BSC

Design Calculation or Analysis Cover Sheet

Complete only applicable items.

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DISCLAIMER

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ACRONYMS AND ABBREVIATIONS

AISI	American Iron and Steel Institute
ASM	American Society for Metals
ASTM	American Society for Testing and Materials
BSC	Bechtel SAIC Company, LLC
CIP	cast-in-place
DIRS	Document Input Reference System
DST	Drift Scale Test
ESF	Exploratory Studies Facility
ECRB	Enhanced Characterization of the Repository Block
GPa	gigapascal
HSLA	high-strength low-alloy
kN	kilo Newton
kW/m	kilo Watt per meter
LA	License Application
MIC	microbiologically influenced corrosion
n	neutron
RH	relative humidity
SCC	stress corrosion cracking
SR	Site Recommendation
STN	Software Tracking Number
THC	thermal-hydrological-chemical
Tptpll	Topopah Spring Tuff crystal-poor lower lithophysal zone
Tptpmn	Topopah Spring Tuff crystal-poor middle nonlithophysal zone
μm	micrometer
WIPP	Waste Isolation Pilot Plant
WP	waste package
WWF	welded wire fabric

1. PURPOSE

The purpose of this calculation is to reevaluate the longevity of steel ground support components installed in repository openings that will function throughout the preclosure period of the repository at Yucca Mountain.

The longevity calculation, *Longevity of Emplacement Drift Ground Support Materials for LA* (Reference 2.2.10) (referred to as LEDGS hereafter), which was prepared to support the License Application (LA) design and completed in September 2003, is considered a base calculation for LA. Although the ground support system for emplacement drifts has not been changed, the underground layout configuration and ground support systems for non-emplacement drifts have undergone some modifications since then. The focus of this calculation is to reevaluate the longevity of steel ground support components in the repository openings based on the current repository layout and ground support systems for LA. Notice that although the underground repository openings include emplacement drifts, non-emplacement drifts, and ventilation shafts, the longevity reevaluation is limited to steel ground support components in emplacement drifts and non-emplacement drifts; the concrete lining for ventilation shafts is not included.

The scope of this calculation consists of the following tasks:

- Identify the emplacement drift and non-emplacement drift environmental conditions relevant to current ground support materials,

- Identify the current ground support systems in the repository openings for LA design,

- Reevaluate the longevity of steel ground support components in the emplacement and non-emplacement drift environmental conditions, and

- Present the Exploratory Studies Facility (ESF) ground support performance results based on observations and discuss the need of ground support testing.

It should be noted that the reevaluation of longevity of the steel ground support components is, in general, limited to the final ground support systems; the initial ground support system will not be included unless otherwise noted.

2. INPUTS

2.1 PROCEDURES/DIRECTIVES

2.1.1 EG-PRO-3DP-G04B-00037, Rev. 11. Calculations and Analyses. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20080404.0001.

2.1.2 IT-PRO-0011, Rev. 9. Software Management. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20080416.0010.

2.2 DESIGN INPUTS

2.2.1 ACI (American Concrete Institute) 318-05/318R-05. 2005. Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05) (with Errata). Farmington Hills, Michigan: American Concrete Institute. TIC: 258034. ISBN: 0-87031-171-9

2.2.2 AISC (American Institute of Steel Construction) 1997. Manual of Steel Construction, Allowable Stress Design. 9th Edition, 2nd Revision, 2nd Impression. Chicago, Illinois: American Institute of Steel Construction. TIC: 240772. ISBN: 1-56424-000-2

2.2.3 ASM (American Society of Metals) International 1987. Corrosion. Volume 13 of ASM Handbook. Formerly 9th Edition, Metals Handbook. [Materials Park, Ohio]: ASM International. TIC: 240704. ISBN: 0-87170-007-7 (v. 1)

2.2.4 ASM International 1990. Properties and Selection: Irons, Steels, and High-Performance Alloys. Volume 1 of Metals Handbook. 10th Edition. Materials Park, Ohio: ASM International. TIC: 245666. ISBN: 0-87170-377-7

2.2.5 ASM 1994. "Table 13 Corrosion of AISI-300 Series Stainless Steels in a Marine Atmosphere." ASM Specialty Handbook, Stainless Steels. Davis, J.R., ed. Page 150. Materials Park, Ohio: American Society of Metals. TIC: 247111. [DIRS 114627]

2.2.6 Atlas Copco Swellex Product Manual. Denver, Colorado: Atlas Copco. TIC: 246775. [DIRS 164045]

2.2.7 BSC (Bechtel SAIC Company) 2001. ANSYS Calculations in Support of Natural Ventilation Parametric Study for SR. CAL-SVS-HV-000003 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010613.0250. [DIRS 155246]

2.2.8 BSC 2001. Repository Multiple Waste Package Thermal Calculation. CAL-WIS-TH-000010 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010814.0330. [DIRS 156276]

2.2.9 BSC 2003. Corrosion Evaluation of Steel Ground Support Components. 800-K0C-TEG0-00300-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20030224.0001. [DIRS 162448]

2.2.10 BSC 2003. Longevity of Emplacement Drift Ground Support Materials for LA. 800-K0C-TEG0-01200-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20030922.0004; ENG.20050816.0017. [DIRS 165425]

2.2.11 BSC 2004. Dose Rate Calculation for 21-PWR Waste Package. 000-00C-DSU0-01800-000-00C. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20041102.0003; ENG.20050815.0017. [DIRS 172227]

2.2.12 BSC 2004. In Situ Field Testing of Processes. ANL-NBS-HS-000005 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041109.0001; DOC.20051010.0001. [DIRS 170004]

2.2.13 BSC 2004. Ventilation Model and Analysis Report. ANL-EBS-MD-000030 REV 04. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041025.0002. [DIRS 169862]

2.2.14 BSC 2007. *Ground Control for Emplacement Drifts for LA.* 800-K0C-SSE0-00100-000-00C. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070925.0082; ENG.20080304.0028. . [DIRS 183391]

2.2.15 BSC 2007. *Ground Control for Non-Emplacement Drifts for LA.* 800-K0C-SSD0-00400-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071001.0042; ENG.20071218.0001; ENG.20080304.0027. . [DIRS 183406]

2.2.16 BSC 2007. *Project Design Criteria Document.* 000-3DR-MGR0-00100-000-007. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071016.0005; ENG.20071108.0001; ENG.20080305.0002; ENG.20080305.0011; ENG.20080305.0012; ENG.20071220.0003; ENG.20080107.0001; ENG.20080107.0002; ENG.20080107.0016; ENG.20080107.0017; ENG.20080131.0006; ENG.20080306.0009; ENG.20080313.0004. [DIRS 179641]

2.2.17 BSC 2007. Subsurface Air Properties Entering Emplacement Drifts. 800-KVC-VU00-00200-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070306.0001. [DIRS 180548]

2.2.18 BSC 2008. *Basis of Design for the TAD Canister-Based Repository Design Concept.* 000-3DR-MGR0-00300-000-002. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20080229.0007; ENG.20080306.0007; ENG.20080307.0009; ENG.20080312.0011; ENG.20080312.0012; ENG.20080312.0013; ENG.20080312.0014; ENG.20080312.0021; ENG.20080317.0002; ENG.20080313.0003; ENG.20080406.0003; ENG.20080407.0001; ENG.20080508.0005. [DIRS 185025]

2.2.19 BSC 2008. Evaluation of ESF Installed Ground Support. 800-30R-SSD0-00400-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20080508.0003.

2.2.20 BSC 2008. Impacts of Higher Thermal and Updated Seismic Loads on Repository Drift Stability. 800-K0C-SS00-01200-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20080215.0002. [DIRS 185191]

2.2.21 BSC 2008. FLUENT Thermal Calculation for 2.0 kW/m Thermal Load. 800-KVC-VUE0-00800-000-00A Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20080124.0007. [DIRS 184916]

2.2.22 Commercial Pantex Sika Lattice Girder. Louisville, Kentucky: Commercial Pantex Sika. TIC: 254199.

2.2.23 CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 1998. Waste Package Degradation Expert Elicitation Project. Rev. 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980727.0002. [DIRS 100349]

2.2.24 CRWMS M&O 2000. Environment on the Surfaces of the Drip Shield and Waste Package Outer Barrier. ANL-EBS-MD-000001 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001219.0080. (Note that this document has been cancelled, however, it is used in Section 6.6.3.2 of this calculation for information only)

2.2.25 DSI (Dywidag-Systems International) "DYWIDAG Threadbar." DSI Ground Support Systems. Bolingbrook, Illinois: Dywidag-Systems International. TIC: 255197. [DIRS 166160]

2.2.26 Etherington, H., ed. 1958. Nuclear Engineering Handbook. 1st Edition. New York, New York: McGraw-Hill. TIC: 231758. [DIRS 164789]

2.2.27 Fontana, M.G. 1986. Corrosion Engineering. 3rd Edition. New York, New York: McGraw-Hill. TIC: 240700. [DIRS 100890] ISBN: 0070214638

2.2.28 Gdowski, G.E. and Bullen, D.B. 1988. Oxidation and Corrosion. Volume 2 of Survey Of Degradation Modes of Candidate Materials for High-Level Radioactive-Waste Disposal Containers. UCID-21362. Livermore, California: Lawrence Livermore National Laboratory. ACC: MOL.19980715.0384. [DIRS 100860]

2.2.29 Greenspan, L. 1977. "Humidity Fixed Points of Binary Saturated Aqueous Solutions." Journal of Research of the National Bureau of Standards, 81A, (1), 89-96. Washington, D.C.: U.S. Department of Commerce. TIC: 241138.

2.2.30 International Rollforms. [n.d.]. Split Set® Friction Rock Stabilizers. Deptford, New Jersey: International Rollforms. TIC: 254808. [DIRS 164959]

2.2.31 LL991203505924.094. Approach and Supporting Data for MIC Modeling. Submittal date: 12/13/1999. [DIRS 138343]

2.2.32 Lucas, J.P. 1984. Analysis of Rock Bolt Material Failures at the WIPP Site. SAND84-0224. Albuquerque, New Mexico: Sandia National Laboratories. TIC: 244360. [DIRS 161321]

2.2.33 McCright, R.D. 1998. Corrosion Data and Modeling, Update for Viability Assessment. Volume 3 of Engineered Materials Characterization Report. UCRL-ID-119564, Rev. 1.1.

Livermore, California: Lawrence Livermore National Laboratory. ACC: MOL.19980806.0177. [DIRS 114637]

2.2.34 Merritt, F.S., ed. 1983. Standard Handbook for Civil Engineers. 3rd Edition. New York, New York: McGraw-Hill. TIC: 206892. [DIRS 106824] ISBN: 0-07041515-3

2.2.35 Michel, H. 1999. "Bernold Sheets." Letter from H. Michel (Bernold AG) to M. Grigore (MK), July 2, 1999, with enclosures. ACC: MOL.20030506.0321. [DIRS 163054]

2.2.36 Peng, S.S. 1986. Coal Mine Ground Control. 2nd Edition. New York, New York: John Wiley & Sons. TIC: 243435. [DIRS 106828]

2.2.37 SNL (Sandia National Laboratories) 2007. Drift-Scale THC Seepage Model. MDL-NBS-HS-000001 REV 05. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20071010.0004. [DIRS 177404]

2.2.38 Stahl, D.; McCoy, J.K.; and McCright, R.D. 1995. "Impact of Thermal Loading on Waste Package Material Performance." Scientific Basis for Nuclear Waste Management XVIII, Symposium held October 23-27, 1994, Kyoto, Japan. Murakami, T. and Ewing, R.C., eds. 353, 671-678. Pittsburgh, Pennsylvania: Materials Research Society. TIC: 216341. [DIRS 100933] ISBN: 1558992537

2.2.39 Sedriks, A.J. 1996. *Corrosion of Stainless Steels.* 2nd Edition. Corrosion Monograph Series. New York, New York: John Wiley & Sons. TIC: 245121. [DIRS 164036] ISBN: 0-471-00792-7

2.2.40 Stillborg, B. 1994. Professional Users Handbook for Rock Bolting. Series on Rock and Soil Mechanics Volume 18. 2nd Edition. Clausthal-Zellerfield, Germany: Trans Tech Publications. TIC: 253370. [DIRS 163053]

2.2.41 U.S. Bureau of Mines. 1987. Comparative Study of Rock Support Systems for a High Level Nuclear Waste Geologic Repository in Tuff. Denver, Colorado: U.S. Department of the Interior, Bureau of Mines, Denver Research Center. TIC: 226432. [DIRS 161147]

2.2.42 Williams Form Engineering Corporation 1997. Rock Anchor Systems, No. 397. Grand Rapids, Michigan: Williams Form Engineering Corporation. TIC: 245370. [DIRS 107694]

2.3 DESIGN CONSTRAINTS

No design constraint was used in this calculation.

2.4 DESIGN OUTPUTS

The design output of this calculation provides information for the future development of longevity of ground support materials in repository openings.

3. ASSUMPTIONS

This section contains assumptions used in this calculation and the rationale for use.

3.1 ASSUMPTIONS REQUIRING VERIFICATION

3.1.1 Vendor Data

Assumption: The following assumptions are made related to various types of ground support components:

- Diameter of 3-bar lattice girder, Type 130: 11.9 mm (0.47 in.)
- Diameter of Dwwidag #8 threadbar: 25.4 mm (1 in.)
- Thickness of Bernold Sheet: 1.5, 2.0, and 3.0 mm
- Thickness of Swellex bolt tube: 2 and 3 mm
- Thickness of bearing plate for Split Set bolt: 4 mm (0.16 in.)
- Diameters of Williams bolt R7X hollow bar: 30 mm (outside), 8.3 mm (inside)

Rationale: The above assumptions are based on the vendor data (References 2.2.22, 2.2.25, 2.2.35, 2.2.6, 2.2.30, and 2.2.42, respectively) and are considered appropriate for the purpose of this calculation.

The assumptions are used in Table 1 of Section 6.2.1.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 Initial Water Composition in Repository Opening Environment

Assumption: The initial water composition in repository opening environment is assumed from the initial pore water chemistry in the unsaturated zone at or above the repository horizon. Used in Section 6.4.3.

Rationale: This assumption is based on Section 6.2.2.1 of *Drift-Scale THC Seepage Model* (Reference 2.2.37, p. 6-13). Since perched water and saturated water are more dilute than pore waters, it is adequate to make this assumption. No further confirmation is needed.

3.2.2 Average Initial Water Chemistry at or above Repository Host Horizon

Assumption: The average and range (in parenthesis) concentration of chloride, sulfate, bicarbonate, and pH of initial water at or above the repository host horizon are assumed as 90 (23 – 146), 86 (16 – 126), and 139 (126 – 149) mg/l, and 8.07 (7.7 – 8.31), respectively. Used in Section 6.4.3.

Rationale: The assumed average and range values are from measured data presented on Table 6.2-1 of *Drift-Scale THC Seepage Model* (Reference 2.2.37, p. 6-16). It is considered adequate and does not need further confirmation.

3.2.3 Corrosion Allowance

Assumption: It is assumed that if the total corrosion depth of any steel member exceeds one-tenth of its thickness, the steel member would fail. Used in Section 6.6.3.

Rationale: The one-tenth reduction in thickness due to corrosion is assumed as a design allowance for steel members subject to corrosion based on engineering judgment. This assumption is considered adequate and no confirmation is needed.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

The Subsurface Facility is classified as "not important to safety" (non-ITS) and the emplacement drifts are classified as "important to waste isolation" (ITWI) in the *Basis of Design for the TAD Canister-Based Repository Design Concept* (Reference 2.2.18, Section 8.1.2). Accordingly, this calculation is designated as QA: QA.

The calculation is prepared per EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Reference 2.1.1). In addition, IT-PRO-0011, *Software Management* (Reference 2.1.2), is used for activities related to software usage.

4.2 USE OF SOFTWARE

4.2.1 Level 1 Software Usage

No level 1 software was used in this calculation.

4.2.2 Level 2 Software Usage

Microsoft Excel 2000 (STN: 610236-2000-00) software was used to perform the arithmetic calculations and for preparing the figures. This is considered Level 2 Usage in accordance with IT-PRO-0011, *Software Management* (Reference 2.1.2).

Microsoft Excel 2000 was performed on personal computers with Windows 2000/NT 4.0 operating systems. The Excel computations were confirmed using hand calculations and by visual inspection.

4.3 CALCULATION APPROACH

The same approaches used in the calculation LEDGS (Reference 2.2.10), which include: review of project and external documents, vender information, consultation with experts, and arithmetic calculations, are used in this calculation.

5. LIST OF ATTACHMENTS

No attachment was used in this calculation.

6. BODY OF CALCULATION

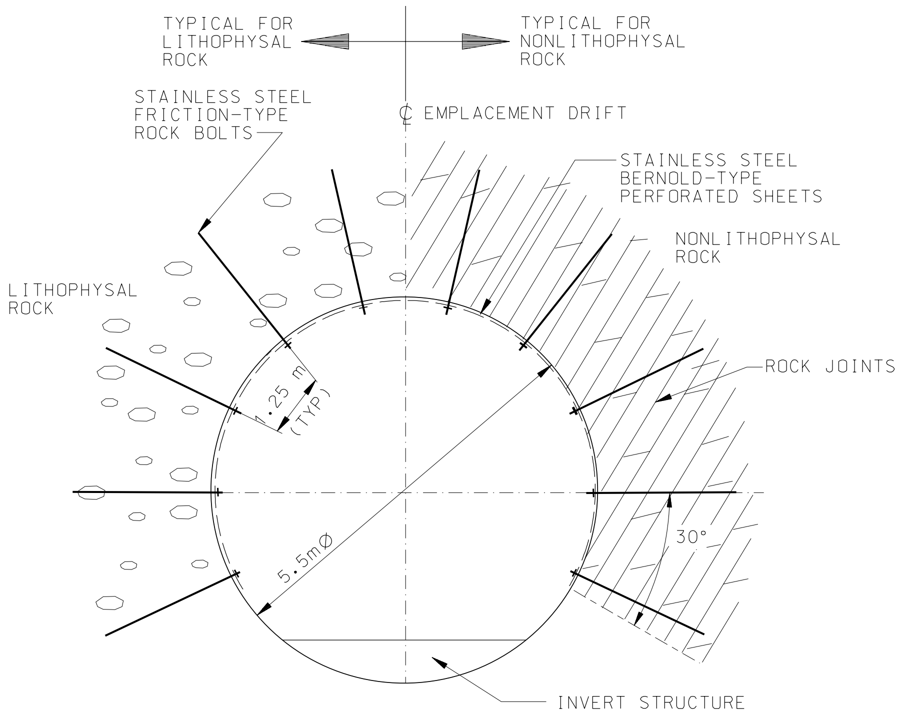
6.1 GENERAL

It is noted in Section 1 that the purpose of this calculation is to reevaluate the longevity of the steel ground support components installed in repository openings. Since the calculation LEDGS (Reference 2.2.10) is effective, to avoid duplications, this current calculation (i.e., longevity reevaluation) will refer to LEDGS for the corresponding information, wherever appropriate.

In order to facilitate the longevity reevaluation, it is essential to be familiar with some background information related to the ground support systems designed for the repository openings. As indicated in Section 6.1 of Reference 2.2.10, the ground support systems in the emplacement drifts have undergone several modifications since the SR design. The current License Application (LA) design for the ground support system in the emplacement drifts consists of stainless steel friction type rockbolts and perforated stainless steel sheets, eliminating use of cementitious materials. Figure 1 shows the current ground support configuration for emplacement drifts (Reference 2.2.14, Figure 6-32).

For the current ground support systems in non-emplacement openings, fully grouted rock bolts with heavy duty WWF will be used in access mains, exhaust mains, observation drift, test alcove, and TBM launch chambers. For intersections between access mains and turnouts and between emplacement drifts and exhaust mains, and ramps, fully grouted rock bolts with steel fiber-reinforced shotcrete will be used for ground support, in addition, steel lattice girders will be used as necessary for roof span control depending on the rock mass condition and roof span size. For emplacement drift turnouts, stainless steel friction-type rock bolts with stainless steel heavy duty WWF will be used (Reference 2.2.15, Section 6.5.4.1). Figure 2 shows the typical ground support configuration for access mains and exhaust mains (Reference 2.2.15, Figure 6-162). Figure 3 shows the typical ground support configuration for emplacement drift turnouts (Reference 2.2.15, Figure 6-164).

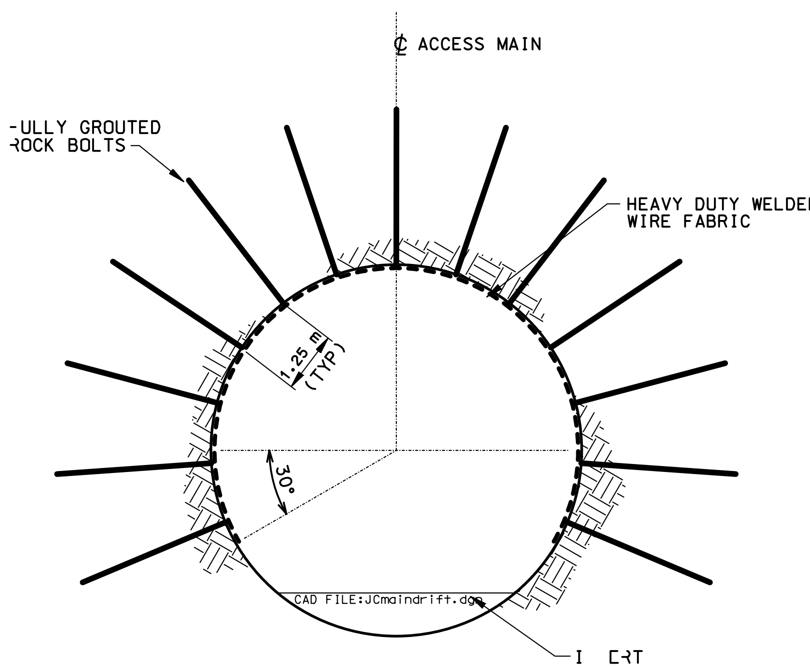
The reevaluation of longevity of steel ground support materials is based on the current ground support systems and the updated environmental conditions in emplacement and non-emplacement drifts. The environmental conditions to be considered include temperature, relative humidity, water and air chemistry, and radiation. The most important factor in longevity of steel ground support is corrosion of steel components, which will be the focus of reevaluation in this calculation.



Source: Reference 2.2.14, Figure 6-32

Note: Figure is not to scale; initial ground support is not shown.

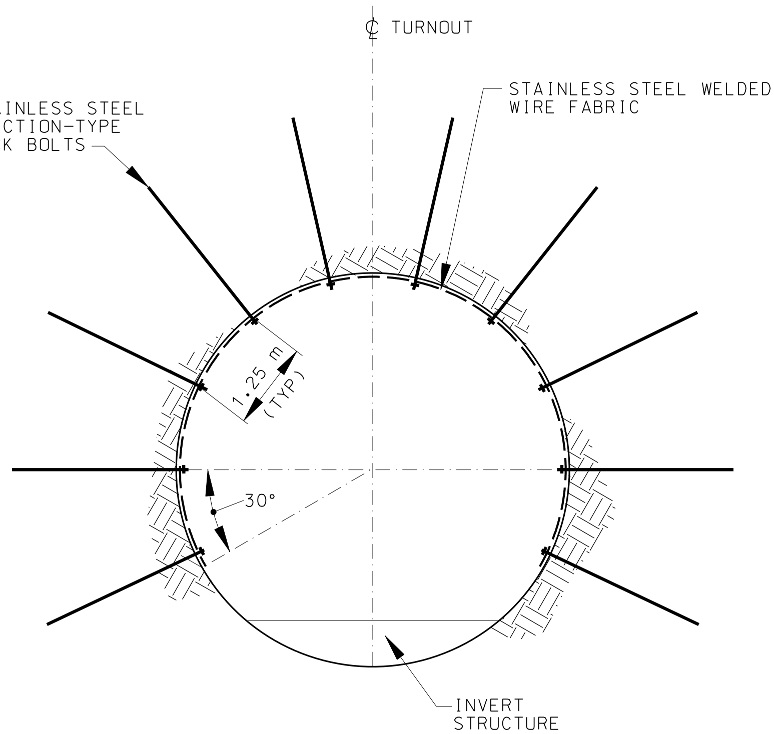
Figure 1. Configuration of Emplacement Drift Ground Support



Source: Reference 2.2.15, Figure 6-162

Note: Figure is not to scale; ground support is the same for exhaust mains; initial ground support is not shown.

Figure 2. Ground Support System in Access Mains



Source: Reference 2.2.15, Figure 6-164

Note: Figure is not to scale, initial ground support is not shown.

Figure 3. Ground Support System in Emplacement Drift Turnouts

6.2 INPUT PARAMETERS

6.2.1 Nominal Thickness and Width Data of Steel Ground Support Components

Table 1 presents the nominal thicknesses, widths, and diameters of typical steel ground support components, which are major candidate steel ground support components for repository openings.

Table 1. Nominal Dimensions of Typical Steel Ground Support Components

Type	Member Designation	Width (mm)	Thickness (mm)	Diameter (mm)	Source of Data
Rock Bolts	Split Set (tube)	NA	2.3	NA	Reference 2.2.36, p. 228
	Swellex bolt (tube)	NA	2[a] 3[b]	NA NA	Reference 2.2.6, p. 10 of Swellex catalog
	Dywidag threadbar (solid)	NA	NA	25.4	Reference 2.2.25, Dywidag #8 threadbar
	Williams bolt (hollow bar)	NA	10.9	30[c] 8.3[d]	Reference 2.2.42, p. 8, R7X hollow bar
Bearing Plates	Bearing plate	150 x 150	4	NA	Reference 2.2.30, p. 9
Steel Channel	C 8 x 11.5	NA	5.6[e]	NA	Reference 2.2.2, p 1-40
Steel Wire Fabric	Wire (W4)	75 x 75 100 x 100	5.7	NA	Reference 2.2.1, Appendix E, p. 408
Lattice Girder	Steel bar	NA	NA	11.9	Reference 2.2.22, 3-bar Type 130
Perforated Steel Sheets	Bernold Sheet	1080 x 1200	1.5, 2.0, 3.0	NA	Reference 2.2.35, p. 11

Note: [a] EXL Swellex bolt, [b] Super Swellex bolt, [c] Outside diameter, [d] Inside diameter, [e] Web.
NA: not applicable.

6.2.2 Steel Ground Support Components in Repository Openings

The steel ground support components to be used in emplacement and non-emplacement drifts are described as follows (Reference 2.2.14, Section 6.2.2.1 and Reference 2.2.15, Section 6.5.4.1):

- Stainless steel friction-type rockbolts and perforated stainless steel sheets for emplacement drifts.
- Fully grouted rock bolts with heavy duty WWF for all non-emplacement drifts except for emplacement drift turnouts, in which stainless steel friction-type rock bolts with stainless steel heavy duty WWF will be used.
- Fully grouted rock bolts with steel fiber-reinforced shotcrete for intersections and ramps.
- Steel lattice girders will be used as necessary for roof span control for intersections between access mains and turnouts and between emplacement drifts and exhaust mains, and ramps.

6.3 GROUND SUPPORT FUNCTIONAL REQUIREMENTS

Ground support design for emplacement and non-emplacement drifts has the following functional and/or performance requirements:

- Prevent rock loosening and potential rockfall onto waste packages during the preclosure period (Reference 2.2.16, Section 4.5.2.2),
- Account for the appropriate worst possible case in terms of combinations of in situ, thermal, seismic, construction, and operation loads (Reference 2.2.16, Section 4.5.2.1),
- Prevent rock falls that could potentially result in personnel injury (Reference 2.2.16, Section 4.5.2.2),
- Interface with Total System Performance Assessment (TSPA) to ensure general acceptance of committed ground support materials (Reference 2.2.16, Section 4.5.2.12),
- Function without planned maintenance during the operational life, while providing for the ability to perform unplanned maintenance in emplacement and non-accessible non-emplacement drifts on as-needed basis (Reference 2.2.16, Section 4.5.2.13),
- The Subsurface Facility shall be designed, constructed and maintained and shall incorporate acceptable materials and practices appropriate for a 100-year operational service life (Reference 2.2.18, Section 8.2.2.1),
- The subsurface ventilation system shall maintain an emplacement drift wall temperature during normal or off-normal operations of less than 200 ^{o}C prior to permanent closure (Reference 2.2.18, Section 22.2.1.3), and
- A corrosion allowance for structural steel members shall be determined to allow for material degradation due to potential corrosion during the preclosure period in the subsurface facility. (Reference 2.2.16, Section 4.2.13.4.2).

6.4 REPOSITORY OPENING ENVIRONMENTAL CONDITIONS

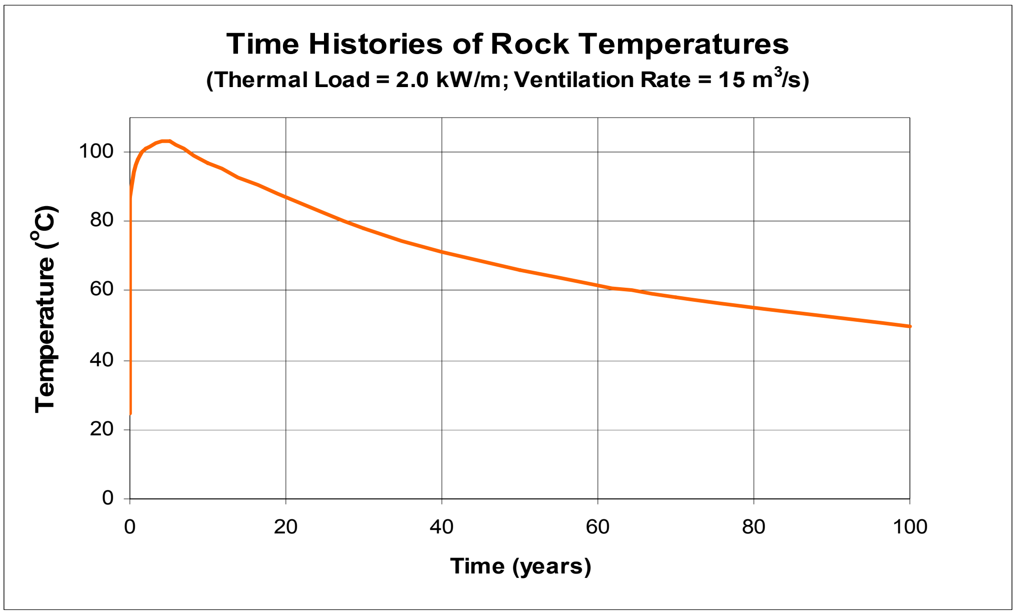
In order to evaluate the longevity of repository opening ground support materials, it is necessary to understand the environmental conditions that the repository openings will be subjected to during the preclosure period. In this section, the important environmental conditions in emplacement drifts and non-emplacement drifts related to longevity of steel components, i.e., temperature, relative humidity, water and air chemistry, and radiation, are presented.

6.4.1 Temperature

A number of thermal analyses have been performed to study the temperatures of waste packages, drift wall, and drift air in the past. In a ventilation model and analysis, for forced ventilation at 15 m^3/s for 50 years and an initial line load of 1.45 kW/m (Reference 2.2.13, pp. 4-10 and 4-13), the drift wall temperature at 600 m from the emplacement drift inlet reaches its peak at about 72 °C at year 2 (Reference 2.2.13, Figure 6-3, p. 6-33). In a recent ventilation thermal calculation, the heat transfer processes in and around a waste emplacement drift of 5.5 m in diameter was simulated for forced ventilation at 15 m^3/s for 100 years and an initial line load of 2.0 kW/m (Reference 2.2.21). Figure 4 shows the drift wall temperatures at emplacement drifts as function of time from this recent thermal calculation. The drift wall temperature profile indicates that the highest temperature at emplacement drift wall based on this higher thermal load is about 103 °C, which is about 30 °C higher than that for the lower thermal load (i.e., 1.45 kW/m).

With regard to the temperatures in the rock, a temperature drop of about 10 to 20 °C was estimated for 1 to 3 m into the rock based on a thermal analysis for 1.45 kW/m thermal loading scenario with 25-yr ventilation (Reference 2.2.8, Figure 6-3, p. 27). It is expected that a similar level of temperature decrease will be anticipated for the depth of rock up to 3 m, at which the distal end of the rock bolt is located.

It should be noted that the temperatures at the non-emplacement drifts are lower than that of the emplacement drifts since there is no heat source in them.



Source: This figure is generated based on data shown in Figures 7 and 8 of Reference 2.2.21.

Figure 4. Drift Wall Temperatures as Function of Time

6.4.2 Relative Humidity

In general, RH is inversely proportional to the temperature and proportional to saturation level in the surrounding rock. In addition, ventilation affects the relative humidity greatly. At the drift wall, moisture or water will be removed by the ventilation, instead of evaporating and migrating into a cooler rock region. Since continuous ventilation will be applied in the repository subsurface openings during the preclosure, the RH in the drift will be relatively low.

In a repository ventilation study, the in-drift relative humidity was calculated for a linear heat load of 1.45 kW/m with the various ventilation scenarios (Reference 2.2.7, p. XXVII-2). This study used an average inlet air of 25 ^{o}C dry bulb temperature at 30 percent relative humidity. The ventilation air was allowed to cross the emplacement drift picking up the heat of the waste packages and most of the potential moisture influx for a 600-m long emplacement drift. The in-drift relative humidity was calculated to range from 3.26 to 10.72 % for the period of the first 100 years (Reference 2.2.7, p. XXVII-7, Table XXVII-2). However, the actual relative humidity at emplacement drifts during the preclosure will probably be lower than these values because the weighted average relative humidity at emplacement drift intake was calculated to be 19.22 % based on a recent calculation on properties of air entering emplacement drifts (Reference 2.2.17, Table 17, p. 27), which is lower than 30% that was used in the ventilation study. It should also be noted that the RH values at access mains are higher than those at emplacement drifts, with an RH of 19.22 % as weighted average. The RH values at exhaust mains will be lower than those at access mains but will be higher than or equal to those at emplacement drifts.

It was also indicated in LEDGS that the effects of external environmental conditions on the relative humidity in the subsurface drifts are negligible (Reference 2.2.10, Section 6.2.2). Therefore, the above RH values are applicable to all ground support components inside the drifts that are exposed to the ventilation air during the normal operation.

For the in-drift relative humidity during the off-normal condition (e.g., ventilation breakdown) and RH inside the boreholes, these RH values will be higher than those exposed to the normal ventilation air and are discussed below.

During and after Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) Cross Drift excavation, the moisture conditions along the drifts and the hydrological conditions in the surrounding rocks have been monitored. Water potentials were measured using psychrometers that allowed for quick equilibration with the surrounding tuff (Reference 2.2.12, Section 6.8.1, p. 6-165). The results of in situ testing indicate the presence of a prominent dry-out zone of up to 3 m into the drift wall caused by ventilation in the ESF. It is apparent that ventilation significantly reduces the potential for free liquid water into the drift.

As indicated in Section 6.2.2 of LEDGS (Reference 2.2.10) that the relative humidity inside of a borehole drilled into the drift wall increases with the distance from the borehole collar. The relative humidity is higher than 98% beyond about 0.5 m inside the borehole collar. With heat generated from waste packages in emplacement drifts, the RH inside of borehole will be lower than that shown in Figure 3 of LEDGS (Reference 2.2.10). However, even the RH inside the emplacement drift will be very low due to the presence of both ventilation and heat generated by waste packages, the relative humidity inside the borehole is expected to be high, especially at the deeper portion near the end of borehole, where the RH value is expected to be greater than 90 %.

6.4.3 Water and Air Chemistry

In assessing the chemistry of the ground water on the longevity of steel ground support components, the initial pore water chemistry in the unsaturated zone at or above the repository horizon is used in this calculation (Assumption 3.2.1). The most important characteristics from the infiltrating water related to steel corrosion are chloride, sulfate, bicarbonate, and pH and their updated average values and ranges (in parenthesis) are 90 (23-146), 86 (16-126), and 139 (126-149) mg/l, and 8.07 (7.7–8.31), respectively (Assumption 3.2.2). Notice that the contents of chlorides and sulfate with these concentrations are generally considered as moderately low and low, respectively, and the pH level of this magnitude is near neutral.

The chemistry of air in the emplacement and non-emplacement drifts is expected to be the same as that on outside surface at ESF since no diesel equipment will be used during the emplacement operation. The ventilation rate of 15 m^3/s plays the major role during the preclosure period. This ventilation air rate far exceeds the air exchange rate inside the rock mass. It is unlikely that the chemistry of ventilated air has significant impact on corrosion of steel ground support components.

6.4.4 Radiation

Radiation hazards from spent nuclear fuel come from different types of radiation including alpha-particles, beta-particles, neutrons, and high-energy photons (gammas and x-rays). Alpha- and beta-particles are both stopped completely by the first few millimeters of waste package material and are therefore unable to affect the ground support materials. X-rays are rendered harmless by the attenuating effects of the waste package as well. Of major concerns are neutrons (with associated secondary gammas) and primary gammas from the fueled region of each spent fuel assembly. Neutrons and gammas are both neutral particles (having no electrical charge) and are able to penetrate through the waste package inner and outer barriers and impinge on the emplacement drift walls. Gammas are stopped by dense material through interactions with atomic electrons, while neutrons are only slowed down by nuclear collisions (most efficiently by collisions with light nuclei, such as hydrogen). A percentage of these particles travel through the ground support and deposit their energy using the above mechanisms.

The quantities of importance for radiation damage are the absorbed dose and the neutron fluence. The cumulative fast neutron fluence at the emplacement drift wall is 1.1×10^{13} n/cm^2 over a period of 300 years of waste emplacement (Reference 2.2.11, Table 6.4-1, p. 49). The cumulative gamma dose to the ground support material is about 66 mega-rads for 300 years of waste emplacement (Reference 2.2.11, Table 6.4-6, p. 55).

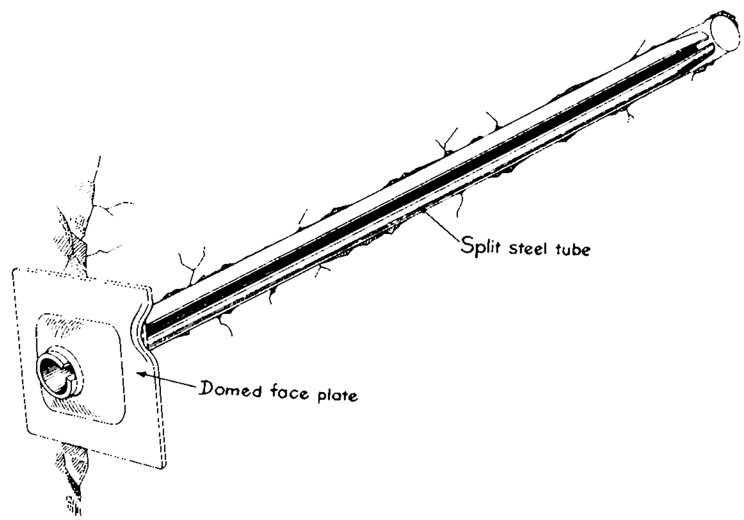
6.5 STEEL GROUND SUPPORT COMPONENTS IN REPOSITORY OPENINGS

6.5.1 Emplacement Drifts

The ground support in the repository emplacement drifts will be stainless steel friction-type rock bolts and stainless steel perforated sheets (see Section 6.2.2). Two friction-type rock bolts, i.e., Split Sets and Swellex rock bolts are considered. Figure 5 through Figure 7 show the configurations of Split Sets, Swellex bolts, and perforated steel sheets, respectively. The detailed discussions on these two types of rock bolts and perforated steel sheets have been presented in Sections 6.6.1.1 and 6.6.1.2 of Reference 2.2.14 and will not be repeated here. However, it is essential to pay attention on their configurations and geometry related to potential corrosion. For example, for Split Sets, the thin tube configuration with its whole-length slot which results in a large surface area (outer plus inner) to cross-sectional area, is susceptible to corrosion on both inside and outside surfaces (see Figure 5). For Swellex bolts, the steel tube may be subject to corrosion only to the outside exposed surface whereas the interior side of the tube is prevented from corrosion due to the sealed ends through welding during the manufacturing process (see Figure 6). For perforated steel sheets, the RH of ventilated air contacting the inside surface of steel sheets is low but the RH between the outside surface of sheets and drift wall may be higher at some localized points (see Figure 7).

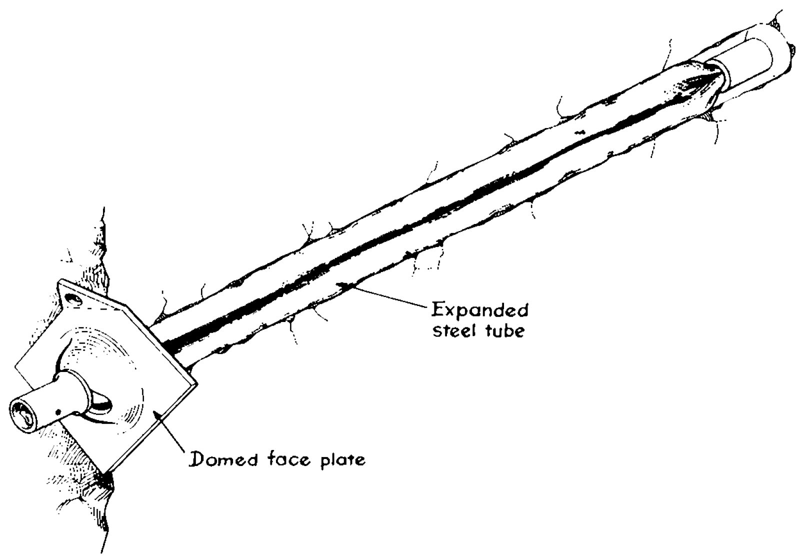
6.5.2 Non-Emplacement Drifts

Fully grouted rock bolts with heavy duty WWF will be used for all non-emplacement drifts except for emplacement drift turnouts, where stainless steel friction-type rock bolts with stainless steel heavy duty WWF will be used. Fully grouted rock bolts with steel fiber-reinforced shotcrete will be used for intersections and ramps. Steel lattice girders will be used as necessary for roof span control for intersections and ramps (see Section 6.2.2). The detailed discussions on ground support systems in non-emplacement drifts have been presented in Section 6.5.4.1 of Reference 2.2.15.



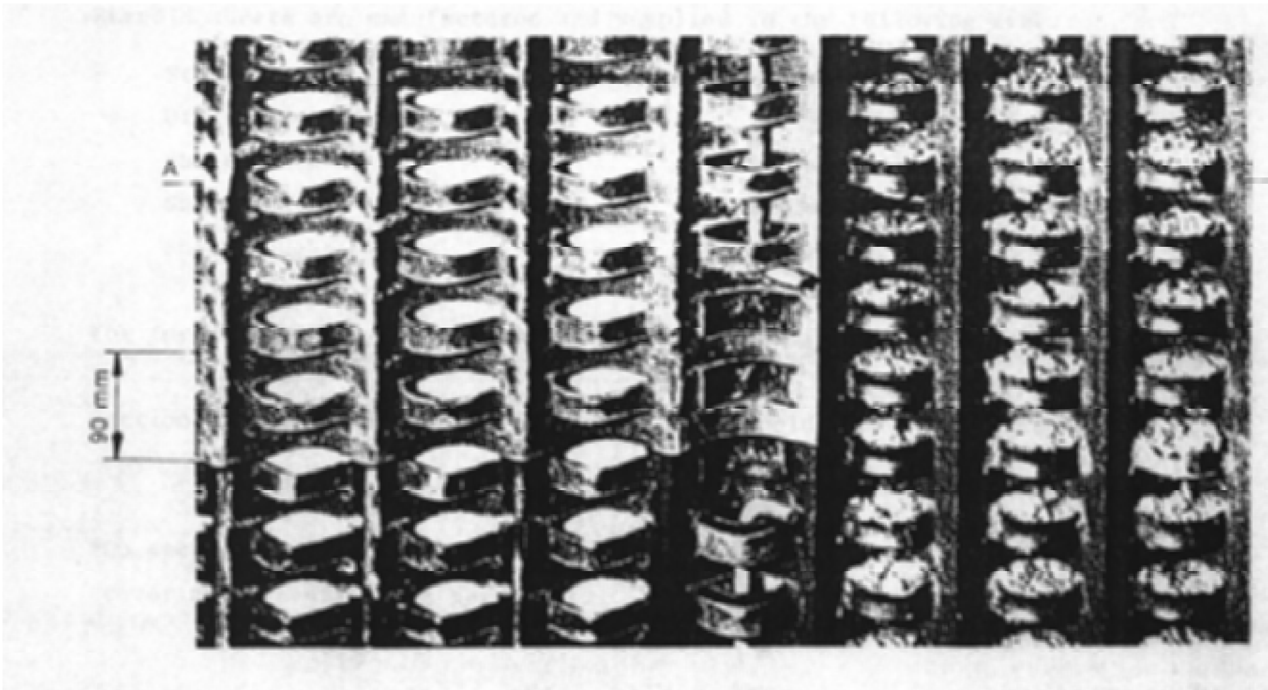
Source: Reference 2.2.40, p. 13

Figure 5. A Typical Split Set Rock Bolt



Source: Reference 2.2.40, p. 14

Figure 6. A Typical Swellex Rock Bolt



Source: Reference 2.2.35, p. 10

Figure 7. Bernold-type Perforated Steel Sheet

6.6 REEVALUATION OF LONGEVITY OF STEEL GROUND SUPPORT COMPONENTS IN REPOSITORY OPENINGS

The longevity reevaluation of steel ground support components in repository openings is presented in this section. The effects of elevated temperature and radiation on mechanical properties of steel components will be discussed first and followed by evaluation of the corrosion of steel components, which is the most important factor related to the longevity of steel ground support components.

Candidate steel ground support materials including carbon steel, HSLA steel, and stainless steel are considered in this reevaluation.

6.6.1 Temperature Effect

The major effects of elevated temperature on mechanical properties of steel materials are discussed in this section (see LEDGS for details (Reference 2.2.10, Section 6.4.1)).

The yield point of structural steel (including carbon steel and HSLA steel) generally decreases linearly from its value at room temperature (i.e., about 20 °C) to about 80 percent of that value at 430 °C, and to about 70 percent at 540 °C (Reference 2.2.34, p. 9-67). By interpolation, the yield strength values at 200 °C (the temperature limit prior to permanent closure), 103 °C (the maximum drift wall temperature based on 2.0 kW/m thermal load) (see Section 6.4.1), and 72 °C (the maximum drift wall temperature during preclosure based on 1.45 kW/m thermal load) (see Section 6.4.1) are about 91, 96, and 97 percent, respectively, of that at room temperature (i.e., about 20 °C).

The modulus of elasticity of structural steel decreases linearly from 200 GPa (29,000 ksi) at about 20 °C to 172 GPa (25,000 ksi) at about 480 °C (Reference 2.2.34, p. 9-67), or about 86 percent of the room-temperature value. By interpolation, the modulus of elasticity of structural steel will be 189 GPa (27,400 ksi), 195 GPa (28,300 ksi), and 197 GPa (28,550 ksi) at 200, 103, and 72 °C, respectively, which decrease about 5, 2.5, and 1.5 percent, respectively, in comparison with the value at 20 °C.

For majority of stainless steels, particularly the austenitic types such as 316, they are used extensively for elevated-temperature (i.e., above 370 °C) applications (Reference 2.2.4, pp. 861 and 930). It is expected that for the temperature range from about 70 °C to 200 °C, the temperature effect on mechanical properties of stainless steel is insignificant.

In conclusion, the temperature effects on mechanical properties of carbon steel, HSLA steel, and stainless steel to be used either in emplacement drifts or non-emplacement drifts are insignificant.

6.6.2 Radiation Effect

The cumulative neutron fluence is important for determining property changes in metallic materials. The cumulative fast neutron fluence at the emplacement drift wall is 1.1×10^{13} n/cm^2

over a period of 300 years of waste emplacement (see Section 6.4.4). Past studies focused on nuclear reactor pressure vessel materials such as ASTM A 302 have indicated that the effects of radiation on fracture toughness of carbon steel is negligible for fast neutron fluence below the order of 10^{18} n/cm^2 (Reference 2.2.4, p. 659, Figure 7). Therefore, the effect of neutron radiation on mechanical property of carbon steel is insignificant. This neutron fluence level (i.e., 1.1 x 10^{13} n/cm^2) is also considerably below the threshold of 5 x 10^{19} n/cm^2 for stainless steel for the change in mechanical properties (hardness, ultimate strength, elongation at rupture) of stainless steel 316 (Reference 2.2.26, p. 10-107). Hence, the impact from neutron radiation on mechanical properties of carbon steel or stainless steel 316 is insignificant.

The cumulative gamma dose to the ground support material at 300 years of waste emplacement is about 66 mega-rads (see Section 6.4.4). Gamma radiation at this level is not expected to produce any significant effects on carbon steel or stainless steel 316 (Reference 2.2.11, p. 55).

It is concluded that the cumulative neutron fluence and gamma dose are too small to cause any appreciable mechanical damage to carbon steel components in non-emplacement drifts or stainless steel components in emplacement drifts and adjacent turnouts during the preclosure period.

6.6.3 Corrosion Evaluation of Steel

The most important factor that controls the longevity of steel ground support is corrosion. The corrosion evaluation of steel in this section applies to the steel ground support components in repository openings including emplacement drifts and non-emplacement drifts.

The simplest and most effective corrosion control practice is selection of a suitable metal or alloy for the service time in a particular environment. For corrosion evaluation, a service life of 100 years (see Section 6.3) is being considered as the basis for selecting the ground support materials in repository subsurface openings. Ground support systems are designed to function without planned maintenance during the operational life, while providing for the ability to perform unplanned maintenance in emplacement and non-accessible non-emplacement drifts on as-needed basis (see Section 6.3).

Among the environmental conditions affecting steel corrosion, which include temperature, relative humidity (RH), and water chemistry, RH is a key environmental factor in controlling the corrosion of steel. It is known that there is a critical (or threshold) relative humidity, below which the corrosion rate is generally negligible, but above which the corrosion condition becomes significant.

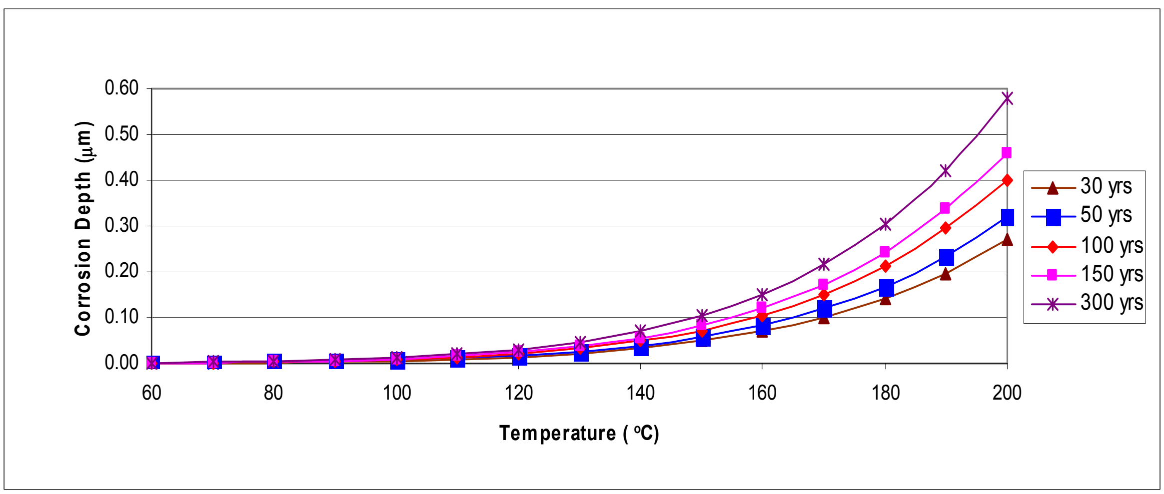
In this section, various corrosion mechanisms and/or forms including dry oxidation, humid-air corrosion, aqueous corrosion, pitting and crevice corrosion, stress corrosion cracking, hydrogen embrittlement, and microbiologically influenced corrosion of steel ground support components are evaluated.

6.6.3.1 Dry Oxidation

The dry oxidation of carbon steel would occur when the emplacement drift is under conditions of high temperature and low RH, i.e., less than about 60 percent (Reference 2.2.23, pp. 3-5 and 3-7). The estimated penetration depth of carbon steel due to dry oxidation was presented in Section 6.3.1 in the *Corrosion Evaluation of Steel Ground Support Components* (Reference 2.2.9). Figure 8 shows the estimated penetration depths of dry oxidation for carbon steel for a temperature range of 60 to 200 °C based on Equation 1 of Reference 2.2.9. As shown in this figure, the estimated corrosion depths under dry oxidation condition for carbon steel are very small; approximately 0.01 μm at 100 °C, and 0.4 μm at 200 °C for a period of 100 years. Therefore, the impact of dry oxidation on the performance of carbon steel is insignificant.

For alloy steel and stainless steel, the oxidation rates are negligible for temperature below about 650 °C (1200 °F) and 760 °C (1400 °F), respectively, (Reference 2.2.27, Table 11-5, p. 526). Therefore, the impact of dry oxidation on the performance of HSLA steel (i.e., alloy steel) and stainless steel at temperatures up to 200 °C is negligible.

Therefore, none of steel ground support components made of carbon steel, HSLA steel, or stainless steel will fail due to corrosion by dry oxidation.



Source: Reference 2.2.9, modified from Fig. 3

Figure 8. Estimated Penetration Depths of Dry Oxidation for Carbon Steel

6.6.3.2 Humid-Air Corrosion

In general, humid-air corrosion of carbon steel occurs for RH ranged from about 60 to 80 percent, depending on the nature of the metal surface. However, in presence of dust, oxides, salts, or a combination of them, humid-air corrosion can take place at RH values lower than 60 percent (Reference 2.2.23, pp. 3-6 to 3-7 and Figure 3-2). The deliquescence points of salts determine the RH at which humid-air corrosion commences. The deliquescence points can cover a broad range. For example, the deliquescence point of sodium nitrate varies from 65 percent

RH at 90 °C to 73 percent RH at 30 °C. The deliquescence point for magnesium chloride increases from 22 percent RH at 100 °C to 32 percent RH at 30 °C. The deliquescence point for sodium chloride is normally 75 percent relative humidity over a temperature range of 30 °C to 80 °C (Reference 2.2.29, Table 2). Therefore, there exists a possibility that some of deliquescence points of mixed salts that deposited on the surfaces of Bernold-type steel sheets, especially the surface contacting the drift wall, and protruding portions of rock bolts, may have a lower RH than that present in emplacement drifts during the preclosure and cause the humid-air corrosion to occur. Furthermore, as discussed in Section 6.4.2, the relative humidity inside the borehole is high, especially at the deeper portion near the end of the borehole, where the RH value is expected to be greater than 90%. For friction-type rock bolts, in which no grout is used to seal the empty space inside the borehole, it is likely that the humid-air corrosion will occur during the preclosure period.

Corrosion depths of steel ground support components under humid-air conditions were estimated using experimental results from tests that investigated the corrosion of waste package materials. A series of long-term corrosion tests have been conducted at Lawrence Livermore National Laboratory (Reference 2.2.33). Although the major purpose of these tests was to investigate the corrosion behavior of waste package materials, the test results for the carbon steel corrosion-allowance materials (definition at that time) are used herein to approximate the humid-air corrosion rates of the steel ground support components. In these tests, the two carbon steel corrosion-allowance materials tested were A 516 and cast carbon steel. The test environments closest to the emplacement drift condition are at the vapor phase of simulated dilute J-13 well water at a 10x concentrated solution with temperatures of 60 °C and 90 °C. The one-year corrosion rates for the test results from the two materials under these two temperature conditions are 27, 37, and 56, 39 (μm/year), respectively (Reference 2.2.33, Table 2.2-9). The average of these four values is 40 μm/year. Notice that the relative humidity for the vapor phase within a test chamber is close to 100 percent because it is a closed vessel with dilute solution maintained at elevated temperatures (i.e., 60 °C and 90 °C). It should also be noted that although the chemical composition of J-13 well water (see composition of J-13 well water in Table 14, p. 36 of Reference 2.2.24) is not the same as that of the initial pore water chemistry in the unsaturated zone at or above the repository horizon (see Assumption 3.2.2), however, the difference in water chemistry between the former and the latter is not expected to cause a significant difference in the corrosion penetration estimate.

Table 2 presents the total corrosion depths for carbon steel based on the corrosion rate of 40 μm/year for 30, 50, 75, and 100 years. The total corrosion depths for single-sided corrosion range from 1.2 to 4.0 mm for 30 to 100 years. If considering corrosion from both sides, the total corrosion depths range from 2.4 to 8.0 mm for 30 to 100 years. Split Set with a whole-length slot along its tube may be subjected to double-sided corrosion whereas the Swellex bolt, which has a closed tube configuration, will probably be subjected to single-sided corrosion. Based on the corrosion allowance stated in Assumption 3.2.3 (i.e., if the total corrosion depth of any steel component exceeds one-tenth of its thickness, the steel component would fail), all steel ground support components except Dywidag #8 threadbar (25.4 mm in diameter) (see Table 1 in Section 6.2.1) made of carbon steel will fail due to humid-air corrosion at 30 years and all will fail at 50 years of service.

Table 2. Estimated Corrosion Depths of Humid-Air Corrosion for Carbon Steel (mm)

	30 years	50 years	75 years	100 years
Single-side	1.2	2.0	3.0	4.0
Double-side	2.4	4.0	6.0	8.0

For ASTM A 242 steel (a HSLA steel), the reduction in thickness due to atmospheric corrosion (i.e., humid-air corrosion) in a rural environment is only 36 μm after 15.5 years (Reference 2.2.3, Table 2, p. 532), of which the average corrosion rate is 2.3 μm/year. By considering this rate to be constant without decay in time (i.e., conservative), the estimated depths of humid-air corrosion for HSLA steel for 30 to 100 years are shown in Table 3. Based on the steel ground support components presented in Table 1 and 10 percent corrosion allowance (Assumption 3.2.3), the following conclusions are made: (a) for Swellex bolts, the Super Swellex bolt (3 mm thick) will not fail for service life up to 100 years, standard Swellex (i.e., EXL Swellex) bolt (2 mm thick) and bearing plate will not fail at 75 years, (b) Split Sets will fail after 50 years, (c) for perforated steel sheets with various thicknesses, the 1.5- and 2-mm ones will fail within 50 years whereas the 3-mm one will fail at 75 years, and (d) Dywidag #8 threadbar, Williams bolt R7X hollow bar, steel channel, steel wire fabric (W4), and lattice girder will not fail at 100 years.

Table 3. Estimated Corrosion Depths of Humid-Air Corrosion for HSLA Steel (mm)

	30 years	50 years	75 years	100 years
Single-side	0.07	0.12	0.17	0.23
Double-side	0.14	0.23	0.35	0.46

Note: the data in the table is for ASTM A 242 steel.

A survey of a series of experimental corrosion studies for stainless steel 316 under various environments indicated that the average atmospheric corrosion rate from 22 measurements for stainless steel 316 is 0.006 μm/year (Reference 2.2.28, Table 2, p. 16). By considering this rate to be constant without decay in time, the estimated depths of humid-air corrosion for stainless steel 316 for 30 to 100 years are shown in Table 4. By comparing the corrosion depths in this table with the thickness data shown in Table 1, none of the steel ground support components made of stainless steel 316 will fail due to humid-air corrosion for service life up to 100 years.

Table 4. Estimated Corrosion Depths of Humid-Air Corrosion for Stainless Steel 316 (mm)

	30 years	50 years	75 years	100 years
Single-side	0.0002	0.0003	0.0005	0.0006
Double-side	0.0004	0.0006	0.0009	0.0012

In summary, with regard to the humid-air corrosion, the following points can be made for steel ground support components listed in Table 1: (a) for carbon steel material, all ground support components except Dywidag #8 threadbar will fail due to humid-air corrosion at 30 years and all will fail at 50 years of service, (b) for HSLA steel material, Dywidag #8 threadbar, Williams bolt R7X hollow bar, steel channels, steel wire fabric (W4), lattice girder, and Super Swellex bolt will not fail for service life of 100 years whereas the others will fail in different times depending on the thickness, and (c) ground support components made of stainless steel 316 steel will not fail for service life of 100 years.

6.6.3.3 Aqueous Corrosion

Although the likelihood of aqueous corrosion to occur is very low during the preclosure period, there is a possibility that aqueous corrosion could occur at some localized surface of some steel ground support, such as the contact points between perforated steel sheets and drift wall or between friction bolts and boreholes, etc.

The estimated penetration depth of carbon steel due to aqueous corrosion was presented in Section 6.3.3 of Reference 2.2.9. Table 5 shows the single-sided corrosion penetration depth for a time period of 30 to 100 years with temperatures ranging from 20 to 200 °C, calculated based on the Equation 2, p. 23 of Reference 2.2.9. As can be seen from this table, the estimated corrosion depths under aqueous corrosion condition are greater than those of humid-air corrosion case (see Table 2) and much greater compared with those of dry oxidation case (see Figure 8). For a period of 30 years, the estimated corrosion depths range from 2 to 6 mm for temperatures of 60 to 100 °C. By comparing these corrosion depths with the thickness data in Table 1 and considering a maximum allowable thickness loss of 10 percent, all steel components in Table 1 would fail at 50 years of service. If using double-sided penetration depths (i.e., twice of the values shown in Table 5), all the steel components in Table 1 will fail in 30 years at temperature of 60 °C.

Table 5. Estimated Corrosion Depths of Aqueous Corrosion for Carbon Steel (mm)

Temp. (°C)	30 years	50 years	75 years	100 years
20	1	1	1	1
60	2	3	4	4
100	6	8	9	11
150	15	19	23	26
200	30	38	46	53

Note: data are for single-sided corrosion depth.

Corrosion rates in the range of about 65 to 125 μm/year were reported for low-alloy steels fully immersed in seawater (Reference 2.2.3, p. 543). Since the environmental conditions in emplacement drifts during preclosure is much benign compared to the condition of full immersion in seawater, a corrosion rate of 65 μm/year is used for evaluating the corrosion potential for low-alloy steel. The corrosion depths based on this corrosion rate are in the same range as those shown in Table 5, therefore, the results of corrosion evaluation for the carbon steel under aqueous condition are in general applicable to those made of low-alloy steel. Note that the results based on this evaluation are conservative, since it is not expected to have an environmental condition in emplacement drifts in which ground support components are fully immersed in groundwater with water condition similar to seawater.

The general corrosion rates for aqueous exposure of stainless steel 316 under seawater and lake water conditions have been measured for various exposure periods. Corrosion rates of 0.16 and 1.25 μm/year were measured for seawater condition and the longest exposure time of 16 years (i.e., more representative than values of very short term measurements) (Reference 2.2.28, Table 3, p. 21). Even though the seawater condition is probably much more severe than that to be expected in emplacement drifts, these corrosion rates are used to evaluate the aqueous corrosion potential for stainless steel 316. By using either of the above corrosion rates, i.e., 0.16 μm/year or, 1.25 μm/year, the corrosion depths for 100 years will be much smaller than the 10% values of those thickness data in Table 1, therefore, all steel ground components made of stainless steel 316 will not fail due to aqueous corrosion in 100 years.

Based on the discussions above, typical ground support components made of carbon steel or HSLA steel would fail within 30 to 50 years whereas stainless steel 316 will not fail for 100 years of service life.

6.6.3.4 Pitting and Crevice Corrosion

Pitting and crevice corrosions are localized forms of attack that result in relatively rapid penetration at small discrete areas. Due to their small sizes and easily hidden by apparently inoffensive corrosion products, both pitting and crevice corrosion often remain undetected until leaks result from penetration of the wall thickness.

Stainless steel alloys in general are more susceptible to both crevice and pitting corrosion than plain carbon steel due to the disruption of the normally protective stainless steel passivation film by chlorine ions (Reference 2.2.41, Appendix 2, p. 12). Therefore, the presence of considerable chloride amount with stagnant liquids is a primary cause for pitting and crevice corrosion.

In order to minimize the susceptible pitting and crevice corrosion, stainless steel 316 is considered, which is less susceptible to localized corrosion in environments that contain Cl^- than stainless steel 304 due to the addition of molybdenum, which enhances the resistance to pitting and crevice corrosion attack (Reference 2.2.28, p. vii).

As discussed in Section 6.6.3.3, the carbon steel will fail within 30 to 50 years under aqueous condition. For pitting corrosion of carbon steel, a pitting factor of four is multiplied to that for the general aqueous corrosion (see Reference 2.2.38, p. 674). Consequently, all carbon steel components would fail in a short period, i.e., about 10 years or less.

The penetration rate for pitting corrosion for stainless steel 316 in a marine environment was calculated to be 0.00167 mm/year based on the average pit depth of 0.025 mm for 15 years of exposure (Reference 2.2.5, Table 13). The total penetration depths based on this rate for 50, 75, and 100 years are calculated to be 0.08, 0.125, and 0.167 mm, respectively. By comparing these results with 10% of thickness data in Table 1, all stainless steel components in Table 1 will not fail at 100 years except perforated steel sheet with 1.5 mm in thickness, which will fail after about 90 years of service. The above result clearly indicates stainless steel 316's superior performance against pitting corrosion.

The crevice corrosion rate for stainless steel 316 exposed to seawater was calculated to be 0.0026 mm/year based on a weight loss of 8.96 mg/cm^2 (Reference 2.2.39, Figure 5.10, p. 190). By using this penetration rate for crevice corrosion and no decay in rate with time for conservatism, the penetration depths for 50, 75, and 100 years were calculated to be 0.13, 0.195 and 0.26 mm, respectively. By comparing these values with 10% of thickness data in Table 1, it indicates that all stainless steel components except 1.5 mm thick perforated sheet will not fail in 75 years and most of stainless steel components except Split Set (2.3 mm thick), Swellex bolt (2 mm thick), and perforated steel sheet with 2 or 1.5 mm of thickness will not fail for a service life of 100 years. Note that stainless steel heavy-duty wire mesh (W4) (5.7 mm thick) is designed to be used in emplacement drift turnouts (see Section 6.5.2), which will not fail in 100 years of service.

It should be noted that the corrosion rates for stainless steel 316 discussed previously were mainly obtained from ambient atmospheric and ocean environmental conditions. Based on the discussion in Section 6.4.4.4 of Reference 2.2.10, the potential effect of higher temperature on general and localized corrosion for stainless steel 316 is not considered significant for the temperature ranges to be expected in emplacement and non-emplacement drifts.

6.6.3.5 Stress Corrosion Cracking

Stress corrosion cracking (SCC) refers to cracking caused by the simultaneous presence of tensile stress and a specific corrosive medium. During stress corrosion cracking, the metal or alloy is virtually unattacked over most of its surface, while fine cracks progress through it (Reference 2.2.27, p. 109). In a most recent ground control calculation, the maximum axial bolt forces in Swellex-type rock bolts installed in emplacement drifts and in fully grouted rock bolts in exhaust mains were calculated to be about 87 and 99 kN, respectively, under the combined in situ, thermal and seismic loads (Reference 2.2.20, Section 6.7). Since these maximum tensile bolt forces are much smaller than the corresponding limit axial bolt forces, i.e., 298 and 264 kN respectively, (Reference 2.2.20, Tables 6-6 and 6-7) for stainless steel and carbon steel bolts, the SCC for stainless steel friction-type rock blots and fully grouted rock bolts of carbon steel will not occur from the stress viewpoint. It was also indicated in Section 6.4.4.5 of Reference 2.2.10 that, for stainless steel 316, the temperature to initiate cracking is above 100 ^{o}C. As discussed in Section 6.4.1, the maximum drift wall temperature in the ventilated emplacement drift is about 100 ^{o}C and the temperature is 10 to 20 ^{o}C lower for rock mass 1 to 3 m inside the drift wall. It should also be pointed out that in order to have SSC to occur to steel rock bolts, it must have an aqueous environment containing chloride, which is generally not expected to exist for friction-type rock bolts at emplacement drifts and fully grouted rock bolts in non-emplacement openings during the preclosure period. In addition, for fully grouted rock bolts, the cement grout acts not only as a secure sealant to prevent water from contacting the bolt, but also inhibiting the steel bolt from corrosion due to the alkaline environment created by cement grout.

Therefore, based on the tensile stress level at the bolts, temperature and ground water conditions in the repository openings, it is not expected that SCC will occur to steel rock bolts during the preclosure.

6.6.3.6 Hydrogen Embrittlement

Exact mechanism for hydrogen embrittlement has not yet been determined. It is known that in some metals hydrogen reacts to form brittle corrosion products. The phenomenon common to all forms of hydrogen embrittlement is a loss of ductility in the metal or alloy. When sufficiently high external or residual stress is present, loss of ductility due to hydrogen embrittlement can result in failure (Reference 2.2.41, Appendix 2, p. 15).

Failure analysis was performed on rock bolts that failed in service at the WIPP site. The rock bolt material was AISI 1040 grade plain carbon steel. The analysis results indicated that fracture was assisted by the major environmental conditions that existed at the thread root where cracks occurred, which include moisture, salt, low [O_2] at thread root behind the salt and high [O_2] elsewhere near the thread root, stress concentration at thread root, and probable acid solution, etc (Reference 2.2.32, p. 33). However, most of these conditions do not exist at the emplacement drift environment in which friction-type rock bolts are to be installed: (a) the host rock is tuff not salt, (b) the pH of the ground water is 8.07 (Section 6.4.3), which is nearly neutral, not acidic, (c) there is no thread in the friction-type bolt, and (d) no stress concentration at certain locations since stresses are generally distributed along the whole length of bolts. For rock bolts made of stainless steels, ductility and toughness of most stainless steels are higher than the same properties of carbon steels. For fully grouted rock bolts installed in non-emplacement openings, all the above conditions except condition (c) also apply. In addition, the completely filled cement grout will prevent bolt from corrosion and minimize any liquid flow. Therefore, the potential impact of hydrogen embrittlement on friction-type rock bolts or fully grouted bolts is insignificant.

6.6.3.7 Microbiologically Influenced Corrosion

Microbes can thrive over a wide range of pH, under high hydrostatic pressures, in highly saline conditions, and in high radiation conditions that would normally be lethal to humans. Microbes live in nutrient starved environments and can be expected to continue to live even if the nutrient supply of introduced repository materials becomes exhausted. Microbes can alter their environment by creating biofilms. Biofilms make it possible for anaerobic microbes to live in aerobic conditions by isolating them from the normal atmospheric conditions in which they would not survive. Biofilms also initiate pitting corrosion on metals via microbiologically influenced corrosion (MIC).

As discussed in Section 6.4.4.7 of Reference 2.2.10, microbes are able to grow and produce their metabolic byproducts when the temperature is <120 ^{o}C and the water activity is > 0.90, i.e., RH > 90%. As discussed in Sections 6.4.1 and 6.4.2, the peak temperature in the emplacement drifts during the preclosure period is 103 ^{o}C whereas the RH inside the drifts is low, i.e., much lower than 90%, the potential impact for MIC on steel supports inside the drifts will be insignificant below a RH of 90%. However, for the portions of rock bolts deep inside the boreholes, since the RH values may be higher than 90% (see Section 6.4.2), there is a potential for microbial activity in these locations during the preclosure period.

Corrosion rates for carbon steel 1020 and stainless steel 304 by Yucca Mountain microbes have been studied and listed as 8.8 and 0.035 μm/year, respectively (Reference 2.2.31). Since the composition of stainless steel 316 is similar to that of 304, it is expected that the MIC on stainless steel 316 will have similar effect as that on stainless steel 304. Based on these corrosion rates, all carbon steel components except Dywidag #8 threadbar, Williams bolt R7X hollow bar, and lattice girder shown in Table 1 will fail in 100 years whereas the ground support components made of stainless steel 316 will not fail in 100 years. Note that fully grouted rock bolts are the major ground support system in the non-emplacement drifts and the steel bolts are made of carbon steel with the bolt configuration of either solid bar (similar to Dywidag bar) or hollow bar (similar to Williams bolt). Based on the corrosion depth, these bolts with thickness data shown in Table 1 would not fail in 100 years.

Therefore, the MIC effect on friction-type rock bolts made of stainless steel 316 in emplacement drifts and fully grouted rock bolts made of carbon steel in non-emplacement drifts is insignificant during the preclosure.

6.7 OBSERVATIONS OF GROUND SUPPORT PERFORMANCE

6.7.1 ESF and Surface Excavation

This section presents the results of observations on corrosion of steel ground support components obtained from the existing ESF and surface excavations, the details of which are presented in a study *Evaluation of ESF Installed Ground Support* (Reference 2.2.19, Section 7). It should be noted that although the field observations on corrosion of steel ground support components are limited, they do provide valuable on-site performance information and some insights for evaluating the corrosion potential of steel ground support components of proposed for the repository openings.

Figure 9 (Reference 2.2.19, Figure 7-7) shows a Swellex rock bolt with WWF at the South Portal about 9 years after installation. As can be seen clearly, this figure shows general overall corrosion on the surface of bolt head, bearing plate and WWF after they were exposed to the atmospheric condition for a period of approximately 9 years. This is a clear illustration of carbon steel subjected to humid-air corrosion.

Figure 10 (Reference 2.2.19, Figure 7-27) shows a portion of tunnel inside the ESF Main Drift, in which Swellex rock bolts, WWF, steel channels, straps and part of steel set were installed for approximately 10 years. It can be seen from this figure that there is no obvious sign of corrosion for all the exposed carbon steel components. It appears that the general corrosions such as humid-air and aqueous corrosion has not occurred to a noticeable stage for a period of approximately 10 years in this underground opening. It is probably due to the low relative humidity inside the tunnel caused by the surrounding dry rock mass and continuous ventilation.

Figure 11 (Reference 2.2.19, Figure 7-61) is a close-up view of intersection at North Ramp and ECRB cross drift showing a thin layer of shotcrete applied over WWF and rock bolts after about 7.5 years of service. No obvious corrosion in steel components was observed in this photo. Note that the shotcrete layer is relatively thin that it is insufficient to cover the entire underlying wire mesh (see some partially covered wire mesh pointed by arrows shown in the photo). Nevertheless, it does indicate that shotcrete provides some protection and stabilization of the opening and prevent it from the ingress of moisture or water contacting the underlying steel ground support components.

Figure 12 (Reference 2.2.19, Figure 7-10) shows a series of photos presenting sections of a 10-foot Williams rock bolt recovered from the North Ramp about 9 years installed in the lithophysal rock, i.e., Tptpul lithostratigraphic unit. This figure shows various degrees of corrosion in three sections of rock bolt. In the first two and half feet section of the bolt at the proximal end including the face plate and nut, no corrosion was observed except some stains on the plate, which were probably occurred prior to installation underground. From the end of the first section to the thrust ring of the bolt at 114 inches from the open end, an overall moderate corrosion was evident. From the thrust ring to the distal end of the bolt with a length of 4 inches, more severe corrosion was observed. It should be noted that this bolt was not grouted in the bolthole. The different degrees of corrosion on the bolt clearly indicates the different RH levels, i.e., very low RH at the first two to three feet into the borehole, moderate RH level, probably about 60 to 85% at the central part, and very high RH, i.e., greater than 90% at the distal end beyond the thrust ring, which was tightly contacted with the surrounding rock, thus blocking the moisture at the end of the borehole. This RH distribution along the borehole confirmed the RH discussion in Section 6.4.2. It also indicates the importance of the grout for protecting the steel bolt from corrosion since there was no grout found in this borehole. This confirms the current design on rock bolt system to be used in the non-emplacement drifts, i.e., fully grouted rock bolts.

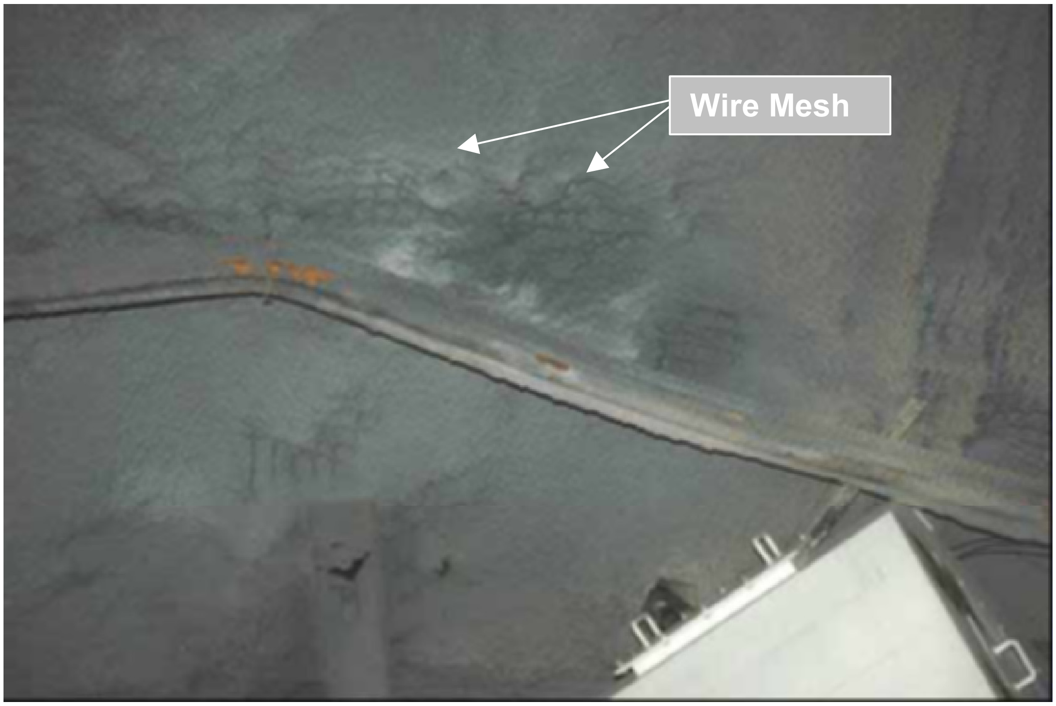
Figure 13 (Reference 2.2.19, Figure 7-15) shows a series of photographs of a two-foot carbon steel Super Swellex rock bolt section recovered from the North Ramp/ECRB intersection after installation in the lithophysal rock (Tptpul unit) for about two years. The bolt was removed during the excavation of the intersection. General corrosion was observed on various parts of the bolt section. This figure also showed that the bolt was expanded a little more in several locations where the voids of the lithophysal rock might be located. The observation of corrosion on this bolt confirms the current design on ground support materials to be used in the emplacement drifts, i.e., stainless steel (316 equivalent or better in terms of corrosion control) friction-type rock bolts, such as Super Swellex rock bolts. The expanded portion of the bolt also confirms the advantage of using this type of bolt to adapt its shape to the irregularities of the borehole, such as the voids in the lithophysal rock.

Source: Reference 2.2.19, Figure 7-7

Figure 9. Swellex Rock Bolt and WWF at the South Portal after about 9 years of installation

Source: Reference 2.2.19, Figure 7-27

Figure 10. Swellex Rock Bolts, WWF, Steel Channel, Straps and Steel Set at the Main Drift



Source: Reference 2.2.19, Figure 7-61

Figure 11. North Ramp/ECRB Intersection Showing Thin Layer of Shotcrete Applied Over WWF and Rockbolts after Installation of about 7.5 years

Source: Reference 2.2.19, Figure 7-10

Figure 12. Sections of Williams Rockbolt Recovered from North Ramp after about 9 Years in the Ground

Source: Reference 2.2.19, Figure 7-15

Figure 13. A series of Photos of the Carbon Steel Super Swellex Rock Bolt Section Recovered from North Ramp/ECRB Intersection after Installation for about Two Years

6.7.2 Drift Scale Test

Drift Scale Test (DST) is a full-scale in situ thermal test within Yucca Mountain to: (a) develop and enhance a better understanding of the in situ rock thermal, mechanical, hydrological, and chemical processes, as well as the interactions between those processes when the rock mass is subjected to elevated heating and cooling, (b) gather information on the performance of the metal components of the waste packages through use of surrogate containers, and (c) demonstrate the performance of ground support systems subjected to sustained high temperature first and followed by turning off the heat and entering a naturally cooling period (Reference 2.2.19, Section 7.2.1.4).

The heated drift of the DST is 5 m in diameter and 47.5 m in length, with one portion of the drift is supported with CIP concrete lining and the rest is supported with friction-type rock bolts and wire mesh made of carbon steel (Figure 14 (Reference 2.2.19, Figure 7-33)). The heaters in the heated drift were turned on December 31, 1997, and the heat output was controlled to sustain a nearly steady drift temperature of 200 °C for almost four years. Heaters were turned off on January 14, 2002. It took another four years before the rock surrounding the drift cooled down to 40 ^{o}C, such that human reentry into the drift on April 3, 2006 was possible.

Notice that the DST heated drift resembles an emplacement drift under off-normal temperature scenarios because of the high temperature of 200 °C applied during the testing. Figure 15 (Reference 2.2.19, Figure 7-35(b)) shows a roof section of the drift in which thin rock flakes, ranging in thickness from very thin to less than approximately two inches, were formed in the roof parallel to the tunnel wall surface and were believed to result from high thermally induced stresses. Some bolt sections protruding into the drift show stains, which most likely can be linked to rock bolt installation and a relatively humid environment prior to heating. Figure 16 (Reference 2.2.19, Figure 7-39) depicts a portion of DST Heated Drift, in which concrete lining, Swellex rock bolts, and WWF had subjected to approximately 8 years of heating and cooling. No obvious sign of corrosion was observed on the exposed steel components except the bearing plate of one bolt at the lower right corner showing some stain. Observations performed during the heating period did not show water originating from the rock strata. This would indicate that the increasing temperature yielded an environment less aggressive that slowed or stopped the corrosion process substantially (Reference 2.2.19, Section 7.2.1.4). Observation results confirm that the relative humidity in the emplacement drifts will be very low due to the heat generated from waste packages, which will prevent or minimize humid-air or aqueous corrosion of steel ground support components during preclosure.

The DST heated drift is excavated entirely in the nonlithophysal rock, i.e., the Tptpmn lithostratigraphic unit. The ground support systems includes the use of Swellex bolts and wire mesh (all made of carbon steel) that are functionally similar to those proposed for emplacement drift ground support system (note that wire mesh is for initial ground support) but of materials less resistant to corrosion. Visual observations from the DST heated drift indicate that maintenance needs for emplacement drifts and their ground support systems under normal operational conditions would be minimal, particularly for drifts excavated in the nonlithophysal rock. Even when the emplacement drift temperature approaches what is considered to be the maximum temperature limit prior to closure (i.e., 200 ^{o}C), maintenance or repair tasks, if any, would be minimal as well. However, it should be pointed out that the heating period at heated drift is only about 4 years, which is much shorter compared to 100 years of service life for the emplacement drifts. Also, the majority of emplacement drifts will be located in the lithophysal rock, i.e., the Tptpll lithostratigraphic unit, in which the porosity is higher and the strength is lower than that of the nonlithophysal rock. This indicates a need to conduct the corrosion tests and pull-out tests on rock bolts to be installed in the RHH host rock, which will be discussed in Section 6.8.

Source: Reference 2.2.19, Figure 7-33

Figure 14. Drift Scale Test in Operational Stage Showing Canisters and Ground Support System Including WWF, Rock Bolts and Concrete Lining at end

Source: Reference 2.2.19, Figure 7-35(b)

Figure 15. DST Heated Drift – Loose Rock Fragments Retained by Wire Mesh and Rock Bolts

Source: Reference 2.2.19, Figure 7-39

Figure 16. DST Heated Drift – Drift Face with Concrete Lining, Swellex Rock Bolts and WWF

6.8 GROUND SUPPORT TESTING

In order to ensure that the ground support materials will function without failure due to corrosion within the 100-year service life, there is a strong need to conduct corrosion testing for the proposed ground support materials. Until present, no corrosion testing for ground support materials made of stainless steel 316 (equivalent or better in terms of corrosion resistance) has been performed in the expected groundwater in emplacement drifts. Therefore, it is very important to conduct corrosion tests based on proper ASTM standards and perform on selected specimens from candidate steel ground support materials exposed to the ground water condition to be expected in the emplacement and non-emplacement drift environment during the preclosure period.

In addition to corrosion testing, a limited number of in situ pull-out tests on friction-type rock bolts and fully grouted rock bolts will be proposed to help determine the anchorage capacity and bolt behavior, and grout integrity, especially in the lithophysal rock. Overcoring installed friction-type rock bolts and examining the split overcores will provide information on how a friction-type rock bolt interacts with lithophysal cavities encountered by a borehole, and also reveal whether there are localized areas along the bolt where stress corrosion cracking (SCC) is initiated. Overcoring installed fully grouted rock bolts and examining the split overcores will provide information on how well the cement grout binds a bolt to the rock, the integrity of the grout along the whole bolt length, and signs of corrosion of the bolt.

The testing program will be initiated by the Project’s engineering design organizations, and coordinated among the interested or impacted project organizations.

7. RESULTS AND CONCLUSIONS

The longevity calculation, *Longevity of Emplacement Drift Ground Support Materials for LA* (Reference 2.2.10), prepared to support the License Application (LA) design, was completed in September 2003. Although the ground support system for emplacement drifts has not changed, the underground layout configuration and ground support systems for non-emplacement drifts have undergone some modifications since then.

In this calculation, the longevity of steel ground support components in the repository openings for LA has been reevaluated based on the updated subsurface environmental conditions and recent evaluations on ESF ground support systems.

It should be pointed out that the conclusions made in this calculation are preliminary in nature. The output information presented in this calculation is based on published data, project and external documents, assumptions, bounding scenarios for conservatism, and practical considerations. As the design of ground support systems progresses, the information will be updated as necessary. Therefore, outputs/conclusions from this calculation cannot be used as input for documents supporting procurement, fabrication, or construction.

Based on the discussions in the previous sections, the results and conclusions of this calculation are summarized as follows:

Repository Opening Environmental Conditions

- The repository design ensures that the emplacement drift wall temperature during normal or off-normal operations is less than 200 ^{o}C prior to permanent closure. The highest temperature at the emplacement drift wall based on the higher thermal load of 2.0 kW/m is about 103 °C. The temperatures in the non-emplacement drifts are lower than those of the adjacent emplacement drifts since there is no heat source in them.
- The in-drift relative humidity in the emplacement drifts is about 10 percent and lower based on continuous ventilation during the preclosure. The RH values in exhaust mains will be higher than or equal to those in emplacement drifts and lower than those in access mains. The relative humidity inside the borehole is high, especially at the deeper portion near the end of boreholes, where the RH value is expected to be greater than 90%.
- The most important characteristics of the infiltrating water at or above the repository host horizon related to steel corrosion are the concentrations of chloride, sulfate, bicarbonate, and pH with average values of 90, 86, and 139 mg/l, and 8.07, respectively.
- The cumulative fast neutron fluence at the emplacement drift wall is 1.1×10^{13} n/cm^2 over a period of 300 years of waste emplacement. The cumulative gamma dose to the ground support material is about 66 mega-rads for 300 years of waste emplacement.

Longevity Reevaluation of Steel Ground Support Components

The longevity of steel ground support components is dependent on corrosion rates and service life. Potential corrosion on steel components (carbon, HSLA, and stainless steel) expected from updated environmental conditions was evaluated and is summarized by corrosion types below.

Dry Oxidation

The impact of dry oxidation on the performance of carbon steel, HSLA steel, and stainless steel is insignificant or negligible. None of steel ground support components made of carbon steel, HSLA steel, or stainless steel will fail due to corrosion by dry oxidation.

Humid-Air Corrosion

- Carbon steel: all ground support components except Dywidag #8 threadbar will fail after service life of 30 years due to humid-air corrosion and all will fail at 50 years of service.
- HSLA steel: Dywidag #8 threadbar, Williams bolt R7X hollow bar, steel channels, steel wire fabric (W4), lattice girder, and Super Swellex bolt will not fail for service life of 100 years whereas the others will fail in different times depending on the thickness.
- Stainless steel: all ground support components made of stainless steel 316 steel will provide a service life of 100 years without failure.

Aqueous Corrosion

Typical ground support components made of carbon steel or HSLA steel would fail within 30 to 50 years whereas stainless steel 316 will not fail during 100 years of service life.

Pitting and Crevice Corrosion

Carbon steel components fail in a short period (about 10 years or less) whereas stainless steel 316 indicates superior performance against pitting and crevice corrosion. Super Swellex bolts and heavy-duty WWF made of stainless steel 316 will not fail in 100 years. The potential effect of higher temperature on general and localized corrosion for stainless steel 316 is insignificant.

Stress Corrosion Cracking

Based on the stress level in bolts and the temperature and ground water conditions in repository openings, it is not expected that SCC will occur to friction-type rock bolts in emplacement drifts and also will not occur to fully grouted rock bolts in non-emplacement drifts.

Hydrogen Embrittlement

The potential impact of hydrogen embrittlement on friction-type rock bolts or fully grouted rock bolts is insignificant.

Microbiologically Influenced Corrosion

The effect of microbiologically influenced corrosion on friction-type bolts made of stainless steel 316 or fully grouted rock bolts made of carbon steel is expected to be insignificant during the preclosure.

Observations of Ground Support Performance and Testing

Observations of corrosion on steel ground support components obtained from the existing ESF (portals and underground) as well as the Drift Scale Test provide valuable on-site performance information and some insights useful for evaluating the potential for corrosion of steel ground support components proposed for repository openings. Major findings are summarized as follows:

ESF and Surface Excavation

- A Swellex rock bolt with WWF at the South Portal shows general corrosion on the surface of bolt head, bearing plate and WWF after they were exposed to atmospheric conditions for a period of approximately 9 years, which is a clear illustration of humid-air corrosion.
- A portion of tunnel inside the ESF Main Drift shows no obvious signs of corrosion for the exposed carbon steel components about 10 years after installation. It appears that the general corrosion has not occurred to a noticeable stage in this underground location. This is probably due to the low relative humidity inside the tunnel caused by the surrounding dry rock mass and continuous ventilation, which supports our discussion on low humidity in the drift due to the continuous ventilation.
- The close-up view of the intersection at the North Ramp and ECRB cross drift where a thin layer of shotcrete applied over WWF and rock bolts after about 7.5 years of service shows no obvious corrosion in steel components. This view indicates that shotcrete does provide some protection and stabilization to the opening. The shotcrete prevents the ingress of moisture or from water contacting the underlying steel ground support components.
- A 10-foot Williams rock bolt recovered from the North Ramp shows different degrees of corrosion on the bolt 9 year after installation indicates the RH at different depths into the lithophysal rock. This RH distribution along the borehole confirms the RH discussion in Section 6.4.2. It also highlights the importance of grout for protecting steel bolt from corrosion. There was no grout found in this borehole. This confirms the recommendations of fully grouted rock bolts to be used in non-emplacement drifts in the current ground support design.
- A two-foot carbon steel Super Swellex rock bolt section recovered from the North Ramp/ECRB intersection shows general corrosion on various parts of the bolt sections about two years after installation in lithophysal rock. The bolt was also expanded more in locations corresponding to voids in the lithophysal rock. The observation of this bolt confirms the current design on stainless steel friction-type rock bolts to be used for emplacement drifts.

Drift Scale Test

A portion of DST Heated Drift, in which concrete lining, Swellex rock bolts, and WWF were subjected to 8 years of heating and cooling, shows no sign of corrosion on exposed steel components except the bearing plate of one bolt showing stain. Observations performed during the heating period did not show water originating from the rock strata. This would indicate that the increasing temperature yielded an environment less aggressive that slowed or stopped the corrosion process substantially. Observation results confirm that the relative humidity in the emplacement drifts will be very low due to the heat generated from waste packages, which will prevent or minimize humid-air or aqueous corrosion of steel ground support components during preclosure.

Ground Support Testing

In order to ensure that the ground support materials will function without failure due to corrosion within the 100-year service life, there is a strong need to conduct corrosion testing for the proposed ground support materials. Corrosion testing for ground support materials made of stainless steel 316 (equivalent or better in terms of corrosion resistance) has not been performed by the Project in expected environmental conditions. It is imperative that activities be planned to conduct corrosion tests in the future. These tests will be based on applicable ASTM standards and performed on selected specimens from candidate steel ground support materials.

In addition to corrosion testing, a limited number of in situ pull-out tests on friction-type rock bolts and fully grouted rock bolts will be proposed to help determine the anchorage capacity, bolt behavior, and grout integrity, especially in the lithophysal rock. Overcoring friction-type rock bolts and examining the split overcore will provide information on how a friction-type rock bolt interacts with lithophysal cavities encountered by a borehole, and also reveal whether there are localized areas along the bolt where stress corrosion cracking is initiated. Overcoring fully grouted rock bolts and examining the split overcore will provide information on how well the cement grout binds bolt to the rock, the integrity of the grout along the whole bolt length, and signs of corrosion of the bolt.

The testing program will be initiated by the Project's engineering design organizations, and coordinated among the interested or impacted project organizations. The testing results will be considered in finalizing ground support drawings, specifications, and maintenance plans.

In conclusion, the steel ground support components in repository openings based on the current repository design for LA have been evaluated. Potential types of corrosion on steel components in the repository environment including dry oxidation, humid-air corrosion, aqueous corrosion, pitting/crevice corrosion, stress corrosion cracking, hydrogen embrittlement, and microbiologically influenced corrosion were evaluated. Based on the results of this reevaluation, the conclusions made in the longevity calculation *Longevity of Emplacement Drift Ground Support Materials for LA* (Reference 2.2.10) remain unchanged, i.e., the steel ground support materials to be used in emplacement drifts for a service life of 100 years during the preclosure need to be made of stainless steel 316 (equivalent or better) from the viewpoint of corrosion control. Fully grouted rock bolts need to be used in all of non-emplacement drifts with the exception of stainless steel friction-type rock bolts in emplacement drift turnouts to ensure the longevity for the intended service life. The observations on corrosion of steel ground support components obtained from the existing ESF, surface excavations, and Drift Scale Test provide valuable on-site performance information and insights for evaluating the corrosion potential of steel ground support components proposed for the repository openings. ESF observation results confirm the current ground support systems and steel ground support materials to be used for repository openings for LA. Observation results also highlight the strong need to conduct corrosion testing for the proposed ground support materials in emplacement drifts and inaccessible non-emplacement drifts in order to ensure that ground support materials will function without failure due to corrosion within the 100-year service life during the preclosure period.