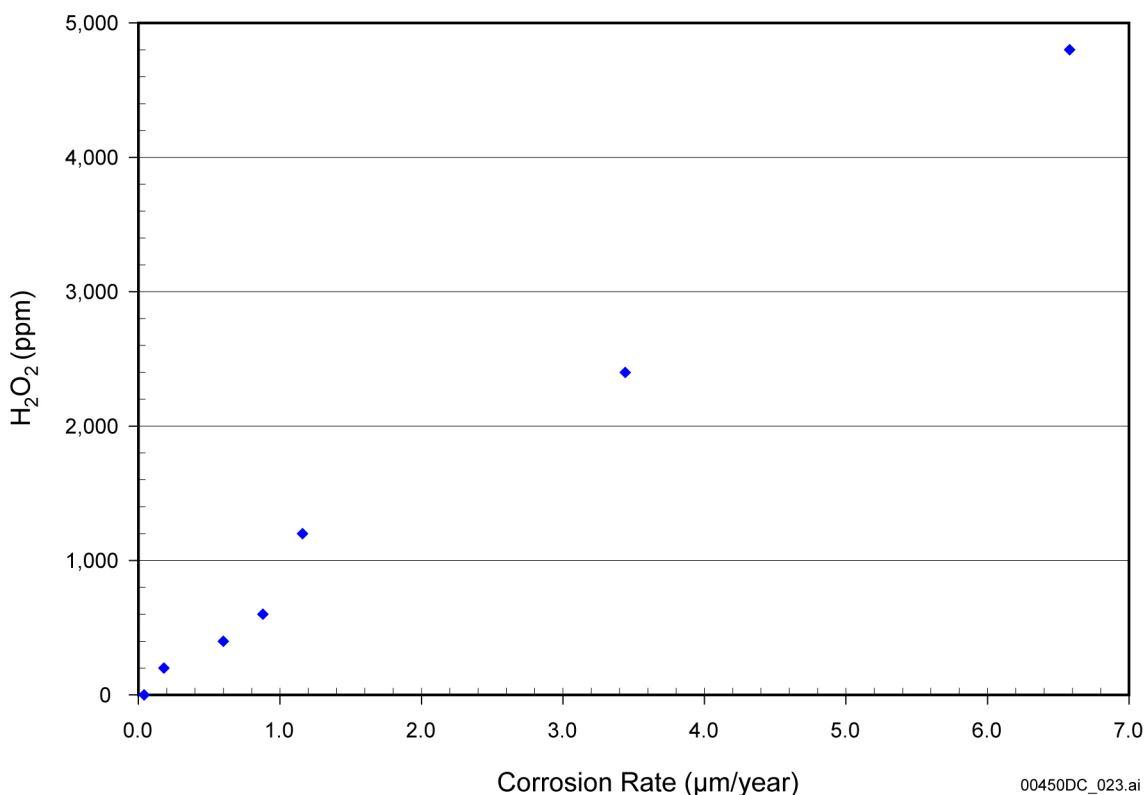
NOTE: Graphical representation of values in Table 4-6. Graphed in *aqueous-304L.xls* in Appendix II. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-6. Experimental Results of Boil-Down Tests

6.2.1.4 Effects of Radiolysis

Radiolysis is defined as chemical decomposition caused by radiation. In aqueous solutions, radiolysis can produce a number of transient radicals, ions, and molecular species, including $\text{H}\cdot$, $\cdot\text{OH}$, e_{aq}^- , H_3O^+ , OH^- , H_2 , H_2O_2 , O_2 , O_2^- , HO_2 , oxides of nitrogen, and dilute nitric acid (Beavers and Durr 1991 [DIRS 159341], McCright et al. 1987 [DIRS 159336], Glass et al. 1986 [DIRS 105021]). When J-13 well water undergoes radiolysis, the oxygenated water would allow O_2 and H_2O_2 to form as the dominant species in solution with smaller concentrations of O_2^- and much smaller steady state concentrations of H_2 , $\cdot\text{OH}$ and $\text{H}\cdot$ (Glass et al. 1986 [DIRS 105021]). Therefore, radiolysis is expected to increase the oxidizing nature of the aqueous fluid entering the waste package. From the report by Wallen and Olsson (1977 [DIRS 164948]), it is known

that the addition of molybdenum can have a corrosive effect in highly oxidizing conditions. This indicates that if radiolysis increases the oxidizing conditions of the waste package, the corrosion rate of the Stainless Steel Type 316 series and Neutronit will increase. Beavers and Durr (1991 [DIRS 159341]) show that with increasing H_2O_2 concentration, the corrosion rate of Stainless Steel Type 304L increases (Table 4-7). The results of those experiments are shown in Figure 6-7.



NOTE: Graphical representation of values in Table 4-7. Graphed in *aqueous-304L.xls* in Appendix II. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-7. Corrosion Rate of Stainless Steel Type 304L as a Function of H_2O_2 from Radiolysis

6.2.1.5 Stainless Steel Sensitization

Stainless steels are susceptible to developing a “sensitized” microstructure when exposed to high temperatures over short time periods. Sensitization causes chromium rich carbides to precipitate from solid solution in the steel, producing chromium-depleted zones around the carbides (McCright et al. 1987 [DIRS 159336]; Fox and McCright 1983 [DIRS 159344]). The protective passive film that forms on the sensitized grain boundary is, therefore, not as stable as that on the bulk of the material because of the depleted zones of chromium. This leaves the stainless steel surface open to preferential attack (localized corrosion), especially by oxidizing media.

High carbon-content steels (Stainless Steel Types 316/304) are very susceptible to sensitization. Lower carbon-content steels are preferable (Stainless Steel Types 316L/304L), as these have been shown to hold up better to sensitization than their higher carbon counterparts (Gdowski and Bullen 1988 [DIRS 100860]; Shreir et al. 1998 [DIRS 100891], pp. 3-54 through 3-57). For

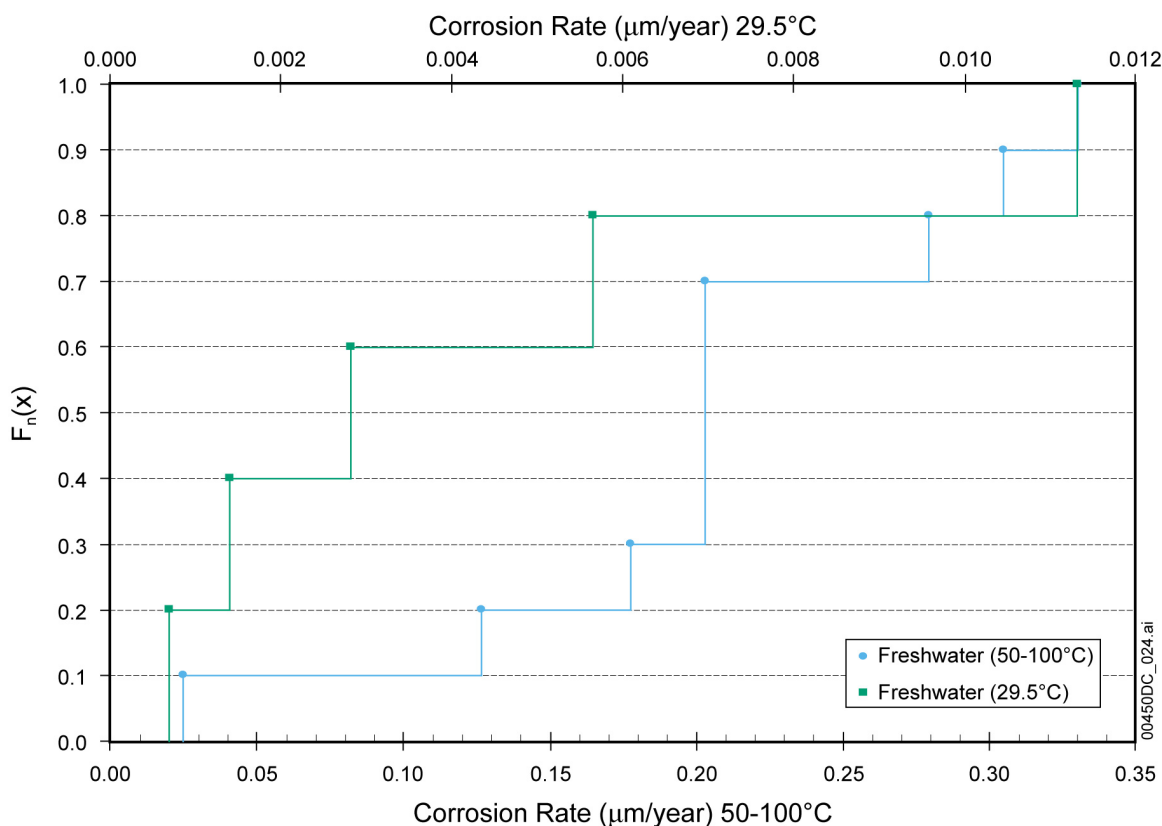
Stainless Steel Type 316 NG, with carbon content below 0.02%, no sensitization has been observed (Gdowski and Bullen 1988 [DIRS 100860]). In fact, Stainless Steel Type 316NG is the material suggested to replace Stainless Steel Type 304L in BWRs, since sensitization of Stainless Steel Type 304L causes it to corrode (Fox and McCright 1983 [DIRS 159344]). Other work shows that the molybdenum in the Stainless Steel Type 316 series impedes the diffusion of carbon atoms, slowing the growth of carbide nuclei, thus making the Stainless Steel Type 316 more resistant to sensitization (McCright et al. 1987 [DIRS 159336]).

Chromium carbide precipitation usually occurs in the temperature range from 500°C to 850°C (through heat treatments) with the rate of precipitation controlled by chromium diffusion (Gdowski and Bullen 1988 [DIRS 100860]; Fox and McCright 1983 [DIRS 159344]). However, steels are rarely kept at these high temperatures for sufficient amounts of time to become sensitized. Therefore, it must be determined whether stainless steel placed in the repository environment, with temperatures ranging from 85°C to 280°C, will undergo low temperature sensitization (LTS). *Drift-Scale Coupled Processes (DST and THC Seepage) Models* (BSC 2004 [DIRS 168848], Section 6.5.5.1) indicates that the repository temperatures will decrease over time. Briant et al. (1982 [DIRS 159345]) estimate that at 200°C, it would take 4,000 years for Stainless Steel Type 304L to become sensitized. From these two references, it can be inferred that sensitization of the Stainless Steel Types 304 series, 316 series, and Neutronit by early repository temperatures is unlikely. Therefore, no analysis on the corrosion of a sensitized stainless steel is presented here.

6.2.2 Steel Containing Neutron Absorbers

6.2.2.1 Neutronit

Kügler (1997 [DIRS 134327]) states that the corrosion resistance of Neutronit is similar to that of AISI Stainless Steel Type 321. The corrosion rates of Neutronit (based on the corrosion of Stainless Steel Type 321) can be found in Tables 4-8 and 4-9. Like other stainless steels, it displays excellent corrosion resistance, especially in dilute waters. A rate of 40 $\mu\text{m}/\text{yr}$ has been suggested in *Scoping Corrosion Tests on Candidate Waste Package Basket Materials for the Yucca Mountain Project* (Van Konynenburg et al. 1998 [DIRS 100948]) after 96-hour exposure to highly corrosive media containing 0.01-molar concentrations of radiolysis products (nitric acid and hydrogen peroxide) and chloride buffered at pH 4. *In-Package Chemistry Abstraction* (BSC 2004 [DIRS 167621], Appendix III) has shown that lower concentrations of nitric acid and hydrogen peroxide will be produced by radiolysis, having little effect on the pH and chemistry inside the waste package. Therefore, the test conditions used by Van Konynenburg et al. (1998 [DIRS 100948]) are not representative of expected repository conditions and their rate value was not used for this analysis. The statistical information on the corrosion of Stainless Steel Type 321 is located in Table 6-6, Figure 6-8 and Figure 6-9.



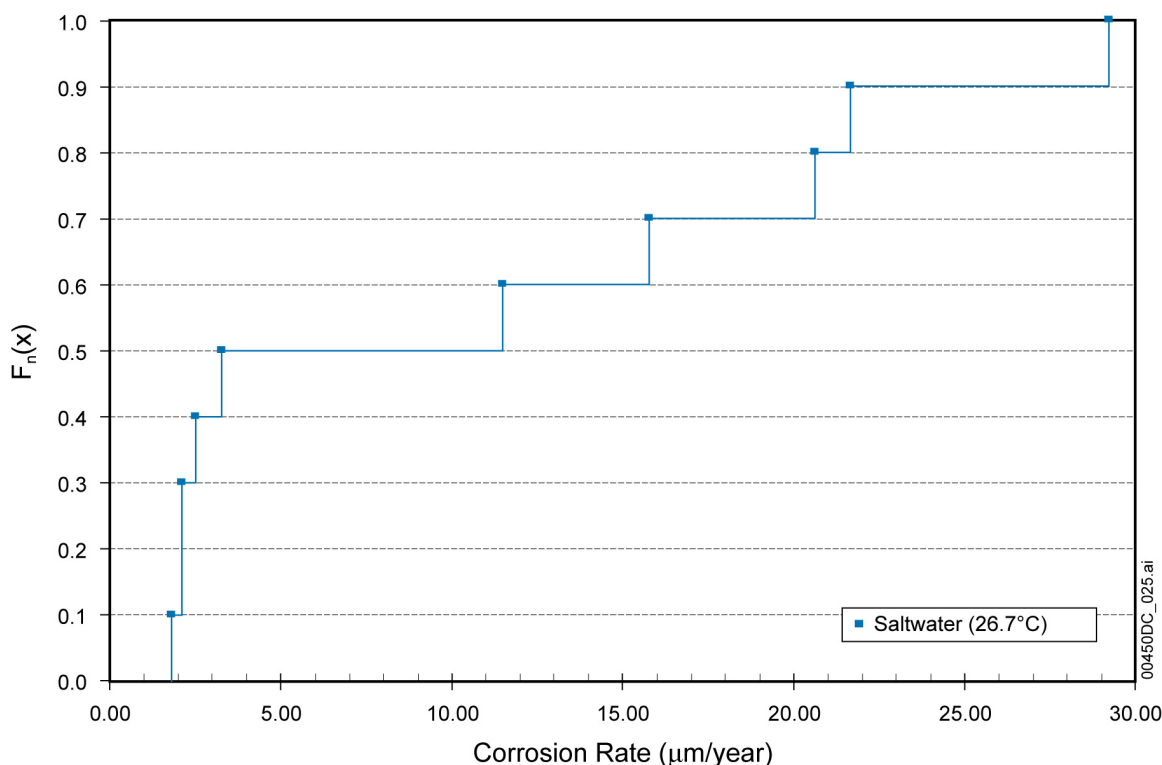
NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-8. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-8. ECDF for Neutronit (Using Stainless Steel Type 321 Surrogate) in Freshwater

Table 6-6. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Neutronit (Using Stainless Steel Type 321 Surrogate)

Environment	Corrosion Rate ($\mu\text{m}/\text{yr}$)				Standard Deviation
	Minimum	Maximum	Median	Mean	
Freshwater (29.5°C)	0.001	0.011	0.003	0.004	0.004
Freshwater (50°C to 100°C)	0.025	0.330	0.203	0.206	0.088
Saltwater (26.7°C)	1.81	29.22	7.38	11.06	10.19

NOTE: Calculated in *aqueous-B-Gd-steels.xls* in Appendix II from values in Table 4-8 and Table 4-9. Archived in output DTN: MO0409SPAACRWP.000.



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-9. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-9. ECDF for Neutronit (Using Stainless Steel Type 321 Surrogate) in Saltwater

6.2.2.2 Borated Stainless Steel Type 304L

The effects of boron content have also been studied for Stainless Steel Type 304. Most corrosion tests for this material have been conducted in extremely hostile environments such as boiling nitric acid, sulfuric acid and 7N-HNO₃ (Smith et al. 1992 [DIRS 103441]; EPRI 1986 [DIRS 159367]; and Butler 1963 [DIRS 159368]).

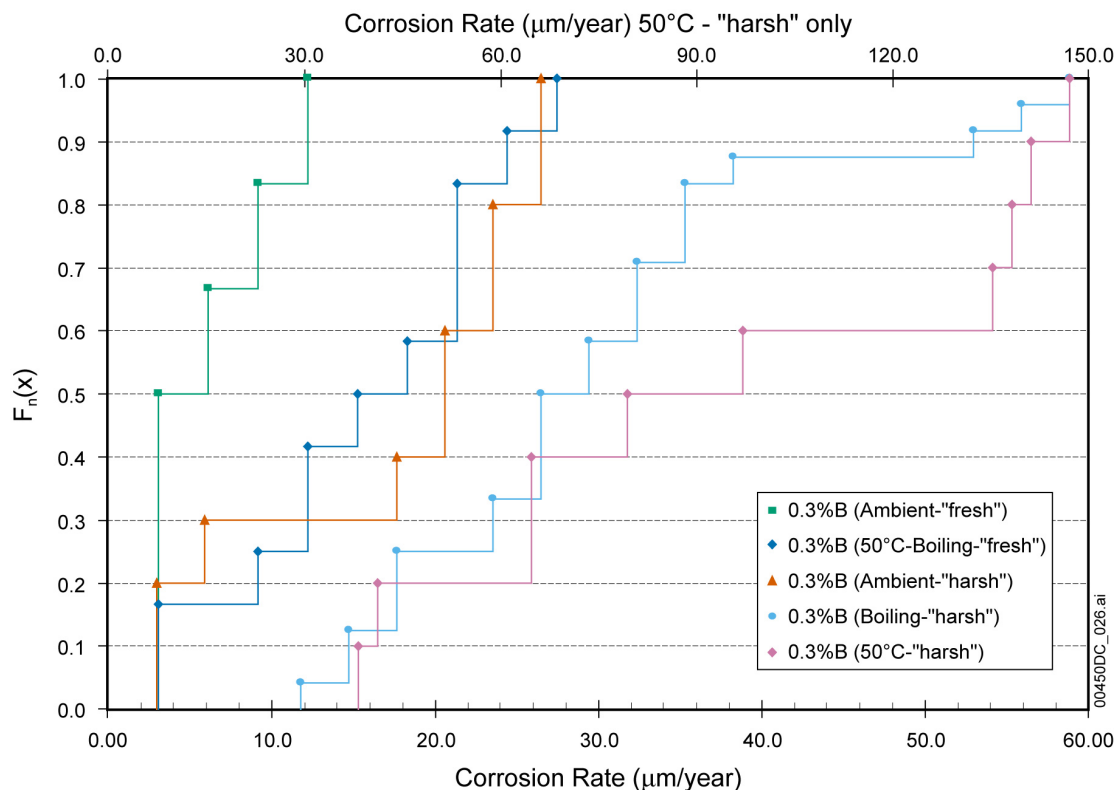
Cole (1976 [DIRS 159369]) presents data on corrosion of borated Stainless Steel Type 304 in environments, which may be encountered in the waste package, and had the following conclusions:

- Stainless steel alloyed with 1.5 percent boron degraded faster than steel containing only 0.3 percent boron showing that increasing boron content increases degradation rate
- Corrosion at 50°C in concentrated solutions was much greater than at ambient temperatures in dilute solutions.

Other conclusions on the effects of zirconium and aluminum on the corrosion rates included:

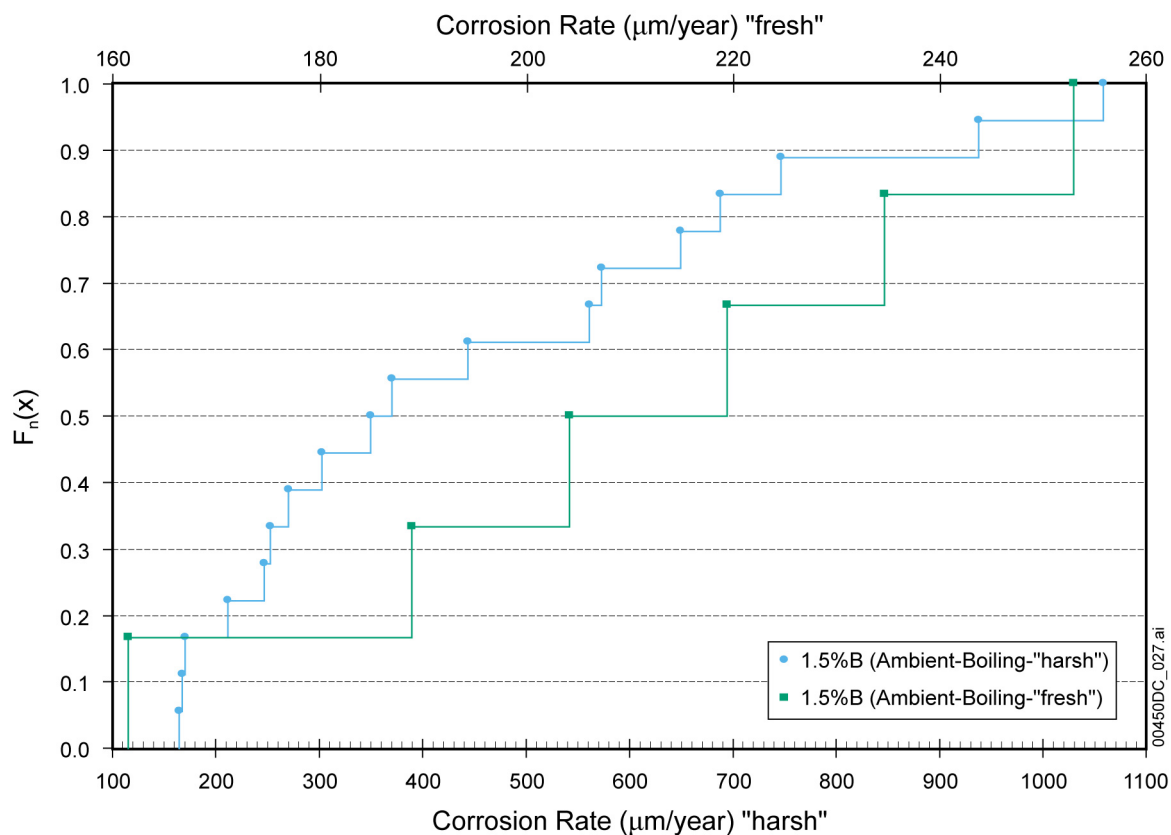
- Corrosion decreased as aluminum complexing of the solution increased, and
- Zirconium serves as a sacrificial metal to reduce the corrosion of borated Stainless Steel Type 304 with 1.5 percent boron.

The statistical information on the corrosion of Stainless Steel Type 304L is located in Table 6-7, Figure 6-10, and Figure 6-11. For this analysis, the values for 1.5 percent boron at 100°C corresponding to 6.04 and 6.44 mils per month (Table 4-11) as well as 6.14 and 5.99 mils per month (Table 4-11) for ambient temperatures were not used (1 mil = 25.4 μm). Because these rates are so much higher than the other rates shown for similar conditions, it is likely that these values represent localized corrosion data and are therefore inappropriate for use in the analysis.



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-10 and Table 4-11. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-10. ECDF for 0.3 Percent Borated Stainless Steel Type 304 in All Water Types Investigated



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-10 and Table 4-11. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-11. ECDF for 1.5 Percent Borated Stainless Steel Type 304 in All Water Types Investigated

Table 6-7. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Borated Stainless Steel Type 304

Environment	Corrosion Rate ($\mu\text{m}/\text{yr}$)				Standard Deviation
	Minimum	Maximum	Median	Mean	
0.3%B (Ambient-"Fresh")	3.05	12.19	4.57	6.10	3.86
0.3%B (50°C-Boiling-"Fresh")	3.05	27.43	16.76	15.75	7.99
1.5%B (Ambient-Boiling-"Fresh")	161.54	252.98	211.84	210.31	32.77
0.3%B (Ambient-"Harsh")	2.94	26.46	20.58	17.05	9.48
0.3%B (50°C-"Harsh")	38.22	147.00	88.20	94.69	42.85
0.3%B (Boiling-"Harsh")	11.76	58.80	27.93	29.77	12.48
1.5%B (Ambient-Boiling-"Harsh")	164.64	1,058.40	360.15	453.74	272.96

NOTE: Calculated in *aqueous-B-Gd-steels.xls* in Appendix II from values in Table 4-10 and Table 4-11. Archived in output DTN: MO0409SPAACRWP.000.

6.2.2.3 Gadolinium-Alloyed Stainless Steel Type 304L

Cole (1976 [DIRS 159369]) presents data on corrosion of a gadolinium-alloyed Stainless Steel Type 304 in environments that may be encountered in the waste package. The statistical information on the corrosion of gadolinium-alloyed Stainless Steel Type 304L is located in Table 6-8.

Table 6-8. Comparison of Minimum, Maximum, Mean, and Median Corrosion Rates of Gadolinium-Alloyed and Non Gadolinium-Alloyed Stainless Steel Type 304L

Environment	Corrosion Rate ($\mu\text{m/yr}$)		
	Minimum	Maximum	Mean
0.3% Gd 304 (Ambient-Boiling-"Fresh") ^a	3.05	15.24	9.14
304L Freshwater (25°C to 100°C) ^b	0.001	1.57	0.214
Increase in Corrosion	3,050 times	9.71 times	33.27 times
0.3% Gd 304 (Ambient-"Harsh") ^a	2.94	2.94	2.94
304L Saltwater (<27°C) ^b	1.588	39.147	11.44
Increase in Corrosion	1.85 times	0.08 times	0.26 times
0.3% Gd 304 (Boiling-"Harsh") ^a	5.88	23.52	11.03
304L Saltwater (90°C) ^b	0.66	15.9	5.816
Increase in Corrosion	8.91 times	1.48 times	1.90 times

NOTES: ^aValues calculated in *aqueous-B-Gd-steels.xls* in Appendix II from values in Table 4-12; archived in output DTN: MO0409SPAACRWP.000.

^bValues from Table 6-4.

6.2.3 Carbon Steel Type A516

As pointed out in the sections above, the extent to which corrosion proceeds is highly dependent on the elemental composition of the material. Carbon steel does not have the protective alloying effects from the addition of chromium, nickel, and molybdenum. Therefore, its rates of corrosion tend to be much higher than those of stainless steel. The corrosion rates of Carbon Steel Type A516 can be found in *aqueous-A516.xls* in Appendix II and Tables 4-13 through 4-20.

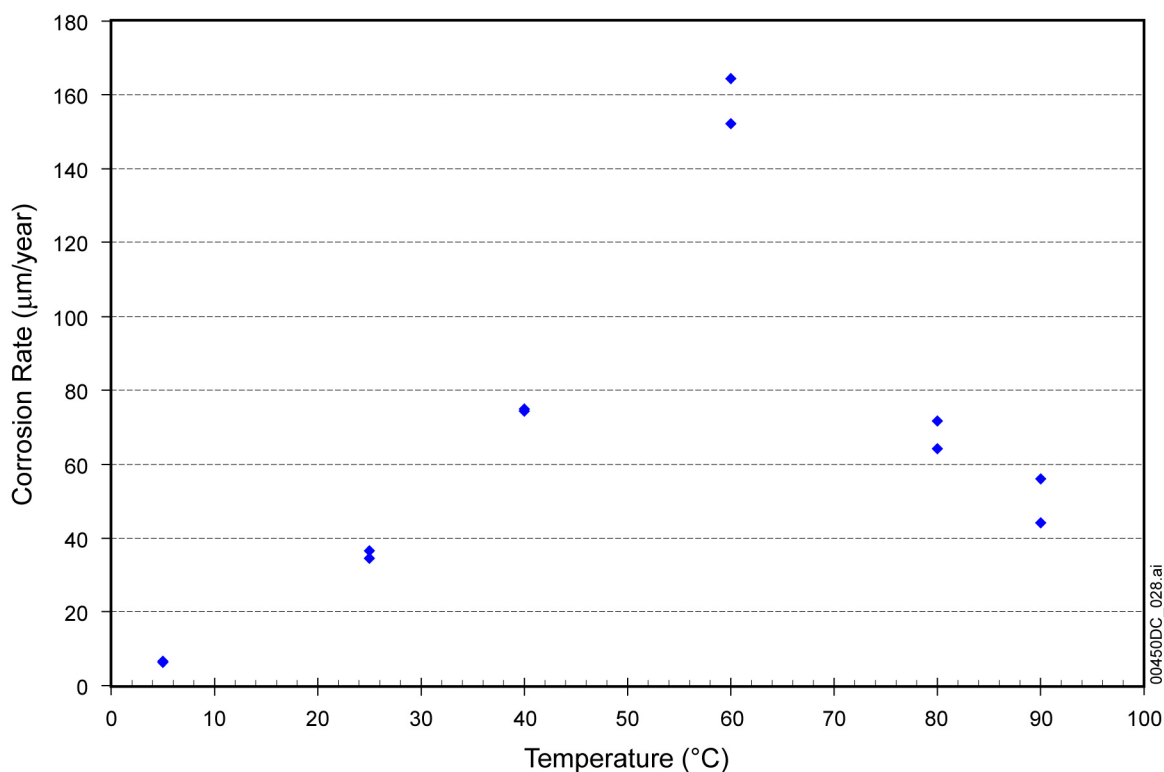
Unlike stainless steel, the corrosion rate of carbon steel is highly dependent on the temperature of the system. From the experimental data of McCright (1998 [DIRS 114637]) presented in Table 4-13 through Table 4-20, it is shown that corrosion at 60°C is more aggressive than corrosion at 90°C. This is corroborated by Brasher and Mercer (1968 [DIRS 100883]), whose data on the corrosion of mild/carbon steel for different temperatures is shown in Figure 6-12. The highest corrosion rate occurs at 60°C. From this temperature (60°C), the corrosion rate decreases when the temperature either increases or decreases (i.e., corrosion rates for both 25°C and 90°C will be lower than the 60°C rates). As can be seen from Figure 6-12, the rates for the mild steel are within the same range as those for the Carbon Steel Type A516 from *Corrosion Data and Modeling, Update for Viability Assessment* (McCright 1998 [DIRS 114637]). Although no specific data have been located for corrosion of Carbon Steel Type A516 at 25°C,

Figure 6-12 shows that the rates for mild steel at 25°C are slightly lower than mild steel at 90°C. Therefore, in the absence of 25°C data for Carbon Steel Type A516, those presented for mild steel at 90°C can be used as a surrogate.

In addition, unlike stainless steel, carbon steel corrosion decreases with increasing salinity of the corroding medium. Tables 4-13 through 4-20 in Section 4.1.3.3 show that the corrosion rates for water concentrated to 1,000× that of J-13 well water (SCW) are significantly lower than those at the 10× concentration (SDW). These values are for laboratory conditions and not a natural setting. In the case of carbon steel, this has a great effect on the corrosion rates. In natural saline water (i.e., ocean or tidal), many other factors can increase corrosion rates, which may not be seen in waste package corrosion. These effects include water flow rates, biofouling, and pollution. With stainless steels, there was little difference between the corrosion rates in natural and laboratory settings. However, for carbon steel, the results of laboratory experiments may more closely represent the actual rates since they do not include the three factors mentioned above.

In the experiments conducted by McCright (1998 [DIRS 114637]), the corrosion rate decreases from the 0.5-year to the 1-year time period. The same behavior is shown in Figure 1 of “Carbon Steel—Corrosion by Seawater” (Matsushima 2000 [DIRS 164942]) in which the rates decrease significantly in the first 10 to 20 years. As with stainless steel, this is caused by the formation of an oxide film at the surface of the metal. However, because of the absence of chromium, nickel, and molybdenum, these films are composed of iron oxides. While intact, these films can effectively slow the corrosion of the metal, but are not as efficient as the thin hydrous chromium, silicon, and molybdenum enriched oxides that protect stainless steels. Therefore, even though a protective film forms, it cannot completely stop corrosion on the surface of the steel (Matsushima 2000 [DIRS 164944]).

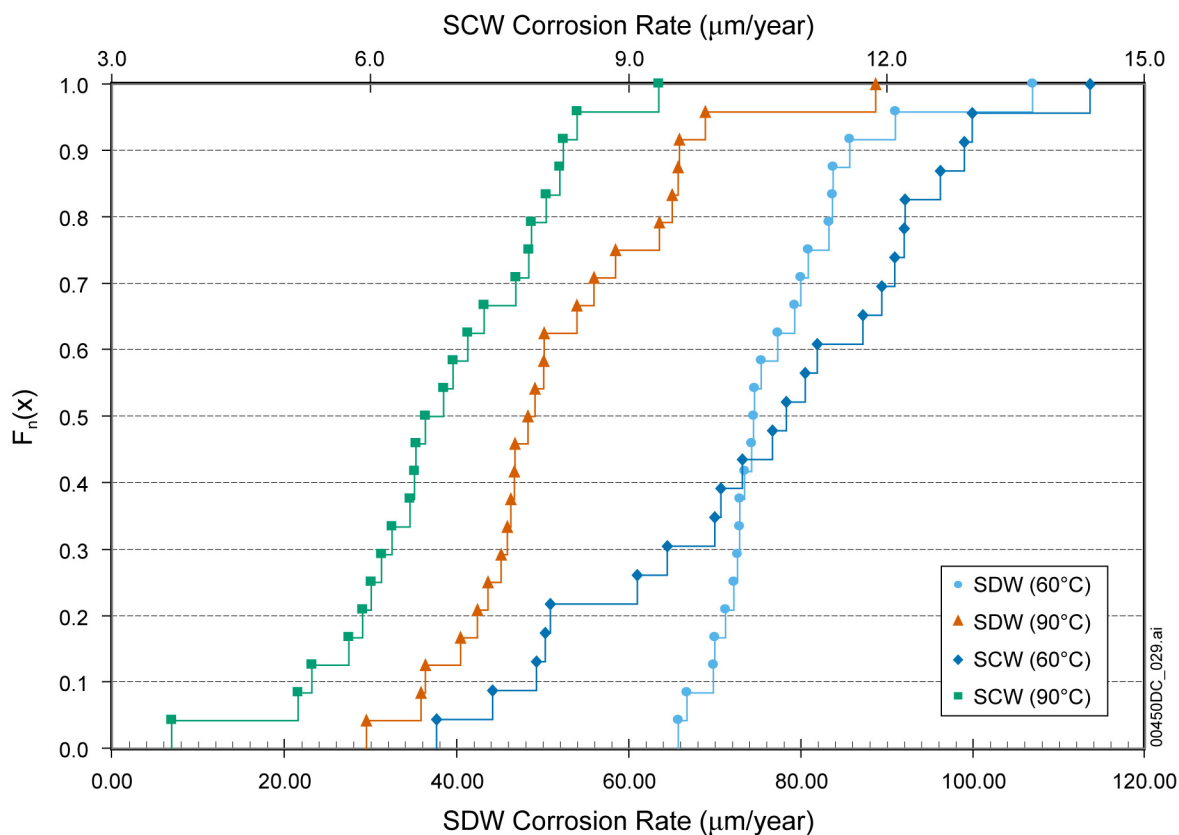
Other factors affecting the corrosion of carbon steel in freshwaters include pH, Cl^- , bicarbonate (HCO_3^-), and SO_4^{2-} (Matsushima 2000 [DIRS 164944]). It is generally considered that over the pH range of approximately 4 to 10, the corrosion rate of carbon steel is independent of the pH (Matsushima 2000 [DIRS 164944]). However, this changes when high concentrations of Cl^- and SO_4^{2-} are present in solution. The data from *Corrosion Data and Modeling, Update for Viability Assessment* (McCright 1998 [DIRS 114637]) shows that even in solutions with high levels of these two anions, the corrosion rates were still lower in concentrated solutions than in dilute solutions. Matsushima (2000 [DIRS 164944]) points out that as long as dissolved oxygen is controlling corrosion, the Cl^- and SO_4^{2-} ions will essentially have no effect on the overall general corrosion rate of steel because they do not effect the solubility of oxygen. However, they may cause a breakdown of the passive oxide film and accelerate localized corrosion. This effect is even more pronounced at lower pH values as shown by Satyanarayana (1981 [DIRS 159371], Figure 8). On the other hand, HCO_3^- may counteract this effect. In the presence of Ca^{2+} , a protective CaCO_3 film forms. In the absence of Ca^{2+} , FeCO_3 can form. Though not as protective as minerals such as $\text{Fe}(\text{OH})_2$, this layer will still have a passivating effect on the surface of the steel.



NOTE: Graphical representation of values from Brasher and Mercer 1968 [DIRS 100883]. Graphed in *aqueous-A516.xls* in Appendix II. Archived in DTN: MO0409SPAACRWP.000.

Figure 6-12. Corrosion Rates versus Temperature for Mild Steel

The rates used to describe the corrosion of Carbon Steel Type A516 are found in Tables 4-13 through 4-20. Since carbon and low alloy steels are used extensively by many industries, a large amount of corrosion data is available in the literature. For this analysis, the data from McCright (1998 [DIRS 114637]) for Carbon Steel Types A516 and A27 was used since this study was conducted using environmental conditions expected to be present in the repository. Since Carbon Steel Type A27 is low-alloy carbon steel similar to Carbon Steel Type A516, and their corrosion rates are, therefore, similar, Carbon Steel Type A27 was also used to describe the corrosion of Carbon Steel Type A516. The statistical information on the corrosion of Carbon Steel Type A516 is located in Table 6-9 and Figure 6-13.



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-13 through Table 4-16. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-13. ECDF for Carbon Steel Type A516 in All Water Types Investigated (Time ≥ 1 Year)

Table 6-9. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Carbon Steel Type A516

Environment	Corrosion Rate (μm/yr)				Standard Deviation
	Minimum	Maximum	Median	Mean	
Short term (≤ 0.53 years)					
SDW (60°C)	78.71	130.70	101.95	102.71	12.37
SDW (90°C)	58.08	130.02	77.05	81.14	15.13
SCW (60°C)	50.25	104.20	62.77	68.08	14.17
SCW (90°C)	7.39	22.06	12.42	12.78	3.77
Long term (≥ 1 year)					
SDW (60°C)	65.77	106.93	74.56	77.43	8.83
SDW (90°C)	29.53	88.68	48.70	51.80	12.99
SCW (60°C)	6.77	14.36	10.83	10.61	2.02
SCW (90°C)	3.69	9.35	6.75	6.84	1.25

NOTE: Calculated in *aqueous-A516.xls* in Appendix II from values in Tables 4-13 through 4-20. Archived in output DTN: MO0409SPAACRWP.000.

6.2.4 Aluminum Alloys

A brief synopsis of aluminum corrosion (Hollingsworth and Hunsicker 1987 [DIRS 150403]; Ghali 2000 [DIRS 164946]) is presented below.

Aluminum Alloy Type 1100 (“commercially pure aluminum”) contains 99.0 to 99.3 percent aluminum and has a higher resistance to corrosion in most acid and neutral solutions than lower purity aluminum or aluminum alloys. The nonheat-treatable alloys (1xxx, 3xxx, 4xxx, and 5xxx series), as well as the heat-treatable alloys of the group 6xxx and noncopper containing 7xxx alloys are highly resistant to general corrosion, with the 6xxx and 7xxx being the least resistant. Alloys of the 2xxx and copper containing 7xxx series generally have lower resistance to general corrosion. Aluminum is a surface active metal and its resistance to corrosion thus depends highly on the formation of a protective oxide film. Aluminum passivity develops in the pH range of about 5 to 8.5. This passivity depends greatly on the temperature, the form of the oxide, O₂ content, pH, and the aqueous medium.

At low temperatures, aqueous solutions are usually less corrosive than at high temperatures. However, for some solutions, increasing temperatures (usually above 80°C) results in a decrease in aluminum corrosion. The protective oxide film at ambient temperatures is only a few nanometers thick and usually amorphous or predominantly bayerite (Al(OH)₃). At high temperatures, thicker films may form. Highly protective crystalline films of boehmite (AlOOH) may form in water near the boiling point. The formation of crystalline films is more likely in alkaline solutions. During aging of aluminum hydroxides, gibbsite (Al(OH)₃) may also form. A protective film does not form above 230°C.

Oxygen also affects the rate of corrosion for aluminum. In deaerated solutions, the corrosion of aluminum tends to be very slow, whereas in the presence of oxygen, corrosion is accelerated. This is even more pronounced in acidic solutions. Other dissolved gases such as carbon dioxide and hydrogen sulfide appear to have slight inhibiting action on the corrosion of aluminum by aqueous mediums whereas hydrogen chloride is very corrosive to aluminum.

As mentioned above, aluminum and its alloys tend to be passivated between pH 5 and 8.5. It corrodes under both acidic and alkaline conditions to produce Al³⁺ and AlO₂⁻ (aluminate) ions respectively. There is no general relationship between pH and corrosion rate because other ions present in solution largely influence corrosion rates. For example, concentrated solutions of nitric or acetic acid may not effect the corrosion rate while dilute solutions of nitric, sulfuric, and hydrochloric acid solutions are very corrosive. Likewise, alkaline solutions may not attack aluminum in the presence of silicates, but in the absence of silicates, corrosion rates may be very high.

In distilled water, even at high temperatures, aluminum corrosion is quite low. This is also true of clean natural waters. However, some waters can cause severe localized corrosion such as pitting. In natural freshwaters, the important factors for corrosion have been presented above. For seawater, corrosion is primarily through pitting. Rates of pitting usually range from 3 to 6 µm/yr during the first year. An average over a 10-year period shows the rate of pitting to be 0.8 to 1.5 µm/yr. The decreasing rates over time indicate the tendency of older pits to become inactive. This is corroborated by Table 6-10, which shows the occurrence of pits on aluminum

when exposed to tap water from Kingston, Ontario. Pitting tends to be the main corrosion behavior of aluminum. Pitting weight-loss data for aluminum are converted to general rates for use in EQ6 for this analysis.

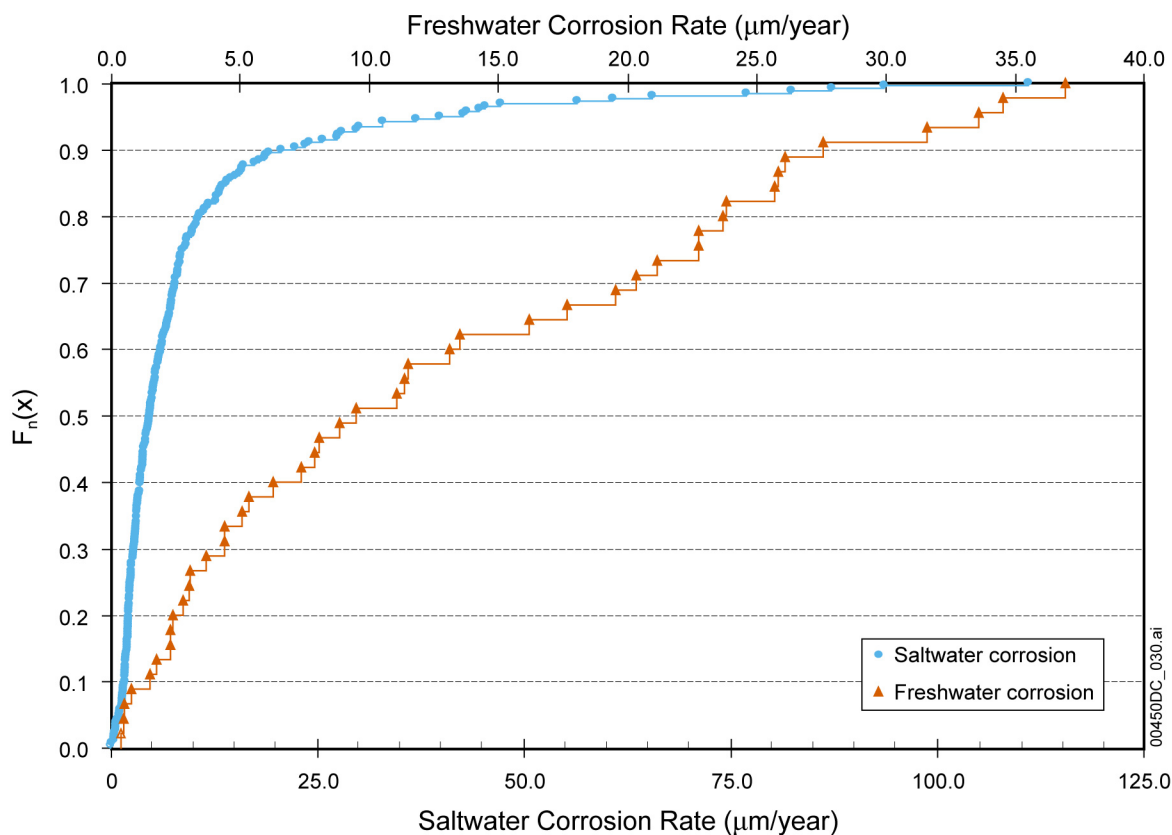
Table 6-10. Pitting in Aluminum Alloys

Pit Depth Range (microns)	Number of Pits within the Pit Depth Ranges in Time Period					
	2 weeks	1 Month	2 Months	4 Months	6 Months	1 year
0 to 99	176	216	155	171	111	140
100 to 199	54	49	22	24	27	11
200 to 299	49	73	19	24	26	17
300 to 399	21	98	48	37	41	18
400 to 499	14	71	56	65	52	47
500 to 599	1	68	51	60	50	48
600 to 699	0	30	38	33	37	36
700 to 799	1	16	32	43	43	22
800 to 899	—	4	4	15	9	7
900 to 999	—	1	—	3	3	1
1,000 to 1,099	—	—	—	—	1	0

Source: Aziz 1956 [DIRS 159379].

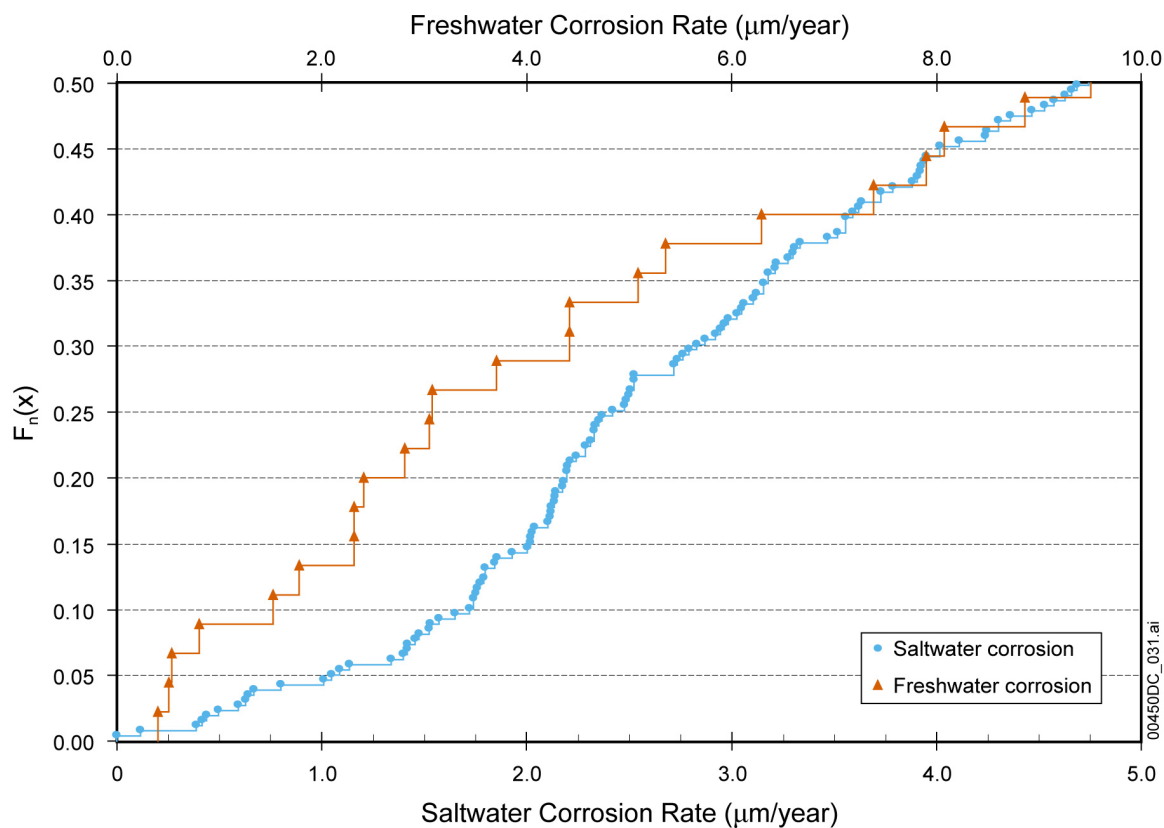
NOTE: Kingston, Ontario tap water (no other data on this water was available).

Since aluminum alloys are used in many industries, saltwater corrosion data for many different types can be found in the literature. For this analysis, it was decided to use the data from one large study since using a full bibliography of values is unreasonable. The chosen values come from Hollingsworth and Hunsicker (1987 [DIRS 150403]). The corrosion rates for aluminum alloys used in this analysis for fresh and seawater are located in Section 4.1.3.4 and in *aluminum.xls* on Appendix II. The statistical information on the corrosion of aluminum alloys is located in Table 6-11 and Figure 6-14. More detail of the ECDF is presented in Figure 6-15 through Figure 6-17.



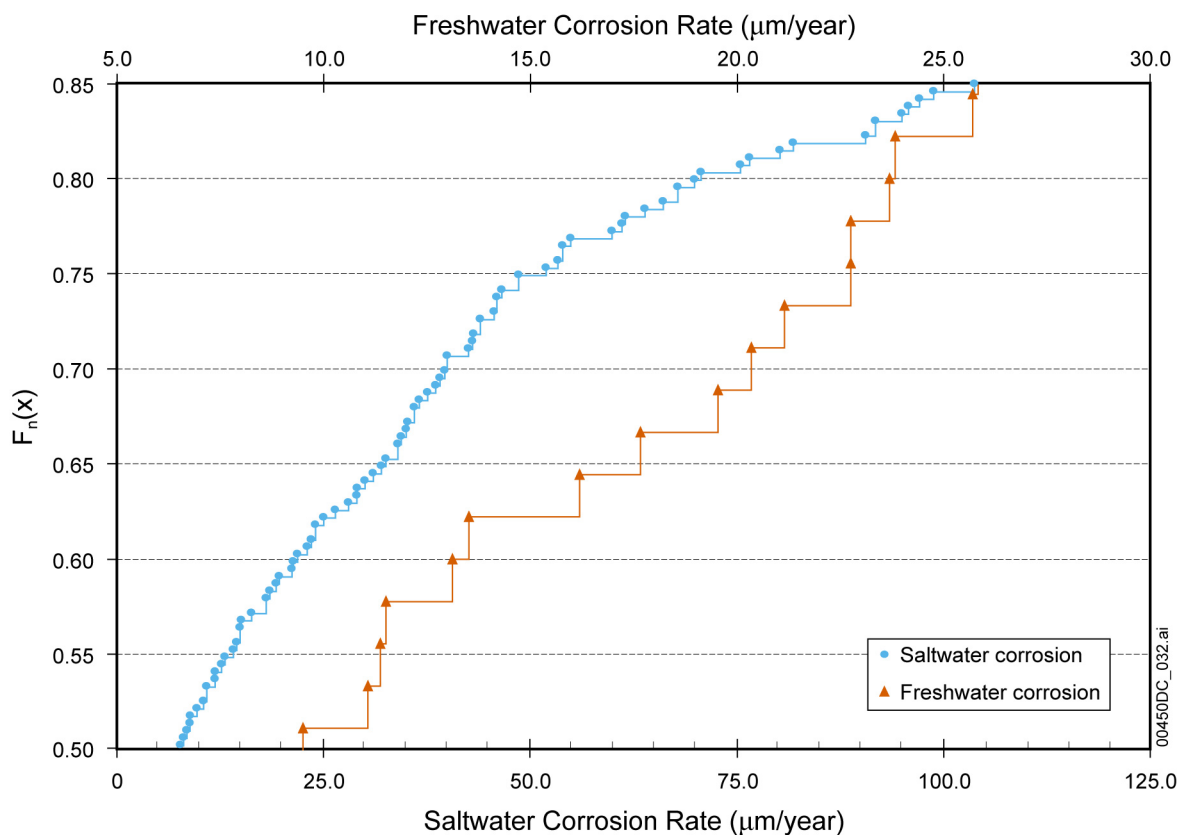
NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-21 and Table 4-22. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-14. ECDF for Aluminum Alloy



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-21 and Table 4-22. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-15. ECDF for Aluminum Alloy For $F_n(x)$ Less than 0.50



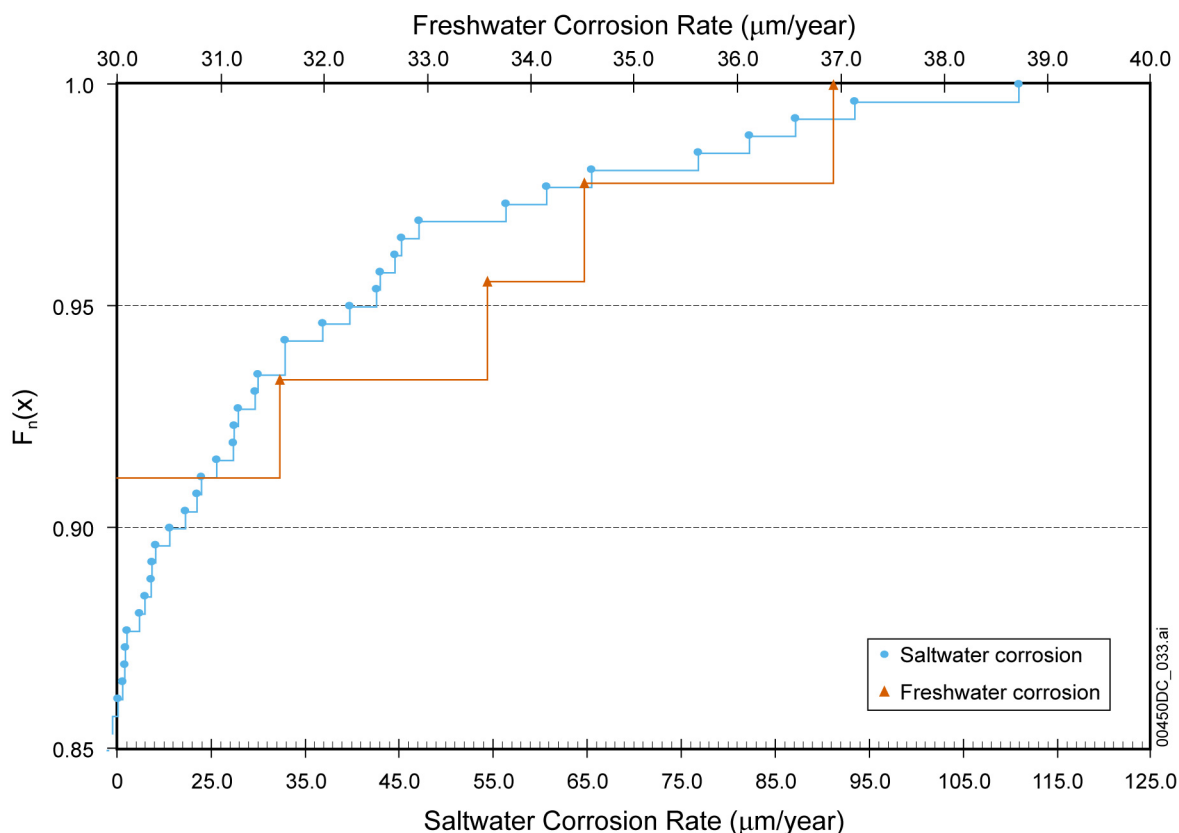
NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-21 and Table 4-22. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-16. ECDF for Aluminum Alloy For $F_n(x)$ Between 0.50 and 0.85

Table 6-11. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Aluminum Alloy

Environment	Corrosion Rate ($\mu\text{m}/\text{yr}$)				Standard Deviation
	Minimum	Maximum	Median	Mean	
Freshwater	0.40	36.93	9.50	12.95	10.84
Saltwater	0.12	110.91	4.76	9.69	15.34

NOTE: Calculated in *aluminum.xls* in Appendix II from values in Table 4-21 and Table 4-22. Archived in output DTN: MO0409SPAACRWP.000.



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-21 and Table 4-22. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-17. ECDF for Aluminum Alloy For $F_n(x)$ Between 1.0 and 0.85

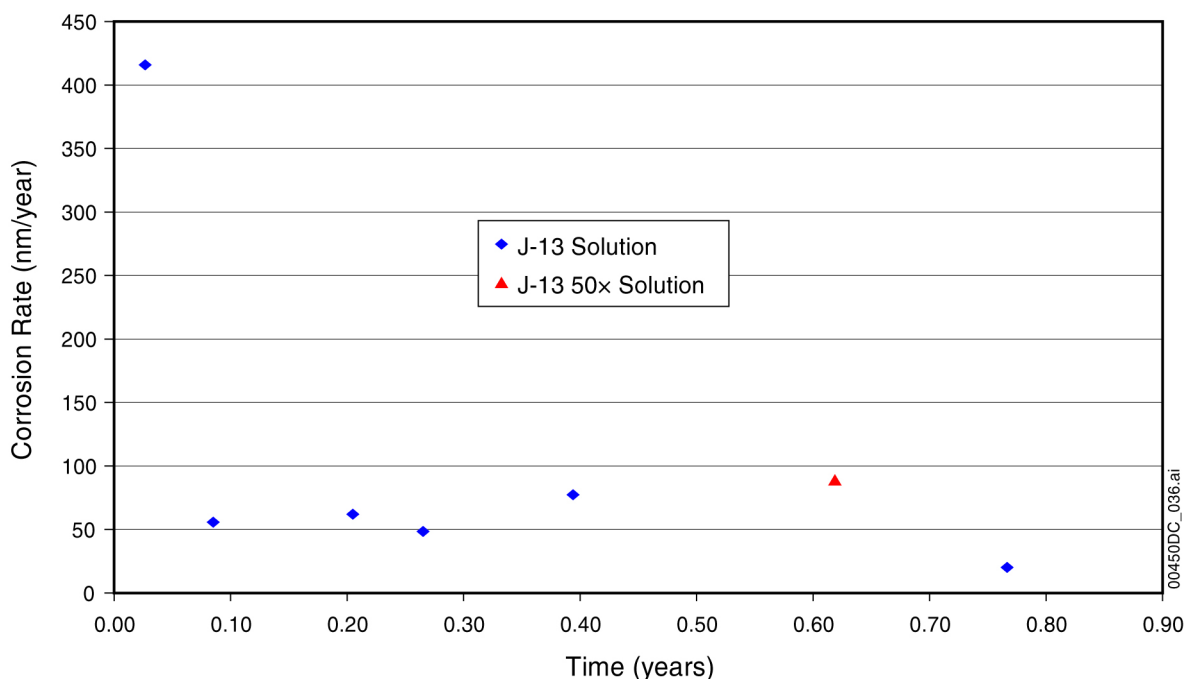
6.2.5 Zircaloy (2 and 4)

As mentioned in Section 4.1.3.5, most information on the corrosion of zircaloy is from high temperature experiments in which the weight gain over time is measured (i.e., Hillner et al. 1998 [DIRS 100455]; Rothman 1984 [DIRS 100417]). Hillner et al. (1998 [DIRS 100455]) conclude that oxide growth in the Yucca Mountain repository over a period of one million years would be extremely small (0.3 mils, 1 mil = 25.4 μm). The data for the corrosion of zircaloy at low temperatures (21.5°C to 43°C) recorded by Uziemblo and Smith (1989 [DIRS 101231]) corroborates this by indicating a degradation rate of zero for all experiments in dilute solution. Rothman (1984 [DIRS 100417]) summarizes data by other authors for a case with a constant temperature of 180°C for 10,000 years, which yields a depth of oxidized zircaloy ranging from 4 to 53 μm with an average of 17 μm . However, the repository is not expected to remain at temperatures near 180°C for 10,000 years (BSC 2004 [DIRS 168848], Section 6.5.5.1). Therefore, for the purposes of this analysis, this metal is considered insoluble and, consequently, has no associated statistical analysis.

6.2.6 Alloy N06464

Corrosion data for a Ni-Cr-Mo-Gd alloy—Alloy N06464 (presented in Table 4-23) shows the metal to hold up well to corrosion. These data are presented in Figure 6-18. Statistical

information on the corrosion of Alloy N06464 is located in Figure 6-19 and Table 6-12. The first point at 0.03 years (415.8 nm/yr) is not used as it is not consistent with the rest of the data.



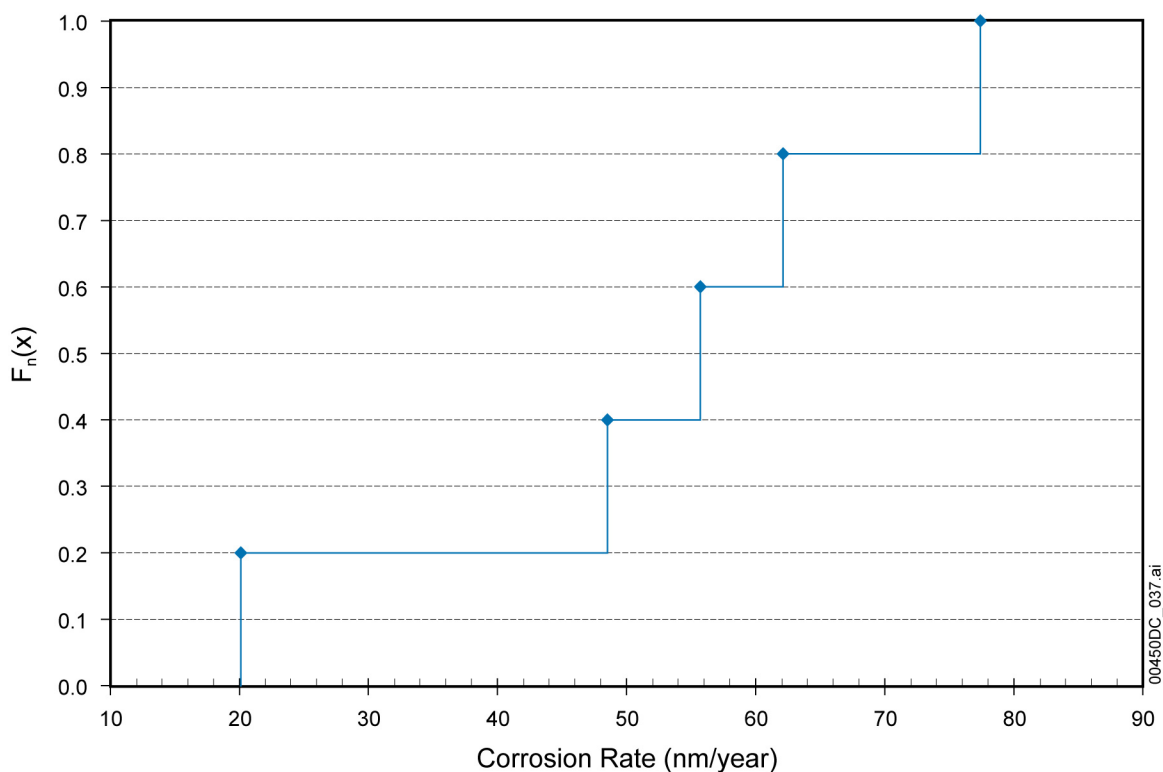
NOTE: Graphical representation of values in Table 4-23. Graphed in *NiCrMoGdalloy.xls* in Appendix II. Archived in output DTN: MO0409SPAACRWP.000.

Figure 6-18. Corrosion of Alloy N06464

Table 6-12. Minimum, Maximum, Mean, and Median Corrosion Rates of Alloy N06464 in Solution

Environment	Corrosion Rate (nm/yr)				Standard Deviation
	Minimum	Maximum	Median	Mean	
Freshwater	20.1	77.4	55.7	52.8	21.1

NOTE: Calculated in *NiCrMoGdalloy.xls* in Appendix II from values in Table 4-23; archived in output DTN: MO0409SPAACRWP.000.

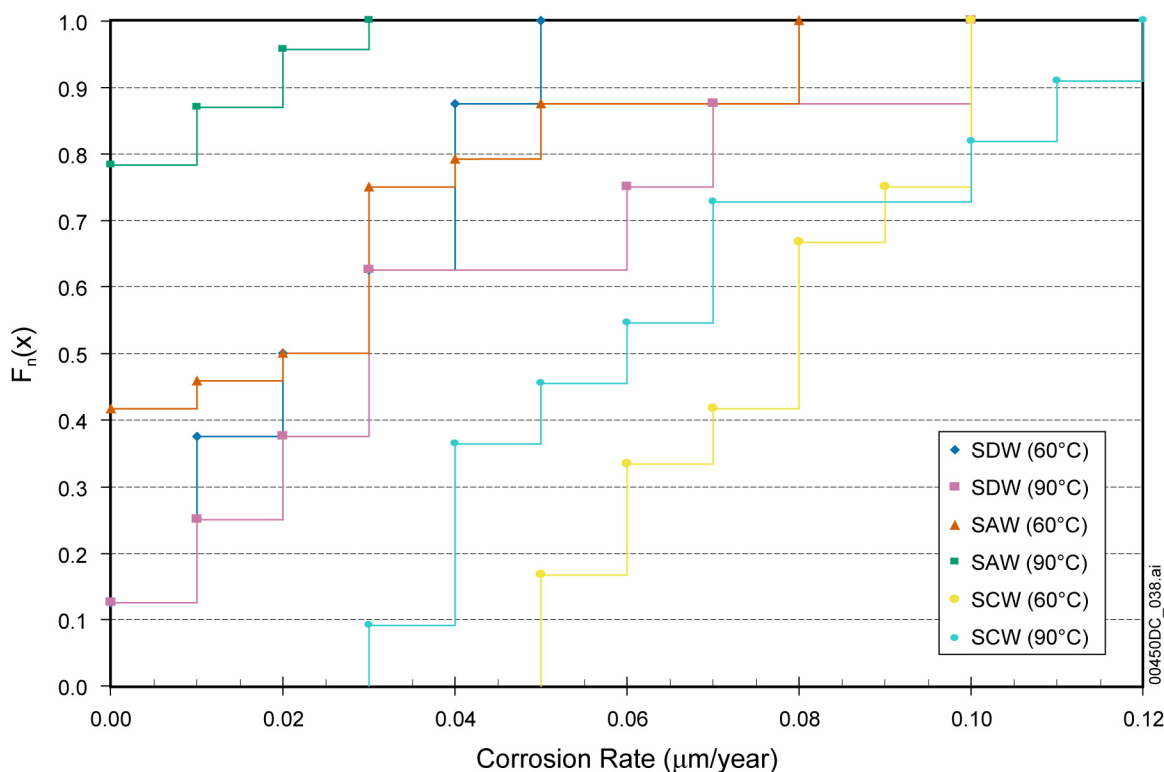


NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-23; archived in output DTN: MO0409SPAACRWP.000.

Figure 6-19. ECDF for Alloy N06464 in Freshwater at Time ≤ 0.8 Years

6.2.7 Inconel Alloys

Due to the lack of corrosion data on Inconel Alloy 600 and X-750, Inconel Alloy 625 was used as a surrogate for Inconel Alloys X-750 and 600. This approach is reasonable since the composition of Inconel Alloys X-750 and 600 is similar to that of Inconel Alloy 625 (Section 5.2.1). The most in-depth study found for the corrosion of Inconel Alloy 625 is *Corrosion Data and Modeling, Update for Viability Assessment* (McCright 1998 [DIRS 114637]). Given the short duration of the tests (one year), the values for the corrosion rates in Table 4-24 through Table 4-26 might be slightly high for long-term predictions. The statistical information on the corrosion of Inconel alloys is located in Table 6-13 and Figure 6-20.



NOTE: ECDF calculated in *ECDF_metals.xls* in Appendix II from values in Table 4-24 through Table 4-26. Archived in DTN: MO0409SPAACRWP.000.

Figure 6-20. ECDF for Inconel Alloys in All Water Types Investigated

Table 6-13. Minimum, Maximum, Mean, and Median Aqueous Corrosion Rates of Inconel Alloys

Environment	Corrosion Rate (μm/yr)				Standard Deviation
	Minimum	Maximum	Median	Mean	
SDW (60°C)	0.00	0.05	0.025	0.025	0.018
SDW (90°C)	0.00	0.10	0.030	0.040	0.034
SAW (60°C)	0.00	0.08	0.025	0.027	0.027
SAW (90°C)	0.00	0.03	0.00	0.004	0.008
SCW (60°C)	0.05	0.10	0.08	0.077	0.019
SCW (90°C)	0.03	0.12	0.06	0.066	0.031

NOTE: Calculated in *aqueous Inconel-Alloy.xls* in Appendix II from values in Table 4-24 through Table 4-26; archived in output DTN: MO0409SPAACRWP.000.

6.2.8 Alloy 22

Corrosion rate information for Alloy 22 can be found in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2003 [DIRS 166834]).

6.3 MISCELLANEOUS MATERIALS

Section 6.3 contains the rate analyses of the sintered compounds and GdPO_4 . Values for 25°C were extrapolated from high temperature rate information. The extrapolated values are provided for comparison to previously utilized rates rather than attempting a statistical analysis.

6.3.1 Silicon Carbide (SiC) Oxidation

For SiC corrosion, the following equation was suggested by Rechar (1995 [DIRS 101084], Section 11.1.3, Equation 11.1.3-3) to use when the surface area of the material is difficult to estimate. The equation applies to both humid and wet oxid conditions (Section 11.3, for “TRISO Coating for Metal Carbide Fuel”).

$$M = Ae^{-B/T} (t_2^C - t_1^C) DEM_{\text{layer}} \quad (\text{Eq. 2})$$

where:

- M = Mass of layer corroded in time step (kg)
- A = Arrhenius-type pre-exponential term (1/s)
- B = Arrhenius-type activation energy term (K)
- T = Temperature of the material (K)
- t_2, t_1 = Time at beginning and end of time step (s)
- C = Time-dependent term (-)
- D = Saturation-dependence term (-)
- E = Oxygen Concentration-dependence term (-)
- M_{layer} = Mass of layer at time zero (kg).

Sections 11.3 and 11.4 of Rechar (1995 [DIRS 101084]) indicate that $A=3 \times 10^{-12}$, $B=0$, $C=1$, $D=1$, and $E=0.2$. The Arrhenius-type term is set at 3.0×10^{-12} based on the assumption by Rechar (1995 [DIRS 101084]) that TRISO will not fail in the first 10,000 years after repository closure. Lotts et al. (1992 [DIRS 164916]) indicate that TRISO particles will only breach (SiC layer breached) under “unknown mechanisms.” *DOE Spent Nuclear Fuel Information in Support of TSPA-SR* (DOE 2002 [DIRS 158405]), using the equation above, reports a corrosion rate of $6.0 \times 10^{-13} \text{ kg/m}^2\cdot\text{sec}$. However, the results of the equation above are a mass loss ratio, 6.0×10^{-13} mass corroded/total mass layer (M/M_{layer}), and not an actual corrosion rate.

Most of the studies on the oxidation of SiC are done in excess of $1,000^\circ\text{C}$ in humid air environments. These studies (Jorgensen et al. 1959 [DIRS 164912]; Opila 1999 [DIRS 155502]) show that even at these temperatures, SiC holds up well to oxidation and is still a good barrier. For comparison, the high temperature data of Opila (1999 [DIRS 155502]) are extrapolated in *Misc_Materials.xls* (Appendix II). These values are archived in output DTN: MO0409SPAACRWP.000 and give an approximate calculated rate of oxidation at 25°C of $1.61 \times 10^{-9} \text{ } \mu\text{m/yr}$ (equal to an EQ6 rate of $1.61 \times 10^{-22} \text{ mol/cm}^2\cdot\text{s}$). In agreement with this calculated value, Lide (2002 [DIRS 160832], p. 4-82) indicates that SiC is essentially insoluble in water at 25°C . Therefore, SiC is considered insoluble for the purposes of this analysis and, consequently, has no statistical analysis associated with it.

6.3.2 Pyrolytic Carbon and Graphite Oxidation

Graphite and pyrolytic carbon are also resistant to oxidation (Section 4.1.4, Table 4-28). The 25°C extrapolated values of graphite oxidation are located in Table 6-14 (Appendix II, *Misc_Materials.xls*). The values are archived in output DTN: MO0409SPAACRWP.000. Propp (1998 [DIRS 149395]) indicates that oxidation of graphite in water should be slower than air oxidation. However, Gurwell (1981 [DIRS 164911]) indicates a rate for water oxidation faster than that indicated for air oxidation by Lotts et al. (1992 [DIRS 164916]) and Propp (1998 [DIRS 149395]). These rates are for experiments carried out in deionized water and may be faster than oxidation in natural waters. However, values for both air and water oxidation indicate an extremely low oxidation rate for this material. Therefore, for the purposes of this analysis, these substances are also considered insoluble. Consequently, graphite and pyrolytic carbon have no statistical analysis associated with them.

Table 6-14. Approximate Values of Oxidation for Graphite and Pyrolytic Carbon

	From Extrapolation of Lotts et al. 1992 [DIRS 164916] data	From Extrapolation of Gurwell 1981 [DIRS 164911] data	From Extrapolation of Propp 1998 [DIRS 149395] Data
μm/yr	1.81×10^{-12}	5.62×10^{-6}	9.59×10^{-10}
Equivalent EQ6 Rate (100g-mol/cm ² ·s)	1.26×10^{-25}	3.92×10^{-19}	6.69×10^{-23}

NOTE: Values calculated in *Misc_Materials.xls* in Appendix II. Archived in output DTN: MO0409SPAACRWP.000.

6.3.3 Gadolinium Phosphate (GdPO₄) Dissolution

Natural analogue data (Boatner and Sales 1988 [DIRS 164908]) and data from manufacturers (Lansdowne n.d. [DIRS 164914]) indicate that gadolinium phosphate is essentially insoluble at low temperatures and pressures. However, several studies indicate that the material corrodes in harsh environments or when containing impurities. Tests on synthetic monazite mixed with 20 wt% Savannah River defense waste indicate that <0.001 g/m²·day of the lanthanide was released from the material and that the monazite matrix had a corrosion rate of less than 0.002 g/m²·day in water at 90°C (Boatner and Sales 1988 [DIRS 164908], Figure 23 and Section 8.2). This translates into a corrosion rate of approximately 0.12 μm/yr (Appendix II, *Misc_Materials.xls*). Values are archived in output DTN: MO0409SPAACRWP.000. Van Konynenburg et al. (1998 [DIRS 100948]) report the dissolution of GdPO₄ at 0.19 mm/yr after 96-hour exposure to highly corrosive media containing 0.01 molar concentrations of radiolysis products (nitric acid and hydrogen peroxide) and chloride buffered at pH 4. *In-Package Chemistry Abstraction* (BSC 2004 [DIRS 167621], Appendix III) has shown that lower concentrations of nitric acid and hydrogen peroxide will be produced by radiolysis, having little effect on the pH and chemistry inside the waste package. Therefore, the test conditions used by Van Konynenburg et al. (1998 [DIRS 100948]) are not representative of expected repository conditions and their rate value was not used for this analysis. For the purpose of this analysis, GdPO₄ is considered insoluble since there is strong natural analogue evidence for extreme stability at earth surface temperature and pressure. Therefore, GdPO₄ has no statistical analysis associated with it.

6.4 SPENT FUELS AND WASTE FORMS

6.4.1 DOE Spent Nuclear Fuel

Dissolution rate models for these fuel types are presented in *DSNF and Other Waste Form Degradation Abstraction* (BSC 2004 [DIRS 167618], Section 6.3).

6.4.2 Commercial Spent Nuclear Fuel

A CSNF degradation rate model is developed and presented in *CSNF Waste Form Degradation: Summary Abstraction* (BSC 2004 [DIRS 169987]).

6.4.3 Defense High-Level Waste Glass

6.4.3.1 Fracture Factor

In EQ6 calculations (i.e., BSC 2003 [DIRS 169107] and BSC 2001 [DIRS 157640]) the geometric surface area of the glass was increased by a factor of 21 to account for fractures due to cooling and dropping of the glass pour canister during loading. This value was used for consistency with *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998 [DIRS 100362], p. 6-79). However, in that document, the fracture factor of 21 is an average taken over 100 glass pour canisters and does not take into account loading of damaged canisters into a waste package containing only 5 glass pour canisters. *glass-fracturefac.xls* (Appendix II) uses the same technique as presented in that document to calculate averaged increase of surface area. This technique is based on determining the increase in surface area by thermal cracking of canistered glass that is cooled by free air convection and for impact cracking using the following equation.

$$(\{\text{impact cracking} \times \text{thermal cracking} \times \text{percentage of canisters damaged in a drop}\} + \{\text{thermal cracking} \times \text{percentage of canisters that have not been damaged in a drop}\}) \quad (\text{Eq. 3})$$

However, the fracture factor determinations in this analysis (see *glass-fracturefac.xls* in Appendix II) account for there only being 5 canisters per waste package. The calculations in this analysis also account for only a fraction of the surfaces being available for reaction. For more information on the glass fracture factor see Sections 5.4.1 through 5.4.4.

The probability of loading damaged glass pour canisters is calculated with a binomial distribution (Table 6-15) using the assumed loading of damaged glass pour canisters, number of glass pour canisters damaged in a drop, and 5 glass pour canisters per waste package. *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998 [DIRS 100362], p. 6-79) assumes that 1 in every 100 glass pour canisters will be dropped and damaged during loading. However, the probabilities of 1 in 250, 1 in 500, and 1 in 1,000 glass pour canisters being dropped are also displayed here since safeguards could presumably be implemented to reduce the occurrence of dropped glass pour canisters. These distributions are then used to determine the probabilities of the fracture factor as indicated below.

Table 6-15. Probability of Loading Damaged Glass Pour Canisters into Waste Packages.

	Number of GPCs Dropped While Loading			
	1 in 100	1 in 250	1 in 500	1 in 1,000
	Probability of Waste Package Loading			
Waste Packages Containing 0 Dropped GPCs	9.51E-01	9.80E-01	9.90E-01	9.95E-01
Waste Packages Containing 1 Dropped GPC	4.80E-02	1.97E-02	9.92E-03	4.98E-03
Waste Packages Containing 2 Dropped GPCs	9.70E-04	1.58E-04	3.98E-05	9.97E-06
Waste Packages Containing 3 Dropped GPCs	9.80E-06	6.35E-07	7.97E-08	9.98E-09
Waste Packages Containing 4 Dropped GPCs	4.95E-08	1.27E-09	7.98E-11	5.00E-12
Waste Packages Containing 5 Dropped GPCs	1.00E-10	1.02E-12	3.20E-14	1.00E-15

NOTE: Values calculated in *glass-fracturefac.xls* in Appendix II. Archived in output DTN: MO0404SPAHLWGF.001.
GPC = glass pour canister.

Table 6-16 is a summary of the data in *glass-fracturefac.xls* in Appendix II. Since the degree of availability of reaction surfaces in fractures to aqueous media for glass degradation is unclear, several options are explored here. These provide the range of possible surface area exposure that may occur inside the glass pour canisters due to fracturing of the high level waste glass.

Since references providing the number of fractures in fractured glass are unavailable, a probability distribution for number of fractures or a direct fracture factor is not possible. However, the probability of a particular fracture factor can be derived indirectly from knowing the number of glass pour canisters damaged in a drop, how many damaged glass pour canisters are loaded into a waste package, and the fraction of fractures available for reaction. Table 6-16 provides a range of possible scenarios since it is unknown exactly how many glass pour canisters will be damaged in drops, how many damaged glass pour canisters will be loaded into any one waste package, and the degree of availability of reaction surfaces in fractures. To use Table 6-16, the user will have to make several assumptions about the parameters. An example of this is if we assume that 1 in every 100 glass pour canisters are damaged in a drop. The likelihood of having two of these damaged glass pour canisters in any one waste package is 9.70×10^{-4} . Then reading across the table, the only way to get a fracture factor of approximately, as an example, 12.50 is to have all fractures available to aqueous media. Therefore, with the combined variables of 1 in 100 dropped, two damaged glass pour canisters loaded in a single waste package, and all fractures available for reaction, the probability of having this fracture factor is 9.70×10^{-4} . However, if only half of the fractures are assumed to be available for reaction, the same probability will yield a fracture factor of 6.25 instead of 12.50. The fracture factor of 21 used in previous EQ6 calculations (i.e., BSC 2003 DIRS 169107); BSC

2001 [DIRS 157640]) is, therefore, not possible even if all fractures are available and 3 damaged glass pour canisters are loaded into a waste package. This high fracture factor is only possible if 4 or 5 damaged glass pour canisters are loaded into a waste package, which (Table 6-15) has a very small probability.

Table 6-16. Fracture Factor Probabilities (Fracture Factor Averaged Over 5 Glass Pour Canisters) for High Level Waste Glass Based on Loading Damaged Glass Pour Canisters into Waste Packages.

	Number of GPCs Dropped While Loading				Fraction of total fractures available for reaction		
	1 in 100	1 in 250	1 in 500	1 in 1,000	1/4 available	1/3 available	1/2 available
	Probability of Waste Package Loading				Fracture Factor Associated with Available Fractures		
WPs containing 0 dropped GPCs	9.51E-01	9.80E-01	9.90E-01	9.95E-01	1	1	1
WPs containing 1 dropped GPC	4.80E-02	1.97E-02	9.92E-03	4.98E-03	1.56	2.08	3.13
WPs containing 2 dropped GPCs	9.70E-04	1.58E-04	3.98E-05	9.97E-06	3.13	4.17	6.25
WPs containing 3 dropped GPCs	9.80E-06	6.35E-07	7.97E-08	9.98E-09	4.69	6.25	9.38
	Number of GPCs Dropped While Loading				Fraction of Total Fractures Available for Reaction		
	1 in 100	1 in 250	1 in 500	1 in 1,000	2/3 available	3/4 available	all available
	Probability of waste package loading				Fracture factor associated with available fractures		
WPs containing 0 dropped GPCs	9.51E-01	9.80E-01	9.90E-01	9.95E-01	1	1	1
WPs containing 1 dropped GPC	4.80E-02	1.97E-02	9.92E-03	4.98E-03	4.17	4.69	6.25
WPs containing 2 dropped GPCs	9.70E-04	1.58E-04	3.98E-05	9.97E-06	8.33	9.38	12.50
WPs containing 3 dropped GPCs	9.80E-06	6.35E-07	7.97E-08	9.98E-09	12.50	14.06	18.75

NOTE: GPC = Glass Pour Canister, WP = Waste Package.

Values calculated in *glass-fracturefac.xls* in Appendix II using assumptions presented in Section 5.4.

Archived in output DTN: MO0404SPAHLWGF.001.

The fracture factors presented in Table 6-16 were calculated using the assumptions in Section 5.4. All fractures due to only cooling are considered to have no effect on the reactive surface area (Section 5.4.3) so that the fracture factor for any glass within glass pour canisters that have not been dropped is 1 (or geometric surface area). For canisters that have been dropped, the factor of cooling (12.5) and increase in fracture factor due to a drop (5), from Sections 5.4.1 and 5.4.2, are multiplied by the reactivity of fracture surfaces as compared to unrestricted surfaces ($\frac{1}{2}$, Section 5.4.4).

Another approach would be to use fracture factors only for those canisters that are considered to be damaged and use the geometric surface area for those that have not been dropped or otherwise damaged. Fracture factors calculated using this approach are presented in Table 6-17.

Table 6-17. True Fracture Factors for High-Level Waste Glass in One Glass Pour Canister

Total Fractures available	Fracture Factor		Total Fractures available	Fracture Factor
1/4	7.81		2/3	20.83
1/3	10.42		3/4	23.44
1/2	15.63		All	31.25

NOTE : Values calculated in *glass-fracturefac.xls* in Appendix II using assumptions presented in Section 5.4.
Archived in output DTN: MO0404SPAHLWGF.001.

Defense HLW Glass Degradation Model (BSC 2004 [DIRS 167619]) calculates fracture factors between 4 and 17 with 4 being the most likely and 17 as the maximum. To obtain the maximum value, that document also takes the same approach as *Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document* (CRWMS M&O 1998 [DIRS 100362]) by taking the average over 100 GPCs (1 in 100 dropped), assuming all glass surfaces are available, and that the increase due to a drop is 40. The fracture factor of 4 is derived from assuming that only $\frac{1}{2}$ of the fractures are available to water and the reactivity in these fractures is half that at the surface of the glass. The value of 40 times increase for glass in damaged glass pour canisters comes from using an impact velocity of 117 feet per second, which carries an equivalent drop height of approximately 213 feet (Smith and Ross 1975 [DIRS 102088], pp. 12 to 14 and Figure 41). This extreme velocity represents velocities associated with severe train accidents. Smith and Ross (1975 [DIRS 102088], pp. 12 to 14 and Figure 41) continue to indicate that >99% of freight train accidents occur at velocities lower than 117 feet per second. Also, objects on board trains would experience lower impact velocities than the train, the deformation of the cars and mountings providing cushioning. Therefore this fracture factor of 40 is considered an upper bound. When looking at total repository performance, the fracture factors in *Defense HLW Glass Degradation Model* (BSC 2004 [DIRS 167619]) would be useful as an upper bound. However, this approach does not provide a suitable fracture factor for calculations dealing with single waste packages.

6.4.3.2 pH-Dependent Corrosion Rate

The high-level waste glass degradation rate is a function of a pH-dependent corrosion rate combined with the surface area exposure of the glass. This rate is developed and presented in *Defense HLW Glass Degradation Model* (BSC 2004 [DIRS 167619]).

6.5 TITANIUM GRADES 7 AND 24

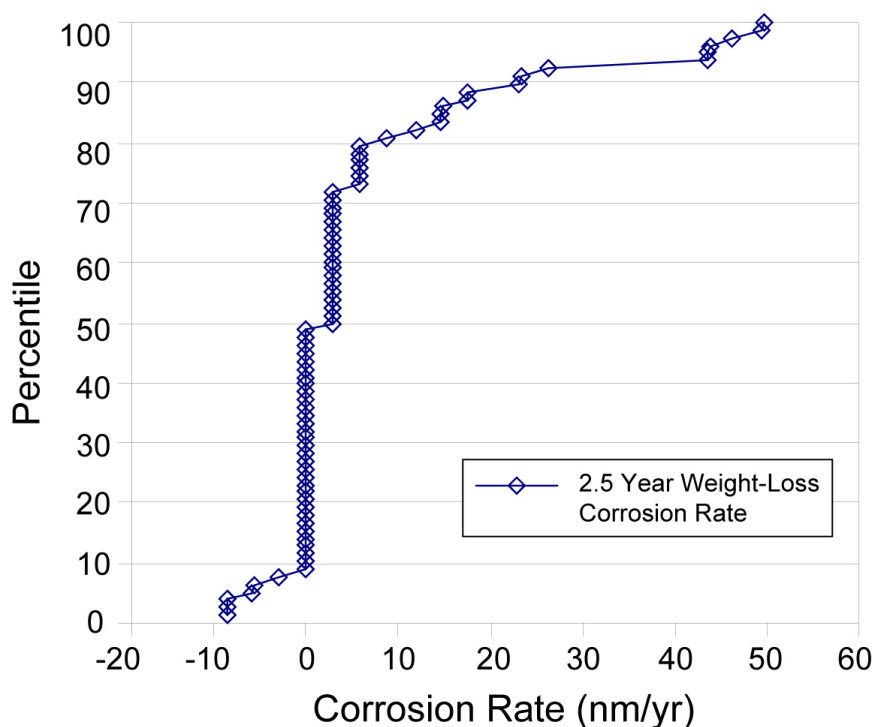
6.5.1 Titanium Grade 7

Corrosion rate data for Titanium Grade 7 is analyzed in *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2004 [DIRS 169845]) and will not be discussed further in this report. The corrosion rates for Titanium Grade 7 are used to calculate the corrosion rates for Titanium Grade 24 in Section 6.5.2.

6.5.2 Titanium Grade 24

Titanium Grade 24, an alloy with ~ 6 wt % Al, 4 wt % V, and ~ 0.04 to 0.08 wt % Pd, is used as the structural material in the design of the drip shield. An experimentally obtained corrosion rate for Titanium Grade 24 under repository conditions is not available at this time. However, the comparative corrosion behavior of Titanium Grade 24 can be estimated based on available data for other titanium alloys.

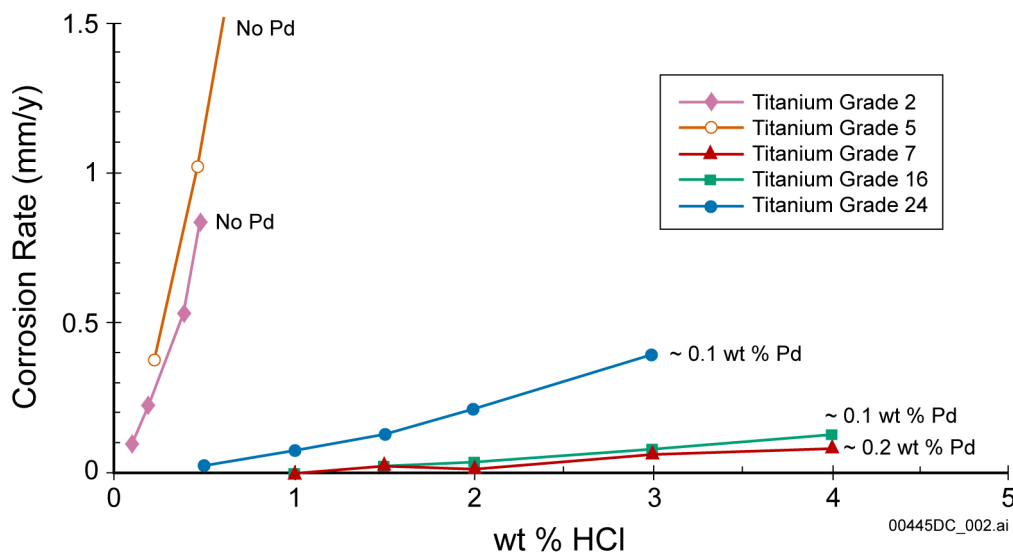
General Corrosion and Localized Corrosion of the Drip Shield (BSC 2004 [DIRS 169845]) plots all of the 2.5-year weight-loss data (vapor, aqueous, and water line) for Titanium Grade 7 from DTN: LL030410012251.056 [DIRS 169583] in the CDF shown in Figure 6-21. The corrosion rate from all weight-loss specimens at the 85% percentile of the cumulative distribution function is about 15 nm/yr.



Source: BSC 2004 [DIRS 169845] Figure 26.

Figure 6-21. Titanium Grade 7 Weight-Loss Corrosion Rates after 2.5 Years

The corrosion rates of Titanium Grades 2 (Titanium with no Pd) and 5 (Ti-6Al-4V with no Pd) in hydrochloric acid solutions, a very aggressive test media for titanium alloys, are shown in Figure 6-22 along with those of Titanium Grades 7, 16, and 24. The addition of 0.04 to 0.08 wt % of Pd to Titanium Grades 2 and 5 (to produce Titanium Grades 16 and 24) significantly improves the corrosion resistance of the alloy as demonstrated in Figure 6-22. From Figure 6-22, it can be seen that the corrosion rate of Titanium Grade 24 is about five times higher than that of Titanium Grade 7 in 3% boiling HCl. On this basis, a conservative estimate of the corrosion rate of Titanium Grade 24 in less aggressive repository environments would be a corrosion rate five times higher than that of Titanium Grade 7.



Source: BSC 2004 [DIRS 169847] (Figure 10).

NOTE: This figure shows the significant improvement in corrosion resistance due to addition of palladium.

Figure 6-22. Corrosion Rates of Titanium Grades 2, 5, 7, 16, and 24 in Boiling HCl

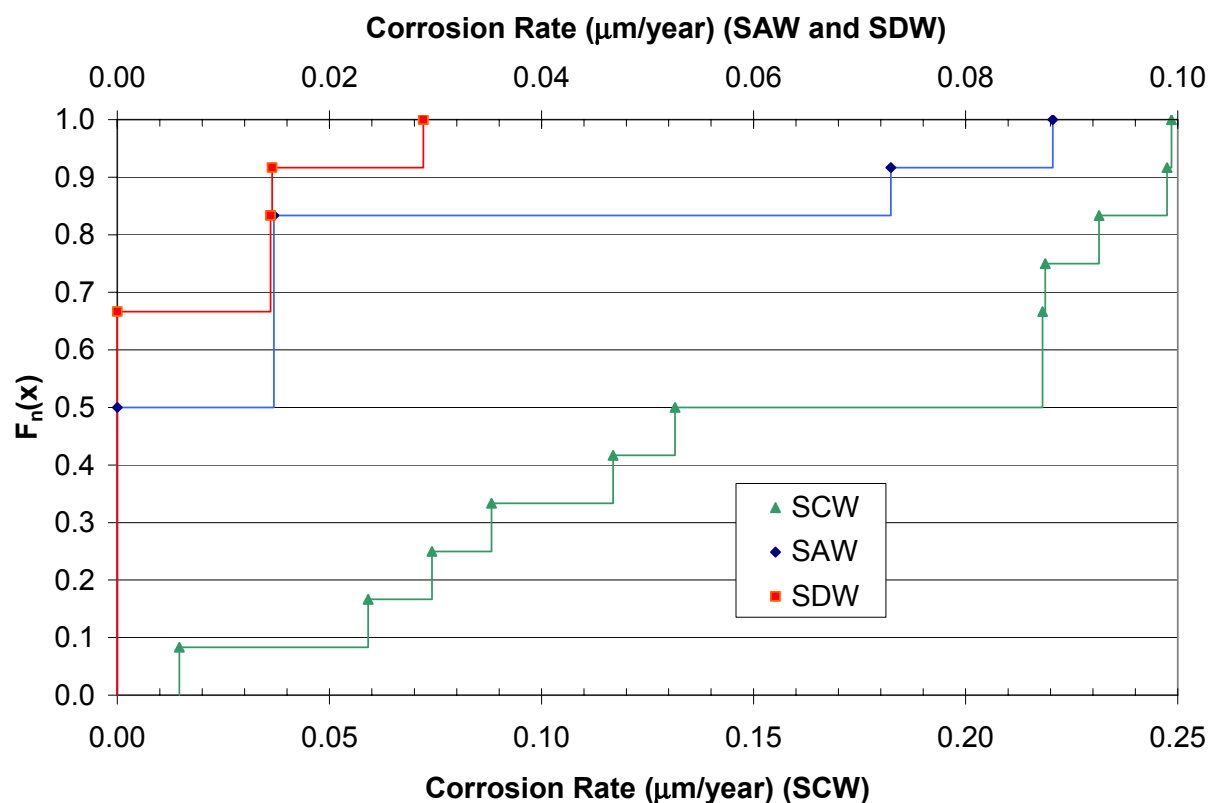
A corrosion allowance of 1 mm per exposed surface is accounted for in the drip shield design (BSC 2004 [DIRS 169220]). The 85th percentile on the cumulative distribution curve (Figure 6-1, based on data collected in all test environments) for the general corrosion rate of Titanium Grade 7 is about 15 nm/yr. Therefore, the estimated corrosion rate of Titanium Grade 24 at the 85th percentile is estimated to be a factor of five greater or about 75 nm/yr. Over a 10,000-year period, this corrosion rate results in a metal loss of about 0.75 mm per exposed surface.

Figure 6-23 and Table 6-18 present simple statistical information on the corrosion of Titanium Grade 24 (based on Titanium Grade 7 data from Table 4-31 multiplied by 5 to account for the increased corrosion of Titanium Grade 24 over that of Titanium Grade 7). The information presented below is only for aqueous corrosion, as vapor (or atmospheric) corrosion is not within the scope of this document. Figure 6-23 shows that a corrosion rate of 0.075 $\mu\text{m}/\text{yr}$ (75 nm/yr) corresponds to the 92nd percentile for the ECDF for corrosion rates in SAW solutions. Over a 10,000-year period, this corrosion rate results in a metal loss of about 0.75 mm per exposed surface.

Table 6-18. Minimum, Maximum, Mean, and Median Corrosion Rates of Titanium Alloy Grade 24 in Solution

Environment	Corrosion Rate ($\mu\text{m}/\text{yr}$)				Standard Deviation
	Minimum	Maximum	Median	Mean	
SAW (60°C to 90°C)	0.00	0.0882	0.0183	0.00728	0.0301
SDW (60°C to 90°C)	0.00	0.0289	0.00603	0.00	0.00966
SCW (90°C)	0.0146	0.249	0.156	0.175	0.0837

NOTE: Calculated in *titanium.xls* in Appendix II from values in Table 4-31; archived in output DTN: MO0409SPAACRWP.000.



NOTE: Calculated in *titanium.xls* in Appendix II from values in Table 4-31; archived in output DTN: MO0409SPAACRWP.000.

Figure 6-23. ECDF for Titanium Grade 24 in All Water Types Investigated

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7. CONCLUSIONS

This analysis presents statistical analyses and ECDFs for aqueous degradation rates affecting waste package material degradation for various DOE SNF types and drip shield materials. These rates are limited by various aqueous parameters such as temperature (up to 100°C), water type (i.e., fresh versus saline), and pH. Corrosion data of materials at pH extremes (below 4 and above 9) are not included in this analysis as materials commonly display different corrosion behaviors under these conditions. The exception is highly corrosion-resistant materials (Inconel Alloys and Titanium Grade 24) for which rate data from corrosion tests at a pH of approximately 3 were included.

7.1 STEELS AND ALLOYS

Corrosion rates were used to describe statistics of aqueous corrosion of steels and alloys inside the waste package. These rates describe only general corrosion and should not be used for analysis of effects of localized attack on waste package materials. If possible (i.e., if sufficient data existed), the ECDF was used to describe the corrosion data. These are provided in the figures within Section 6. To provide further analysis of the data, the minimum, maximum, mean, and median values (along with their standard deviations) are also presented in Table 7-1. These values are archived in output DTN: MO0409SPAACRWP.000.

Table 7-1. Summary of Statistical Values of Corrosion for Waste Package Metals

Metal	Conditions	Corrosion Rate (μm/yr)				Standard Deviation
		Minimum	Maximum	Median	Mean	
Stainless Steel Types 302/304/304L	Freshwater (25°C to 100°C)	0.001	1.570	0.1285	0.214	0.298
	Saltwater (26.7°C)	1.588	39.147	5.08	11.441	11.134
	Saltwater (90°C)	0.660	15.900	2.03	5.816	5.953
Stainless Steel Types 316/316L/AM-350	Freshwater (29.5°C)	0.0007	0.0475	0.003	0.0083	0.0136
	Freshwater (50°C to 100°C)	0.037	0.51	0.229	0.248	0.146
	Saltwater (26.7°C)	0.0014	14.787	0.7362	1.939	3.346
Neutronit	Freshwater (29.5°C)	0.001	0.011	0.003	0.004	0.004
	Freshwater (50°C to 100°C)	0.025	0.330	0.203	0.206	0.088
	Saltwater (26.7°C)	1.81	29.22	7.38	11.06	10.19
Stainless Steel Type 304 Alloyed with 0.3% Boron	Ambient-"Fresh" Water	3.05	12.19	4.57	6.10	3.86
	50°C-boiling-"Fresh" Water	3.05	27.43	16.76	15.75	7.99
	Ambient-"Harsh" Water	2.94	26.46	20.58	17.05	9.48
	50°C-"Harsh" Water	38.22	147.00	88.20	94.69	42.85
	Boiling-"Harsh" Water	11.76	58.80	27.93	29.77	12.48
Stainless Steel Type 304 Alloyed with 1.5% Boron	Ambient-Boiling-"Fresh" Water	161.54	252.98	211.84	210.31	32.77
	Ambient-Boiling-"Harsh" Water	164.64	1,058.40	360.15	453.74	272.96
Carbon Steel Type A516 (Times Less Than 0.53 Year)	SDW (60°C)	78.71	130.70	101.95	102.71	12.37
	SDW (90°C)	58.08	130.02	77.05	81.14	15.13
	SCW (60°C)	50.25	104.20	62.77	68.08	14.17
	SCW (90°C)	7.39	22.06	12.42	12.78	3.77

Table 7-1. Summary of Statistical Values of Corrosion for Waste Package Metals (Continued)

Metal	Conditions	Corrosion Rate ($\mu\text{m}/\text{yr}$)				Standard Deviation
		Minimum	Maximum	Median	Mean	
Carbon Steel Type A516 (Times Greater Than 1.0 Year)	SDW (60°C)	65.77	106.93	74.56	77.43	8.83
	SDW (90°C)	29.53	88.68	48.70	51.80	12.99
	SCW (60°C)	6.77	14.36	10.83	10.61	2.02
	SCW (90°C)	3.69	9.35	6.75	6.84	1.25
Aluminum Alloy	Freshwater	0.40	36.93	9.50	12.95	10.84
	Saltwater	0.12	110.91	4.76	9.69	15.34
Alloy N06464	Freshwater	20.1 ^a	77.4 ^a	55.7 ^a	52.8 ^a	21.1 ^a
Inconel Alloy	SDW (60°C)	0.00	0.05	0.025	0.025	0.018
	SDW (90°C)	0.00	0.10	0.030	0.040	0.034
	SAW (60°C)	0.00	0.08	0.025	0.026	0.026
	SAW (90°C)	0.00	0.03	0.00	0.004	0.008
	SCW (60°C)	0.05	0.10	0.08	0.077	0.019
	SCW (90°C)	0.03	0.12	0.06	0.066	0.031
Titanium Alloy Grade 24	SAW (60°C to 90°C)	0.00	0.0882	0.0183	0.00728	0.0301
	SDW (60°C to 90°C)	0.00	0.0289	0.00603	0.00	0.00966
	SCW (90°C)	0.0146	0.249	0.156	0.175	0.0837

NOTE: ^a Values are in units of nanometers/year.

Comparison of the change in the rate of Stainless Steel Type 304 and gadolinium-alloyed Stainless Steel Type 304 is presented in (Table 7-2). These values are archived in output DTN: MO0409SPAACRWP.000.

Table 7-2. Comparison of Minimum, Maximum, Mean, and Median Corrosion Rates of Gadolinium-Alloyed and Non Gadolinium-Alloyed Stainless Steel Type 304

Environment	Corrosion Rate ($\mu\text{m}/\text{yr}$)		
	Minimum	Maximum	Mean
0.3% Gd 304 (Ambient-Boiling-"Fresh") ^a	3.05	15.24	9.14
304L Freshwater (25°C to 100°C) ^b	0.001	1.57	0.214
Increase in Corrosion	3,050 times	9.71 times	33.27 times
0.3% Gd 304 (Ambient-"Harsh") ^a	2.94	2.94	2.94
Stainless Steel Type 304L Saltwater (<27°C) ^b	1.588	39.147	11.44
Increase in Corrosion	1.85 times	0.08 times	0.26 times
0.3% Gd 304 (Boiling-"Harsh") ^a	5.88	23.52	11.03
304L Saltwater (90°C) ^b	0.66	15.9	5.816
Increase in Corrosion	8.91 times	1.48 times	1.90 times

NOTES: ^aValues calculated in *aqueous-B-Gd-steels.xls* in Appendix II from values in Table 4-12; archived in output DTN: MO0409SPAACRWP.000.

^bValues taken from Table 6-4.

7.2 MISCELLANEOUS MATERIALS

Section 6.3 shows that these materials are essentially insoluble. Rates derived from high temperature data (Table 7-3), indicate extremely slow corrosion of these materials. Therefore, they are all considered insoluble for the purposes of this analysis. These values are archived in output DTN: MO0409SPAACRWP.000.

Table 7-3. Summary of Corrosion Behavior and Rates for Graphite, SiC, and Gadolinium Phosphate

Material	Rate ($\mu\text{m/yr}$)	Derived from
Graphite	1.84×10^{-12}	From extrapolation data by Lotts et al. 1992 [DIRS 164916]
	5.72×10^{-6}	From extrapolation of Gurwell 1981 [DIRS 164911] data
	9.77×10^{-10}	From extrapolation by Propp 1998 [DIRS 149395] data
	Insoluble	Lide 2002 [DIRS 160832]; Morgan 1981 [DIRS 164920]
SiC	1.61×10^{-9}	From extrapolation of Opila 1999 [DIRS 155502] data
	Insoluble	Lide 2002 [DIRS 160832]
GdPO ₄	Insoluble	Boatner and Sales 1988 [DIRS 164908], Lansdowne (n.d. [DIRS 164914])

7.3 GLASS FRACTURE FACTOR

The corrosion rate of the defense high-level waste glass is dependent on two parameters: a pH dependent dissolution rate combined with a fracture factor. Most references dealing with fractures discuss how surface area increases. To obtain a fracture factor, more information in the form of availability of fracture surfaces and reactivity of fracture surfaces must be taken into account. Since references do not take these additional parameters into account, surface area measurements represent a total surface area instead of an effective surface area. Therefore, a probability distribution for number of fractures or a direct fracture factor is not possible. However, the probability of a particular fracture factor can be derived indirectly from knowing the number of glass pour canisters damaged in a drop, how many damaged glass pour canisters are loaded into a waste package, and the percentage of fractures available for reaction. Table 7-4 exhibits the probability of a fracture factor based on how many glass pour canisters are loaded into a waste package including those from previous calculations where the fracture factor was averaged over all five glass logs within a waste package. However, using another approach, calculations should account for there being undamaged glass pour canisters in the waste package and apply a fracture factor to only those that are damaged. These values can be found in Table 7-5. Values for the fracture factor are archived in output DTN: MO0404SPAHLWGF.001.

Table 7-4. Fracture Factor Probabilities (Fracture Factor Averaged Over 5 Glass Pour Canisters) for High-Level Waste Glass Based on Loading Damaged Glass Pour Canisters into Waste Packages

	Number of GPCs Dropped While Loading				Amount of total fractures available for reaction		
	1 in 100	1 in 250	1 in 500	1 in 1,000	1/4 available	1/3 available	1/2 available
	Probability of waste package loading				Fracture factor associated with available fractures		
WPs containing 0 dropped GPCs	9.51E-01	9.80E-01	9.90E-01	9.95E-01	1	1	1
WPs containing 1 dropped GPC	4.80E-02	1.97E-02	9.92E-03	4.98E-03	1.56	2.08	3.13
WPs containing 2 dropped GPCs	9.70E-04	1.58E-04	3.98E-05	9.97E-06	3.13	4.17	6.25
WPs containing 3 dropped GPCs	9.80E-06	6.35E-07	7.97E-08	9.98E-09	4.69	6.25	9.38
	Number of GPCs Dropped While Loading				Amount of total fractures available for reaction		
	1 in 100	1 in 250	1 in 500	1 in 1,000	2/3 available	3/4 available	all available
	Probability of waste package loading				Fracture factor associated with available fractures		
WPs containing 0 dropped GPCs	9.51E-01	9.80E-01	9.90E-01	9.95E-01	1	1	1
WPs containing 1 dropped GPC	4.80E-02	1.97E-02	9.92E-03	4.98E-03	4.17	4.69	6.25
WPs containing 2 dropped GPCs	9.70E-04	1.58E-04	3.98E-05	9.97E-06	8.33	9.38	12.50
WPs containing 3 dropped GPCs	9.80E-06	6.35E-07	7.97E-08	9.98E-09	12.50	14.06	18.75

NOTE: GPC = Glass Pour Canister, WP = Waste Package.

Table 7-5. True Fracture Factors for High-Level Waste Glass in One Damaged Glass Pour Canister

Total Fractures Available	Fracture Factor		Total Fractures Available	Fracture Factor
1/4	7.81		2/3	20.83
1/3	10.42		3/4	23.44
1/2	15.63		All	31.25

7.4 YUCCA MOUNTAIN REVIEW PLAN ACCEPTANCE CRITERIA

Yucca Mountain Review Plan, Final Report (NRC 2003 [DIRS 163274]) contains Acceptance Criteria that are intended to establish the basis for the review of the material contained in the License Application.

Technical Work Plan for: Regulatory Integration Modeling and Analysis of the Waste Form and Waste Package (BSC 2004 [DIRS 171583], Table 3-1 indicates Acceptance Criteria for this analysis report. The Acceptance Criteria are based on the requirements mentioned in *Project*

Requirements Document (Canori and Leitner 2003 [DIRS 166275] and *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIR 163274]).

System Description and Demonstration of Multiple Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.1.3)

For the Yucca Mountain Review Plan criterion entitled System Description and Demonstration of Multiple Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-014, PRD-002/T-016), the acceptance criteria AC1, AC2, and AC3 do not apply because the purpose of this report is not to describe the performance of engineered barriers for the TSPA-LA. Instead, the analysis provides simple statistics on aqueous corrosion rates of steels and alloys.

Degradation of Engineered Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.3.1.3)

For the Yucca Mountain Review Plan criterion entitled Degradation of Engineered Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.3.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-015), the acceptance criteria AC1, AC2, AC3, AC4, and AC5 do not apply because the purpose of this report is not to describe deterioration or degradation of engineered barriers for TSPA-LA. Instead, the analysis provides simple statistics on aqueous corrosion rates of steels and alloys. Description of the degradation or deterioration of engineered barriers is covered by other analysis and model reports.

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8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

- 169583 LL030410012251.056. LTCTF Corrosion Rate Calculations for 2 1/2 - Year Exposed Titanium Alloy GR7 Specimens Cleaned Under TIP-CM-51. Submittal date: 07/16/2003.
- 151029 MO0006J13WTRCM.000. Recommended Mean Values of Major Constituents in J-13 Well Water. Submittal date: 06/07/2000.
- 155964 MO0109RIB00049.001. Waste Package Material Properties: Neutron Absorbing Materials. Submittal date: 09/17/2001.

8.4 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

MO0409SPAACRWP.000. Aqueous Corrosion Rates for Non-Waste Form Waste Package Materials. Submittal date: 09/16/2004.

MO0404SPAHLWGF.001. HLW Glass Fracture Factor Probabilities for a Single Waste Package. Submittal Date: 04/22/04.

APPENDIX I

LISTING OF FILES ON CD

Directory of d:\

09/14/2004	10:51a	105,472	aluminum_.xls
03/08/2004	04:29p	72,704	aqueous-A516.xls
09/04/2004	11:45a	38,400	aqueous Inconel-
			Alloy_.xls
03/11/2004	09:15a	48,128	aqueous-316L.xls
04/01/2004	04:12p	98,816	aqueous-304L.xls
04/20/2004	09:34a	84,992	aqueous-B-Gd-steels.xls
09/14/2004	02:19p	416,256	ECDF_metals.xls
09/15/2004	09:20a	37,888	glass-fracturefac.xls
08/13/2004	02:35p	35,328	Misc_Materials.xls
08/10/2004	10:37a	20,992	NiCrMoGdalloy.xls
08/10/2004	10:52a	15,872	ppm_.xls
10/04/2004	11:20a	30,208	titanium.xls

Total Files Listed:	
12 File(s)	1,005,056 bytes

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APPENDIX II

Attached CD-ROM

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APPENDIX III

Qualification of Data That Supports Aqueous Corrosion Rates for Waste Packages Materials (ANL-DSD-MD-000001)

III.1 PURPOSE

This analysis relies on data that may not have been collected under an approved quality assurance program that meets the requirements of 10 CFR Part 63, Subpart G [DIRS 156605] or its predecessor, 10 CFR Part 60 (48 FR 28194 [DIRS 100475]). This appendix qualifies the data this analysis uses as direct input.

III.2 METHODS AND CRITERIA

This appendix qualifies direct input data used in this analysis for intended use per AP-SIII.9Q, *Scientific Analyses*. The qualification process indicates (as required in AP-SIII.9Q, Section 5.2.11) that the qualification shall address “the extent to which the data demonstrate the properties of interest.” This is indicated in this appendix by the heading “*Demonstrate properties of interest*.” The qualification process in this appendix also considers at least one of the following factors:

- Reliability of data source
- Qualifications of personnel or organizations generating the data
- Prior use of the data
- Availability of corroborating data.

III.3 QUALIFICATION OF DATA

Table III-1 lists all sources whose data is to be qualified for intended use in this appendix. The table designates the attributes or criteria used in conjunction with the corroborating data and discussion of data collection methodology to qualify the information.

Table III-1. Sources of Data to be Qualified and Criteria Used to Qualify the Data

Data	Source	Criteria
Corrosion Rates of Aluminum Alloys	Ailor 1969 [DIRS 164907]	Corroborating Data
Corrosion Rates of Stainless Steel Types 302, 316, and 321	Alexander et al. 1961 [DIRS 162265]	Corroborating Data Personnel/organization qualifications Reliability of data source
Corrosion rate of monazite	Boatner and Sales 1988 [DIRS 164908]	Corroborating Data
Corrosion Rates of Stainless Steel Types 302 and 316	Bomberger et al. 1954 [DIRS 163699]	Corroborating Data
Corrosion rates of borated and Gd-alloyed Stainless Steel Types 304	Cole et al. 1976 [DIRS 159369]	Corroborating Data
Corrosion Rates of Alloy N06464	DOE 2004 [DIRS 168434]	Personnel/organization qualifications Reliability of data source
Corrosion Rates of Aluminum Alloys	Forgeson et al. 1958 [DIRS 159343]	Corroborating Data Personnel/organization qualifications Reliability of data source
Corrosion Rates of Stainless Steel Types 302, 316, and 321	Glass et al. 1984 [DIRS 159340]	Corroborating Data
Oxidation rate of graphite in water	Gurwell 1981 [DIRS 164911]	Corroborating Data
General Corrosion of Zircalloys	Hillner et al. 1998 [DIRS 100455]	Corroborating Data
Oxidation rate of graphite	Lewis 1990 [DIRS 130543]	Corroborating Data
Oxidation rate of graphite	Lotts et al. 1992 [DIRS 164916]	Corroborating Data
Corrosion Rates of Stainless Steel Types 304 and 316	McCright et al. 1987 [DIRS 159336]	Corroborating Data Personnel/organization qualifications Reliability of data source
Corrosion rates of Inconel alloys and Carbon Steel Types A516 and A27	McCright 1998 [DIRS 114637]	Corroborating Data Personnel/organization qualifications Reliability of data source
Oxidation rate of graphite	Morgan 1981 [DIRS 164920]	Corroborating Data
Oxidation rate of SiC	Opila 1999 [DIRS 155502]	Corroborating Data Personnel/organization qualifications Reliability of data source
Oxidation rate of graphite in air	Propp 1998 [DIRS 149395]	Corroborating Data
General Corrosion of Zircalloys	Rothman 1984 [DIRS 100417]	Corroborating Data
Corrosion Rates of Aluminum Alloys	Sawyer and Brown 1947 [DIRS 164921]	Corroborating Data Reliability of data source
Oxidation rate of graphite	Shreir et al. 1998 [DIRS 164925]	Corroborating Data
Corrosion Rates of Aluminum Alloys Corrosion Rates of Stainless Steel Types 302, 316, and 321 and detection limit	Southwell et al. 1976 [DIRS 100927]	Corroborating Data Personnel/organization qualifications Reliability of data source
Corrosion Rates of 304 Stainless Steel	Wheatfall 1967 [DIRS 164934]	Corroborating Data

III.3.1 Qualification of Data in Ailor, W.H. 1969 [DIRS 164907]

Demonstrate properties of interest: The tests were carried out specifically to assess the corrosion of aluminum in tap waters (dilute waters for the purposes of this analysis).

Corroborating Data: An authoritative source, Hollingsworth and Hunsiker (1987 [DIRS 150403]) corroborate the use of this source, as does Ghali (2000 [DIRS 164946]). Both references provide a synopsis of corrosion behavior of aluminum in different environments. Southwell et al. (1976 [DIRS 100927]) provides quantitative corroboration by showing corrosion rates in good agreement with those of Ailor (1969 [DIRS 164907]).

III.3.2 Qualification of Data in Alexander, A.L.; Southwell, C.R.; and Forgeson, B.W. 1961 [DIRS 162265]

Demonstrate properties of interest: Tests carried out on materials of specific interest in waste package corrosion (Stainless Steel Types 302, 316, and 321) in water types of interest (dilute and salt and concentrated waters)

Corroborating Data: Quantitative corroboration is provided by two authoritative sources, Beavers and Durr 1991 [DIRS 159341] and Beavers et al. 1992 [DIRS 159339], which provide corrosion data on Stainless Steel Type 304L (similar to Stainless Steel Type 302) and Stainless Steel Type 316L (Stainless Steel Type 316 with slightly less carbon content). Glass et al. (1984 [DIRS 159340]) provides corrosion data on Stainless Steel Type 321. Qualitative data used for corroboration through description of stainless steel corrosion behavior in aqueous media include Hudson and Stanners (1955 [DIRS 159334]), Scarberry (1967 [DIRS 159335]), Wallen and Olson (1977 [DIRS 164948]), and Davison et al. (1987 [DIRS 162971]), which is included in ASM International's *Metals Handbook*, considered an authoritative source.

Reliability of data source and Personnel/organization qualifications: The data source is a publication by the NACE. The NACE is currently the largest provider of information on corrosion and is relied upon globally by industries and governments for standards for materials preservation and corrosion control information. All publications from the NACE are rigorously peer reviewed before publication. The authors are recognized scientists in the field of materials corrosion. They have years of experience in experimental design and data collection in corrosion studies and are eminently qualified to conduct these studies.

III.3.3 Qualification of Data in Boatner, L.A. and Sales, B.C. 1988 [DIRS 164908]

Demonstrate properties of interest: The purpose of the assessment done by Boatner and Sales (1988 [DIRS 164908]) was to examine the possibility of using monazite as a medium for nuclear waste disposal. This also included an assessment of the pure material, which is directly applicable to this analysis.

Corroborating Data: Boatner and Sales (1988 [DIRS 164908]) present a degradation rate of monazite containing 20% Savannah River waste at less than 0.001 g/m²/day (approximately 0.12 μm/yr, presented as an upper bound in Section 6.3.3) and continue by stating that pure monazite would have much greater corrosion resistance. This is corroborated by Lansdowne

(n.d. [DIRS 164914]) (an authoritative source and manufacturer of GdPO_4 material), which states that the material is “insoluble in water.”

III.3.4 Qualification of Data in Bomberger, H.B.; Cambourelis, P.J.; and Hutchinson, G.E. 1954 [DIRS 163699]

Demonstrate properties of interest: Tests carried out on materials of specific interest in waste package corrosion (Stainless Steel Types 302 and 316L) in water types of interest (salt and concentrated waters)

Corroborating Data: Quantitative corroboration is provided by two authoritative sources, Beavers and Durr 1991 [DIRS 159341] and Beavers et al. 1992 [DIRS 159339], which provide corrosion data on Stainless Steel Type 304L (similar to Stainless Steel Type 302) and Stainless Steel Type 316L (Stainless Steel Type 316 with slightly less carbon content). Qualitative data used for corroboration through description of stainless steel corrosion in aqueous media include data by Hudson and Stanners (1955 [DIRS 159334]), Scarberry (1967 [DIRS 159335]), Wallen and Olson (1977 [DIRS 164948]), and Davison et al. (1987 [DIRS 162971]), which is included in ASM International’s *Metals Handbook*, considered an authoritative source.

III.3.5 Qualification of Data in Cole, H.S. 1976 [DIRS 159369]

Demonstrate properties of interest: Tests carried out on neutron absorbing materials of specific interest in waste package corrosion (boron-alloyed Stainless Steel Type 304) in water types of interest (“fresh” and “harsh” waters).

Corroborating Data: Cole (1976 [DIRS 159369]) presents the degradation of Stainless Steel Type 304 alloyed with boron. These rates indicate that with increasing boron content, the corrosion rate increases significantly. This is corroborated by Van Konynenburg et al. (1998 [DIRS 100948]); who show increase in corrosion with the addition of boron, and Smith et al. (1992 [DIRS 103441]) (a report published by the Electrical Power Research Institute (EPRI), an authoritative source) who show that as boron content of the stainless steel increases, the corrosion rate of the material also increases. Because of their proximity to one another on the periodic table, boron can be likened to carbon. It is well known that increased carbon content of stainless steels and heat-treating induces carbide formation. These carbides then affect the stability of the oxide film allowing the corrosion rate to increase.

III.3.6 Qualification of Data in DOE 2004 [DIRS 168434]

Demonstrate properties of interest: Tests carried out on Alloy N06464 to qualify material for acceptance in the Yucca Mountain Repository as a neutron absorbing material.

Reliability of data source and Personnel/organization qualifications: The data source was peer reviewed. Preparation and cleaning of test coupons as well as practice for laboratory immersion corrosion testing of metals were conducted following ASTM standards (as stated in Section 3.4 of DOE 2004 [DIRS 168434]). One of the purposes of these tests was to qualify the material for ASTM code qualification. The material was accepted as an ASTM standard and presented in ASTM B 932-04 (2004 [DIRS 168403]).

III.3.7 Qualification of Data in Forgeson, B.W.; Southwell, C.R.; Alexander, A.L.; Mundt, H.W.; and Thompson, L.J. 1958 [DIRS 159343]

Demonstrate properties of interest: Tests carried out on materials of specific interest in waste package corrosion (aluminum alloys) in water types of interest (dilute, salt and concentrated waters).

Corroborating Data: An authoritative source, Hollingsworth and Hunsiker (1987 [DIRS 150403]) corroborate the use of this source, as does Ghali (2000 [DIRS 164946]). Both references provide a synopsis of corrosion behavior of aluminum in different environments. Ailor (1969 [DIRS 164907]) provides quantitative corroboration by showing corrosion rates in good agreement with those by Forgeson et al. (1958 [DIRS 159343]).

Reliability of data source and Personnel/organization qualifications: The data source is a publication by the NACE. The NACE is currently the largest provider of information on corrosion and is relied upon globally by industries and governments for standards for materials preservation and corrosion control information. All publications from the NACE are rigorously peer reviewed before publication. The authors are recognized scientists in the field of materials corrosion. They have years of experience in experimental design and data collection in corrosion studies and are eminently qualified to conduct these studies.

III.3.8 Qualification of Data in Glass, R.S.; Overturf, G.E.; Garrison, R.E.; and McCright, R.D. 1984 [DIRS 159340]

Demonstrate properties of interest: Tests carried out on materials of specific interest in waste package corrosion (Stainless Steel Types 304L, 316L, and 321) in water types of interest (dilute “freshwater”).

Corroborating Data: Quantitative corroboration is provided by two authoritative sources, Beavers and Durr 1991 [DIRS 159341] and Beavers et al. 1992 [DIRS 159339], which provide corrosion data on Stainless Steel Types 304L and 316L (Stainless Steel Type 321 is close in composition to Stainless Steel Type 316L, so it should have similar corrosion properties). Qualitative data used for corroboration through description of stainless steel corrosion in aqueous media include Hudson and Stanners (1955 [DIRS 159334]), Scarberry (1967 [DIRS 159335]), Wallen and Olson (1977 [DIRS 164948]), and Davison et al. 1987 [DIRS 162971], which is included in ASM International’s *Metals Handbook*, considered an authoritative source.

III.3.9 Qualification of Data in Gurwell, W.E. 1981 [DIRS 164911]

Demonstrate properties of interest: Assessment was carried out to evaluate the feasibility of disposal using matrix waste forms (waste pellets or marbles within matrix material). Part of this assessment included evaluation of the oxidation of graphite.

Corroborating Data: Graphite is known to be highly corrosion resistant in both atmospheric and aqueous conditions. Gurwell (1981 [DIRS 164911]) states that graphite reacts very slowly in deionized water with a corrosion rate at 99°C of 10^{-10} g/cm²/day (or approximately 1.7×10^{-4} μm/yr). This rate is slow enough essentially to be considered, noncorrosive to insoluble, especially at lower temperatures. This noncorrosive or insoluble behavior is

corroborated by experimental data from Lotts et al. (1992 [DIRS 164916]) and Propp (1998 [DIRS 149395]) who report corrosion rates even slower than those reported by Gurwell (1981 [DIRS 164911]). Additionally, Lide (2002 [DIRS 160832], an authoritative source), Morgan (1981 [DIRS 164920]), and Shreir et al. 1998 [DIRS 164925] all report that the material is unreactive or insoluble.

III.3.10 Qualification of Data in Hillner, E.; Franklin, D.G.; and Smee, J.D. 1998 [DIRS 100455]

Demonstrate properties of interest: Tests carried out to assess zircaloy cladding corrosion in long term conditions of geologic repository disposal.

Corroborating Data: Three sources corroborate the behavior of zircaloy as described by Hillner et al. (1998 [DIRS 100455]). Yau and Webster (1987 [DIRS 165063]) (an authoritative source) indicate that zirconium and its alloys hold up well to a number of different corrosive environments. Uziemblo and Smith (1989 [DIRS 101231]) further corroborate this by indicating a corrosion rate of zero in the temperature range of 21.5°C to 43°C. Rothman (1984 [DIRS 100417]) indicates that after 10,000 years at 180°C, the depth of oxidation of zircaloy would be between 4 and 53 μm . All references corroborate the slow corrosion or oxidation rate of zircaloy presented by Hillner et al. (1998 [DIRS 100455]).

III.3.11 Qualification of Data in Lewis, C.F., ed. 1990 [DIRS 130543]

Demonstrate properties of interest: gives overview of graphite oxidation. This is directly applicable since carbide fuels will be disposed inside of their original fuel elements composed of high-grade industrial graphite.

Corroborating Data: Graphite is known to be highly corrosion resistant in both atmospheric and aqueous conditions. Lewis (1990 [DIRS 130543]) states that industrial graphite has “excellent corrosion resistance.” This corrosion resistant behavior is corroborated by experimental data from Lotts et al. (1992 [DIRS 164916]), Gurwell (1981 [DIRS 164911]), and Propp (1998 [DIRS 149395]), who record very slow corrosion for graphite (nanometers or less per year depending on temperature). Additionally, Lide (2002 [DIRS 160832], an authoritative source), Morgan (1981 [DIRS 164920]), and Shreir et al. 1998 [DIRS 164925] report that the material is unreactive or insoluble.

III.3.12 Qualification of Data in Lotts, A.L.; Bond, W.D.; Forsberg, C.W.; Glass, R.W.; Harrington, F.E.; Michaels, G.E.; Notz, K.J.; and Wymer, R.G. 1992 [DIRS 164916]

Demonstrate properties of interest: Assessment was carried out to evaluate the feasibility of disposal options for high-temperature gas-cooled (HTGR) reactor fuels. Part of this assessment included evaluation of the oxidation of graphite (material composing the reactor elements). It was this assessment that was used in this analysis.

Corroborating Data: Graphite is known to be highly corrosion resistant in both atmospheric and aqueous conditions. Lotts et al. (1992 [DIRS 164916]) show that air oxidation of graphite

produces a corrosion rate of 4.5×10^{-20} g/cm²/sec (or approximately 6.6×10^{-9} μm/yr) at 100°C. This rate is slow enough to be considered, essentially, noncorrosive to insoluble, especially at lower temperatures. This noncorrosive or insoluble behavior is corroborated by experimental data from Propp (1998 [DIRS 149395]) and Gurwell (1981 [DIRS 164911]). Additionally, Lide (2002 [DIRS 160832]), an authoritative source, Morgan (1981 [DIRS 164920]), and Shreir et al. 1998 [DIRS 164925] all report that the material is unreactive or insoluble.

III.3.13 Qualification of Data in McCright, R.D.; Halsey, W.G.; and Van Konynenburg, R.A. 1987 [DIRS 159336]

Demonstrate properties of interest: Tests carried out on materials of specific interest in waste package corrosion (Stainless Steel Types 304L and 316L) in water types of interest (dilute or fresh waters).

Corroborating Data: Quantitative corroboration is provided by two authoritative sources, Beavers and Durr (1991 [DIRS 159341]) and Beavers et al. (1992 [DIRS 159339]), who provide corrosion data on Stainless Steel Types 304L and 316L. Qualitative data used for corroboration through description of stainless steel corrosion in aqueous media include Hudson and Stanners (1955 [DIRS 159334]), Scarberry (1967 [DIRS 159335]), Wallen and Olson 1977 [DIRS 164948]), and Davison et al. (1987 [DIRS 162971]), which is included in ASM International's *Metals Handbook*, considered an authoritative source.

Personnel/organization qualifications and reliability of source: The experiments and analysis were performed at the Lawrence Livermore National Laboratory using good engineering practices. Also used a well accepted methodology and experiments were carried out in a thorough and comprehensive manner. Preparation and cleaning of test coupons as well as practice for laboratory immersion corrosion testing of metals were conducted following ASTM standards (as stated by McCright et al. (1987 [DIRS 159336], p. 22)).

III.3.14 Qualification of Data in McCright, R.D. 1998 [DIRS 114637]

Demonstrate properties of interest: Experiments carried out specifically to determine the corrosive behavior of candidate materials (Carbon Steel Type A516, Inconel Alloy) proposed for waste packages in a repository setting.

Corroborating Data: Quantitative corroboration is provided by Brasher and Mercer (1968 [DIRS 100883]), who indicate rates of corrosion similar to those presented by McCright (1998 [DIRS 114637]). This reference also shows the strong temperature dependence of corrosion rates that is also demonstrated by McCright (1998 [DIRS 114637]). Qualitative data used for corroboration through description of carbon steel corrosion in aqueous media include those provided by Matsushima (2000 [DIRS 164942]), Matsushima (2000 [DIRS 164944]), Satyanarayana (1981 [DIRS 159371]), and Bryson (1987 [DIRS 168467]), which is included in ASM International's *Metals Handbook*, considered an authoritative source.

Personnel/organization qualifications and reliability of source: The experiments and analysis were performed at the Lawrence Livermore National Laboratory using good engineering practices, a well-accepted methodology, and in a thorough and comprehensive manner. Testing

and analysis were done to an approved activity plan (Gdowski 1998 [DIRS 118106]) and technical implementation plans (McCright 1998 [DIRS 114637], p. 2.2-11 for more detail). Materials were cleaned in accordance with ASTM Standard G 1-90 [DIRS 103515].

III.3.15 Qualification of Data in Morgan, W.C. 1981 [DIRS 164920]

Demonstrate properties of interest: Study carried out specifically answer question on the feasibility of using graphite matrix materials in a repository environment.

Corroborating Data: Graphite is known to be highly corrosion resistant in both atmospheric and aqueous conditions. Morgan (1981 [DIRS 164920]) states that graphite is insoluble at “ordinary temperatures.” This non-corrosive or insoluble behavior is corroborated by experimental data from Lotts et al. (1992 [DIRS 164916]), Gurwell (1981 [DIRS 164911]), and Propp (1998 [DIRS 149395]), which record very slow corrosion for graphite (nanometers or less per year depending on temperature). Additionally, Lide (2002 [DIRS 160832], an authoritative source) and Shreir et al. (1998 [DIRS 164925]) report the material is unreactive or insoluble.

III.3.16 Qualification of Data in Opila, E.J. 1999 [DIRS 155502]

Demonstrate properties of interest: Study carried out specifically to answer question on SiC oxidation in water vapor. Comparisons to oxidation in water at like temperatures were then used to derive the rate required for this analysis.

Personnel/organization qualifications and reliability of source: The experiments and analysis were performed good engineering practices, used a well accepted methodology, and in a thorough and comprehensive manner. Testing included the use of pure material obtained from manufacturer. Equipment used was specifically designed to strictly control and monitor experimental conditions.

Corroborating data: Jorgensen et al. (1959 [DIRS 164912]) corroborate the behavior of SiC at different temperatures and show that the material is extremely durable, even at higher temperatures. The references also show that as the temperature decreases, the corrosion rate decreases significantly. Following this continual decrease, Lide (2002 [DIRS 160832]) indicates that SiC is insoluble at 25°C in water, which is also corroborated by Lotts et al. (1992 [DIRS 164916]) who indicate that the SiC layer on the TRISO particles will fail only under “unknown mechanisms.”

III.3.17 Qualification of Data in Propp, W.A. 1998 [DIRS 149395]

Demonstrate properties of interest: Study carried out specifically to answer question on graphite oxidation in a repository environment.

Corroborating Data: Graphite is known to be highly corrosion resistant in both atmospheric and aqueous conditions. Propp (1998 [DIRS 149395]) states that air oxidation of graphite produces a corrosion rate of 1 mg/cm² in 190,000 years (or approximately 2.4×10^{-5} μm/yr). This rate is slow enough to be considered, essentially, noncorrosive to insoluble, especially at lower temperatures. This noncorrosive or insoluble behavior is corroborated by experimental data from Lotts et al. (1992 [DIRS 164916]) and Gurwell (1981 [DIRS 164911]). Additionally, Lide

(2002 [DIRS 160832], an authoritative source), Morgan (1981 [DIRS 164920]), and Shreir et al. (1998 [DIRS 164925]) report the material is unreactive or insoluble.

III.3.18 Qualification of Data in Rothman, A.J. 1984 [DIRS 100417]

Demonstrate properties of interest: Tests carried out to assess zircaloy cladding corrosion in long term conditions of geologic repository disposal.

Corroborating Data: Three sources corroborate the behavior of zircaloy as described by Rothman (1984 [DIRS 100417]). Yau and Webster (1987 [DIRS 165063]) (an authoritative source) indicate that zirconium and its alloys hold up well to a number of different corrosive environments. Uziemblo and Smith (1989 [DIRS 101231]) further corroborate this by indicating a corrosion rate of zero in the temperature range of 21.5°C to 43°C. Hillner et al. (1998 [DIRS 100455]) indicates that after one million years, oxide growth on zircaloy would be about 0.3 mils (1 mil = 25.4 µm). All references corroborate the slow corrosion or oxidation rate of zircaloy presented by Rothman (1984 [DIRS 100417]).

III.3.19 Qualification of Data in Sawyer, D.W. and Brown, R.H. 1947 [DIRS 164921]

Demonstrate properties of interest: study carried out for materials of specific interest in waste package corrosion (aluminum alloys) in water types of interest (dilute or freshwater).

Corroborating Data: An authoritative source, Hollingsworth and Hunsiker (1987 [DIRS 150403]) corroborate the use of this source, as does Ghali (2000 [DIRS 164946]). Both references provide a synopsis of corrosion behavior of aluminum in different environments. Ailor (1969 [DIRS 164907]) provides quantitative corroboration by showing corrosion rates in good agreement with those by Sawyer and Brown (1947 [DIRS 164921]).

Reliability of data source: The data source is a publication by the NACE. The NACE is currently the largest provider of information on corrosion and is relied upon globally by industries and governments for standards for materials preservation and corrosion control information. All publications from the NACE are rigorously peer reviewed before publication.

III.3.20 Qualification of Data in Shreir, L.L.; Jarman, R.A.; and Burstein, G.T., eds 1998 [DIRS 164925]

Demonstrate properties of interest: Specifically looks at carbonaceous material (Shreir et al. 1998 [DIRS 164925], Section 18.1) and gives properties of durability and corrosion resistance in a number of corrosive environments.

Corroborating Data: Graphite is known to be highly corrosion resistant in both atmospheric and aqueous conditions. Shreir et al. (1998 [DIRS 164925]) state that graphite is generally unreactive at low temperatures and provide a table (18.2) showing that the material is resistant to a great number of highly corrosive environments. This noncorrosive or insoluble behavior is corroborated by experimental data by Lotts et al. (1992 [DIRS 164916]), Gurwell (1981 [DIRS 164911]), and Propp (1998 [DIRS 149395]), which record very slow corrosion for graphite (nanometers or less per year depending on temperature). Additionally, Lide (2002 [DIRS 160832]) (an authoritative source) and Morgan (1981 [DIRS 164920]) report that the material is unreactive or insoluble.

III.3.21 Qualification of Data in Southwell, C.R.; Bultman, J.D.; and Alexander, A.L. 1976 [DIRS 100927]

Demonstrate properties of interest: Tests carried out on materials of specific interest in waste package corrosion (Stainless Steel Types 302 and 316 and aluminum alloys) in water types of interest (dilute and salt or concentrated waters).

Corroborating Data: For stainless steel corrosion, quantitative corroboration is provided by two authoritative sources, Beavers and Durr (1991 [DIRS 159341]) and Beavers et al. (1992 [DIRS 159339]), which provide corrosion data on Stainless Steel Types 304L (similar to Stainless Steel Type 302) and 316L (similar in composition to Stainless Steel Type 316). Glass et al. (1984 [DIRS 159340]) provides corrosion data on Stainless Steel Type 321. Qualitative data used for corroboration through description of stainless steel corrosion in aqueous media include Hudson and Stanners (1955 [DIRS 159334]), Scarberry (1967 [DIRS 159335]), Wallen and Olson (1977 [DIRS 164948]), and Davison et al. (1987 [DIRS 162971]), which is included in ASM International's *Metals Handbook*, considered an authoritative source. For aluminum corrosion, an authoritative source, Hollingsworth and Hunsicker (1987 [DIRS 150403]) corroborate the use of this source, as does Ghali (2000 [DIRS 164946]). The references provide a synopsis of corrosion behavior of aluminum in different environments. Ailor (1969 [DIRS 164907]) provides quantitative corroboration for aluminum corrosion and shows corrosion rates in good agreement with those by Southwell et al. (1976 [DIRS 100927]).

Reliability of data source and Personnel/organization qualifications: The data source is a publication by the NACE. The NACE is currently the largest provider of information on corrosion and is relied upon globally by industries and governments for standards for materials preservation and corrosion control information. All publications from the NACE are rigorously peer reviewed before publication. The authors are recognized scientists in the field of materials corrosion. They have years of experience in experimental design and data collection in corrosion studies and are eminently qualified to conduct these studies.

III.3.22 Qualification of Data in Wheatfall, W.L. 1967 [DIRS 164934]

Demonstrate properties of interest: Tests carried out on materials of specific interest in waste package corrosion (Stainless Steel Type 304) in waters of interest (salt or concentrated waters).

Corroborating Data: Quantitative corroboration is provided by two authoritative sources, Beavers and Durr 1991 [DIRS 159341] and Beavers et al. 1992 [DIRS 159339], which provide corrosion data on Stainless Steel Type 304L (Stainless Steel Type 304 with a slightly lower carbon content). Qualitative data used for corroboration through description of stainless steel corrosion in aqueous media include Hudson and Stanners (1955 [DIRS 159334]), Scarberry (1967 [DIRS 159335]), Wallen and Olson (1977 [DIRS 164948]), and Davison et al. (1987 [DIRS 162971]), which is included in ASM International's *Metals Handbook*, considered an authoritative source.

III.4 CONCLUSION

In conclusion, the data is qualified for its intended use in this analysis.