ENG.20030922.0004

OCRWM	**DESIGN CALCULATION OR ANALYSIS COVER SHEET**	1. QA: QA 2. Page 1 of 45

3. System Subsurface Engineering Barrier System	4. Document Identifier 800-K0C-TEG0-01200-000-00A

5. Title
Longevity of Emplacement Drift Ground Support Materials for LA

6. Group
Facilities Design Department/Geotechnical Group

7. Document Status Designation
☒ Preliminary ☐ Final ☐ Cancelled

8. Notes/Comments

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1) ECN-001, DATED 08/15/2005

Attachments	Total Number of Pages
None	N/A

RECORD OF REVISIONS

9. No.	10. Reason For Revision	11. Total # of Pgs.	12. Last Pg. #	13. Originator (Print/Sign/Date)	14. Checker (Print/Sign/Date)	15. QER (Print/Sign/Date)	16. Approved/Accepted (Print/Sign)	17. Date
00A	Initial Issue	45	45	David H. Tang David H. Tang 9/16/03	Jay B. Cho 9/16/03	William F. Holub Larry Abernathy For 9/16/03	Fei Duan F Duan	9/16/03

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ACRONYMS AND ABBREVIATIONS

AISI	American Iron and Steel Institute
AMR	analysis model report
ASM	American Society for Metals
ASTM	American Society for Testing and Materials
BSC	Bechtel SAIC Company, LLC
CFR	Code of Federal Regulations
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operating Contractor
DOE	U.S. Department of Energy
DST	Drift Scale Test
DTN	data tracking number
ESF	Exploratory Studies Facility
ECRB	Enhanced Characterization of the Repository Block (drift)
GPa	gigapascal
HSLA	high-strength low-alloy
J	joule
ksi	kips per square inch
LA	License Application
LC	localized corrosion
MIC	microbiologically influenced corrosion
MPa	megapascal
n	neutron
QARD	Quality Assurance Requirements and Description
QL	quality level
RH	relative humidity
SAW	simulated acidified well
SCC	stress corrosion cracking
SCW	simulated concentrated well
SR	Site Recommendation

THC	thermal-hydrological-chemical
μm	micrometer
UZ	unsaturated zone
WIPP	Waste Isolation Pilot Plant
WP	waste package
YMP	Yucca Mountain Project

1. PURPOSE

The purpose of this calculation is to evaluate the longevity of emplacement drift ground support materials that will function throughout the preclosure period of a repository at Yucca Mountain. This calculation will be used to support the License Application (LA) design.

The previous longevity analysis, *Longevity of Emplacement Drift Ground Support Materials* (BSC 2001a), was prepared for the Site Recommendation (SR) design. This calculation is prepared based on the current ground support design for LA.

The scope of this calculation consists of the following tasks:

- Review the previous longevity analysis, *Longevity of Emplacement Drift Ground Support Materials* (BSC 2001a).
- Identify the emplacement drift environmental conditions relevant to current ground support materials.
- Provide mechanical and thermal properties of steel ground support components.
- Evaluate impacts of temperature and radiation effects on mechanical and thermal properties of steel components.
- Evaluate corrosion potential of steel components in the emplacement drift environment.

2. QUALITY ASSURANCE

The calculation is developed in accordance with AP-3.12Q, *Design Calculations and Analyses*. The ground control system in emplacement drifts is classified as Quality Level 2 (QL2) (YMP 2001, p. A-4). Therefore, this calculation is subjected to the requirements of the Quality Assurance Requirements and Description (QARD) (DOE 2003).

3. COMPUTER SOFTWARE AND MODEL USAGE

There was no computer software, nor model, other than Microsoft Word and the Excel spreadsheet, used in this calculation.

Microsoft Excel 97 spreadsheet software was used to perform the arithmetic calculations and for preparing the figures. Only standard functions of Excel were used in the calculations and the results are not dependent on the users. Spreadsheet software, such as Excel, are considered to be controlled under the Software Configuration Management Systems and are not required to be qualified or documented under the AP-SI.1Q procedure, *Software Management*.

4. INPUTS

4.1 DATA AND PARAMETERS

4.1.1 Strength and Modulus of Elasticity of Steel

The yield point of structural steel (i.e., carbon steel and low-alloy steel) generally decreases linearly from its value at 20 °C to about 80 percent of that value at 430 °C, and to about 70 percent at 540 °C (Merritt 1983, p. 9-67). The yield strength of ASTM A 36 steel at room temperature is 36 ksi (250 MPa), thus it is about 28.8 and 25.2 ksi (200 and 175 MPa) at 430 °C and 540 °C, respectively. For low-alloy steel, the yield strength of ASTM A 588 steel at room temperature is 50 ksi (345 MPa) and it is about 40 and 35 ksi (276 and 242 MPa) at 430 °C and 540 °C, respectively. The modulus of elasticity of structural steel decreases linearly from 200 GPa (29,000 ksi) at room temperature (i.e., about 20 °C) to about 172 GPa (25,000 ksi) at 480 °C (Merritt 1983, p. 9-67).

Strength of most stainless steels can be raised by cold work. The yield strength of 316 is 30 ksi (205 MPa) in hot-finished condition but 45 ksi (310 MPa) in cold-finished condition for up to ½ in. (12.7 mm) thick. The yield strength of 316L is 25 ksi (170 MPa) in hot-finished condition but 45 ksi (310 MPa) in cold-finished condition for up to ½ in. (12.7 mm) thick (ASTM A 276). The modulus of elasticity of stainless steel is similar to structural carbon steel. For example, stainless steel 316 is 193 GPa (28,000 ksi) (ASM International 1990, Table 21, p. 871).

4.1.2 Toughness of Steel

At 200 °C the notch toughness (in terms of impact energy) of steel with 0.11-percent carbon is about six times that of steel with 0.80-percent carbon. At 100 °C the notch toughness (in terms of impact energy) of a steel with 0.11-percent carbon is about 20 times that of a steel with 0.80-percent carbon. At 70 °C the notch toughness (in terms of impact energy) of steel with 0.11-percent carbon is about 25 times that of steel with 0.80-percent carbon. The Charpy impact energy for carbon steel with 0.31- and 0.11-percent carbon is about 50 and 200 J, respectively, at about 25 °C (ASM International 1990, p. 739, Fig. 9).

Austenitic stainless steels have good notched-bar impact resistance, with Charpy impact energies of 135 J or greater are typical of all types at room temperature (ASM International 1990, p. 859).

4.1.3 Thermal Expansion Coefficient

Structural steels have a range of coefficients of thermal expansion varying from about 11.24×10^{-6}/°C at 25 °C to 11.52×10^{-6}/°C at 70 °C, 11.71×10^{-6}/°C at 100 °C and 12.32×10^{-6}/°C at 200 °C (Merritt 1983, p. 9-67, Eq. 9-75).

The mean thermal expansion coefficients of the stainless steel 316 is 15.9 x 10^{-6}/°C at 0 °C to 100 °C and 16.2 x 10^{-6}/°C at 0 °C to 315 °C (ASM International 1990, Table 21, p. 871).

The thermal expansion coefficients of the TSw2 rock mass vary from 7.50 x 10^{-6}/°C at 25-50 °C to 8.80 x 10^{-6}/°C at 50-75 °C, 9.06 x 10^{-6}/°C at 75-100 °C, and 13.77 x 10^{-6}/°C at 175-200 °C for the heating cycle (BSC 2003g, Table 5-4, p. 11).

4.1.4 Thermal Conductivity and Specific Heat of Steel

The thermal conductivity of carbon steel (grade 1025) for temperatures at 0 °C, 100 °C and 200 °C are 51.9, 51.1 and 49 W/m·K, respectively (ASM International 1990, p. 197). The mean specific heat of carbon steel (grade 1025) for a temperature range of 50 °C to 100 °C and 150 °C to 200 °C are 486 and 519 J/kg·K, respectively (ASM International 1990, p. 198).

The thermal conductivity of stainless steel 316 at 100 °C is 16.2 W/m·K (ASM International 1990, Table 21, p. 871). The specific heat of stainless steel 316 is 500 J/kg·K (ASM International 1990, Table 21, p. 871).

4.1.5 Nominal Thickness and Width Data of Steel Ground Support Components

Table 1. Nominal Thickness and Width of Steel Ground Support Components

Type	Member Designation	Width (cm)	Thickness (mm)	Source of Data
Rock Bolts	Split Set (tube)	-	2.3	Peng 1986, p. 228
	Swellex bolt (tube)	-	2[a] 3[b]	Atlas Copco, p. 10 of Swellex Catalog
Bearing Plates	Bearing plate	15 x 15[c] 15 x 15	- 4	See Note c See Note d
Perforated Steel Sheets	Bernold Sheet	108 x 120	1.5, 2.0, 3.0	Michel 1999, p. 11

Note: [a] EXL Swellex bolt. [b] Super Swellex bolt. [c] Atlas Copco, Swellex Face plate catalog. [d] International Rollforms, p. 9.

4.2 CRITERIA

4.2.1 The ground control system shall be designed to maintain adequate operating envelopes through permanent closure for the emplacement drifts (Minwalla 2003, Section 4.5.2.1, p. 126).

4.2.2 The ground support system shall use materials having acceptable long-term effects on waste isolation (Minwalla 2003, Section 4.5.2.2, p. 129).

4.2.3 The repository must be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated (10 CFR 63 2002, Section 63.111(e)(1)).

4.2.4 Ground support systems in emplacement drifts are required to have a minimum of 75 years with no or minimal maintenance and shall maintain its functionality during the operational life of up to 300 years after final waste emplacement with an appropriate maintenance and monitoring program (Duan and Board 2003, p. 5).

4.2.5 The ground control system for emplacement drifts shall be designed to function during the preclosure period without planned maintenance (Minwalla 2003, Section 4.5.2.6, p. 131).

4.2.6 The repository design shall ensure that the maximum emplacement drift wall temperature, shall not exceed 96 °C during preclosure operations, nor exceed 200 °C during post-closure (Williams 2003, Table 1).

4.2.7 The ground control system shall accommodate geologic mapping of emplacement drifts (Minwalla 2003, Section 4.5.2.1, p. 127).

4.3 CODES AND STANDARDS

Codes and standards applicable to this calculation are listed in the following:

4.3.1 American Society for Testing and Materials (ASTM)

ASTM A 36/ A 36M	*Standard Specification for Carbon Structural Steel*
ASTM A 240/ A 240M	*Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications*
ASTM A 242/ A 242M	*Standard Specification for High-Strength Low-Alloy Structural Steel*
ASTM A 276	*Standard Specification for Stainless Steel Bars and Shapes*
ASTM A 588/ A 588M	*Standard Specification for High-Strength Low-Alloy Structural Steel with 50 ksi [345MPa] Minimum Yield Point to 4–in. [100–mm] Thick*
ASTM F 432	*Standard Specification for Roof and Rock Bolts and Accessories*

5. ASSUMPTIONS

The following assumptions are made in this calculation:

5.1 The highest percolation flux at the repository horizon at Yucca Mountain during the preclosure period is 15 mm/year. Used in Section 6.2.3.

Rationale: Based on Fig. 6.6-1, of an analysis and model report (AMR) document *UZ Flow Models and Submodels* (BSC 2003d, p. 96) the assumed value is the upper bounding value for the present-day condition, therefore, no further confirmation is needed.

5.2 The initial water composition in emplacement drift environment is assumed from the initial pore water chemistry at fracture and matrix in the unsaturated zone (UZ) at or above the repository horizon. Used in Section 6.2.3.

Rationale: This assumption is based on Section 6.2.2.1 of *Drift-Scale Coupled Processes (DST and THC Seepage) Models* (BSC 2003b, p. 70). Since perched water and saturated water are more dilute than pore waters, it is adequate to make this assumption. No further confirmation is needed.

5.3 The average and range (in parenthesis) concentration of chloride, sulfate, bicarbonate, and pH of initial water at or above the repository horizon are 48 (21 – 117), 56 (10 – 116), and 352 (200 – 515) mg/l, and 7.9 (7.4 – 8.31), respectively. Used in Section 6.2.3.

Rationale: This assumption is based Table 6.2-1 of *Drift-Scale Coupled Processes (DST and THC Seepage) Models* (BSC 2003b, p. 73) and Assumption 5.2. It is considered adequate and does not need further confirmation.

5.4 The primary ground support in the emplacement drifts will be friction-type rock bolts and perforated sheets held in place by the rock bolts. Used throughout.

Rationale: This assumption is based on *Ground Support Studies and Design Status* (Duan and Board 2003, p. 10). No further confirmation is needed.

5.5 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 6.4.

Rationale: The one-tenth reduction in thickness due to corrosion is a design allowance for steel members. In other words, design should consider mechanical and strength requirements together with an allowance for corrosion. This assumption is considered adequate and no confirmation is needed.

6. CALCULATION

6.1 BACKGROUND

During the SR design, steel sets were recommended for the emplacement drifts to be excavated in various rock units including the lithophysal and non-lithophysal rocks. Fully grouted rock bolts were recommended for the emplacement drifts excavated in non-lithophysal rock units (BSC 2001b, p. 44). Carbon steel was recommended to be used for steel sets, rock bolts, and wire mesh as ground support system in emplacement drifts.

The ground support systems in the emplacement drifts have undergone several modifications since the SR design. The previous longevity analysis was based on the ground support system consisting of fully grouted rock bolts with steel wire fabric. The steel sets would only be installed on an as-needed basis (BSC 2003a, p. 12). The latest approach for the ground support system in the emplacement drifts includes no use of cementitious materials. This approach requires replacing the uses of fully grouted rock bolts with stainless steel friction-type rock bolts. Also, the steel wire fabric has been replaced with Bernold-type perforated stainless steel sheets in emplacement drifts (BSC 2003c, p. 13). Figure 1 shows the current ground support configuration for emplacement drifts (Trautner 2003, Attachment A).

Since no cementitious materials will be used for ground support in emplacement drifts, this calculation will not include cement grouts, rather, it will be focused on steel components only. The longevity of steel ground support materials in emplacement drifts will first be evaluated in the drift environmental conditions including temperature, relative humidity, water chemistry, and radiation, and followed by the most important factor, corrosion of steel components.

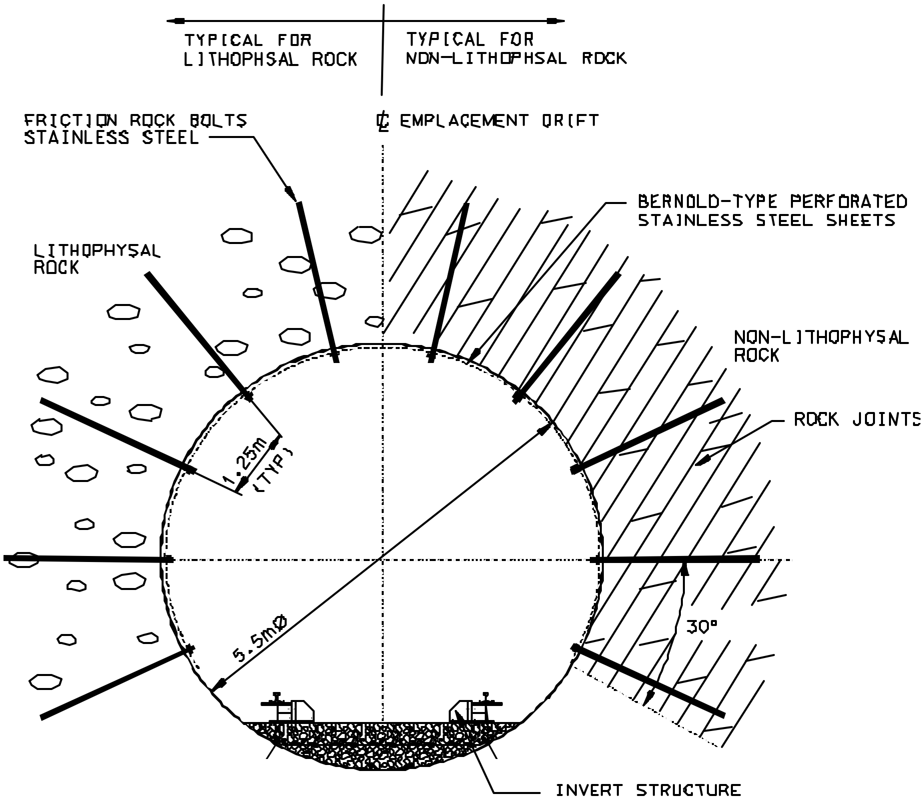
6.2 EMPLACEMENT DRIFT ENVIRONMENTAL CONDITIONS

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

6.2.1 Temperature

An unventilated emplacement drift, upon waste emplacement, will experience increases in temperature from the heat output from the waste packages (WP). The drift wall temperatures will increase due to thermal radiation from the waste packages. The drift wall temperatures will depend on the thermal loading level, WP assembly configuration, WP spacing, drift spacing and diameter and ventilation.

Based on Section 4.2.6, the system shall ensure that the maximum emplacement drift wall temperature shall not exceed 96 °C during the preclosure operation, nor, exceed 200 °C during



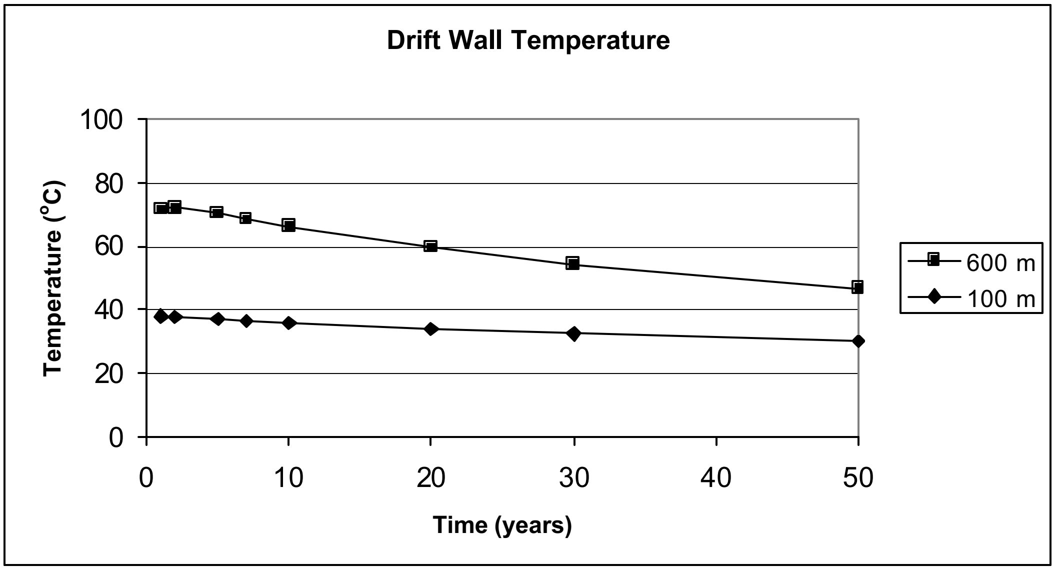
Source: Trautner 2003, Attachment A

Figure 1. Configuration of Emplacement Drift Ground Support

the post-closure.

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 most recent ventilation model and analysis, 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 50 years and an initial line load of 1.45 kW/m (BSC 2003e, pp. 39 and 41). This model and analysis predicts the preclosure temperatures of the waste packages, drift wall and ventilation air. With regard to the ground support longevity in emplacement drifts, the most relevant temperature profile is the one corresponding to the drift wall. Figure 2 shows the drift wall temperatures at locations of 100 m and 600 m from the emplacement drift inlet with continuous ventilation. As it can be seen from the figure, the temperature for the first portion of emplacement drift (i.e., up to 100 m from the drift inlet) decreases from about 40 °C at the year 1 to about 30 °C at year 50 due to the application of ventilation. After ventilation air has carried the elevated temperatures due to the heat released from waste packages along the drift, the drift temperature level increases. The drift wall temperature at 600 m from the emplacement drift inlet indicates higher value and it decreases from about 70 °C at year 1 to about 45 °C at year 50. The drift wall temperature profile clearly shows that the highest temperature at emplacement drift is less than 96 °C (Section 4.2.6), the upper bound temperature limit for preclosure period.

With regard to the temperatures into 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 a high thermal loading scenario with 25-yr ventilation (BSC 2001g, Fig. 6-3, p. 27). It is expected that the same level of temperature decrease will be for the rock bolts installed up to 3 m into the rock.



Source: BSC 2003e, Fig. 6-3, p. 82

Figure 2. Drift Wall Temperatures as Function of Ventilation Time

6.2.2 Relative Humidity

The relative humidity (RH) in an emplacement drift varies with location and time, and depends on the temperature and saturation level in the surrounding rock. Generally speaking, RH is inversely proportional to the former and proportional to the latter. In addition, ventilation will affect the relative humidity greatly. At the drift wall, both in situ rock moisture and water percolation flux through the rock will be removed by the ventilation instead of evaporating and migrating into a cooler rock region as is the case with the unventilated scenario. Since continuous ventilation will be applied in the emplacement drifts during the preclosure, the RH inside the drift will be relatively low.

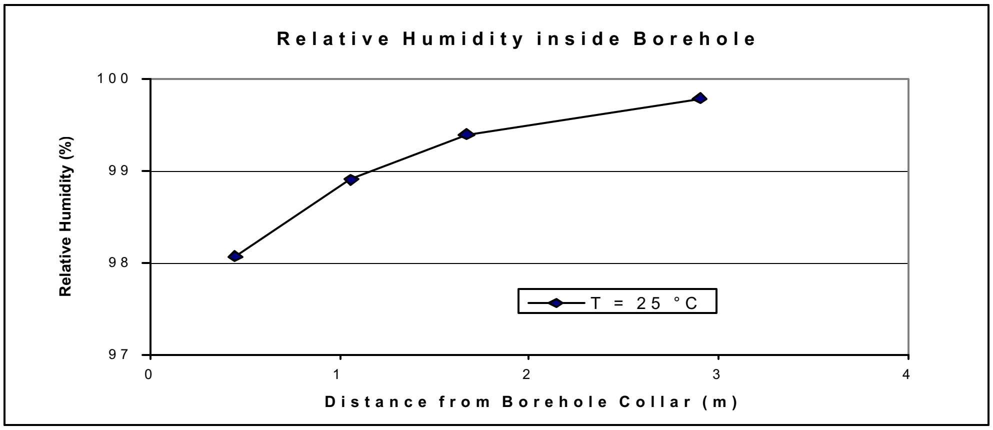
In a recent repository ventilation study, the in-drift relative humidity was calculated for a linear heat load of 1.45 kW/m with the following ventilation scenarios: a forced ventilation air flow rate of 15 m^3/s from 0 to 50 years and natural ventilation air flow rates of 3 m^3/s from 50 to 100 years, 1.5 m^3/s from 100 to 300 years, and 1.0 m^3/s from 300 to 10,000 years (BSC 2001c, p. XXVII-2). The calculation used an average inlet air of 25 ^{o}C dry bulb temperature at 30 percent relative humidity. The ventilation air is allowed to cross the emplacement drift picking up the heat of the waste packages and most of the potential moisture influx of 60 mm/year 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 first 100 years (note that the 27.31% for the time of 0.0001 year is for the initial condition) (BSC 2001c, p. XXVII-7, Table XXVII-2). It should be noted that the actual relative humidity at emplacement drifts during the preclosure will probably be lower than these values due to the following reasons: a) the highest average percolation rate in the repository horizon is 15 mm/year (see Assumption 5.1), which is much lower than 60 mm/year used in the calculation, and b) the weighted average relative humidity at emplacement drift intake is 20.31% based on a recent calculation on properties of air entering emplacement drift (BSC 2002, p. 26), which is smaller than 30% used in the ventilation calculation.

It should be noted that the effects of external environmental conditions on the relative humidity in the subsurface drifts are negligible. For instance, DTN: MO0203SPAESF00.003 presents the surface relative humidity recordings for the year 2000 and plots of surface humidity levels overlain on subsurface plots for the same time periods. The plots presented under MO0203SPAESF00.003 demonstrate no significant increase in subsurface humidity levels as peak nighttime surface humidity gradually increases, and show little effect from general 24-hour cyclic fluctuation.

It should also be pointed out that the above discussion for RH is applicable to all ground support components that are exposed to the ventilation air during the normal operation. However, as discussed in Section 6.4.4.2, hygroscopic salts might be deposited on the surfaces of ground support components by seepage water as well as dusts introduced in the ventilation air. The deliquescence points of these salts may have a lower RH than that present in emplacement drifts. Furthermore, the in-drift relative humidity during the off-normal condition (i.e., ventilation breakdown) and RH inside the bolt holes will be higher than that exposed to the ventilation air, the latter is discussed next.

During and after Exploratory Studies Facility (ESF) Main Drift 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. The AMR *In Situ Field Testing of Processes* (BSC 2001d, Section 6.8, p. 179) documents the data and analysis of both passive monitoring data and active testing of flow and transport processes underground. Water potentials were measured using psychrometers that allowed for quick equilibration with the surrounding tuff (BSC 2001d, Section 6.8.1, p. 179). The water potential values are expressed as negative pressure head in meters (of equivalent water column), with drier conditions having more negative values. For example water potentials of -273 m and -28 m at 0.45 and 2.9 m from borehole collar, respectively, were measured from boreholes in Niche 3107 along the Main Drift of ESF (see Table 6.8.2-3, p. 184 and Figure 6.8.2-2, p. 186 of BSC 2001d). Figure 6.8.2-2 of BSC 2001d clearly shows the presence of a prominent dry-out zone of up to 3 m into the drift wall caused by ventilation in the ESF Main Drift. It is apparent that ventilation significantly reduces the potential for free liquid water into the drift. However, it needs to be pointed out that even though the bolt hole 2 to 3 m into the drift wall is somewhat dried out (i.e., moisture content is reduced), the relative humidity inside the bolt hole is still high.

Figure 3 illustrates the relative humidity inside of a borehole as a function of distance from the borehole collar. This figure is derived based on a temperature of 25 ^oC, the data shown in Table 6.8.2-3 of BSC 2001d, and the Kelvin equation with values of water density, ideal gas constant, and molecular weight of water taken from page XIII-6 of AMR document *Ventilation Model and Analysis Report* (BSC 2003e). This figure indicates that the relative humidity is higher than 98% beyond about 0.5 m inside the borehole collar, based on the water potential measured in the borehole in Niche 3107. However, it should be noted that from about 0.5 m to the collar of the borehole the relative humidity drops rapidly to the level of RH inside the emplacement drift. Moreover, it needs to be pointed out that the water potential measurement was made in the ESF drift in which there is no heat source. With heat generated from waste packages in emplacement drifts, the RH inside of bolt hole will be lower than that shown in the figure. Therefore, 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 bolt hole is expected to be high, especially at the deeper portion near the end of bolt hole, where the RH value is expected to be greater than 90 %.



Source: BSC 2001d, Table 6.8.2-3 and BSC 2003e, p. XIII-6

Figure 3. Relative Humidity vs. Distance from Borehole Collar

6.2.3 Ground Water and Air in Emplacement Drifts

It should be noted that the term “ground water” in this calculation is defined for all subsurface water as distinct from surface water. The repository horizon is located in a zone of the unsaturated rock within Yucca Mountain. There are two potential pathways for ground water flow in the unsaturated zone at Yucca Mountain. The first is matrix flow, or the flux of ground water through the interconnected pores of the rock mass. The second is fracture flow, or the flux of ground water through fissures in the rock mass. Flow occurs primarily through the matrix in non-welded rocks and through fractures under high percolation conditions in welded rocks. Infiltration associated with precipitation events is the natural source of ground water in the unsaturated zone in the Yucca Mountain area. The highest mean total (matrix + fracture) percolation flux at the repository horizon under present-day condition at Yucca Mountain is 15 mm/year (Assumption 5.1). This value is considered adequate for the preclosure period. Although fault zones may be important pathways for ground water flow, the emplacement drifts in the repository have been laid out to avoid major fault zones.

In assessing the effect of the chemistry of the ground water on the longevity of steel ground support components, the infiltrating water from the initial pore water chemistry at fracture and matrix above the potential repository horizon is considered (Assumption 5.2). The most important characteristics from the infiltrating water related to steel corrosion are chloride, sulfate, bicarbonate, and pH, the corresponding average and range (in parenthesis) concentration of which are 48 (21 – 117), 56 (10 – 116), and 352 (200 – 515) mg/l, and 7.9 (7.4 – 8.31), respectively (Assumption 5.3). Sulfate and chloride ions are considered by a number of investigators as the most corrosive of the common ions found in naturally occurring waters, with sulfate generally regarded as the most corrosive (except chloride promotes pitting), while bicarbonate and carbonate ions are considered corrosion inhibitors (Tilman et al. 1984, p. 16). It should be noted that these values are for the initial fracture and matrix water, i.e., these values are compositions of starting water. The concentrations of ions in ground water increase as the concentration factor of seepage at the drift crown increases (see Figure 1, p. 24 of BSC 2001e). Although the concentration of ions in the ground water will increase due to the evaporation process, it is unlikely that the impact of salt precipitation in the evaporative environment will be significant on corrosion of steel ground components in emplacement drifts during the preclosure period.

The chemistry of air in the emplacement drifts is expected the same as that on surface of 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.

6.2.4 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). Alphas and betas are both stopped completely by the first few millimeters of waste package material and are therefore unable to affect the ground support. X-rays are rendered harmless by the attenuating effects of the waste package as well. Of major concern 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 and inverts. 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. Over time, these sub-atomic disruptions may cause changes in the physical properties of metallic materials (BSC 2001a, Section 6.1.3, pp. 23 and 24).

The quantities of importance for radiation damage are the absorbed dose and the neutron fluence. The cumulative fast neutron fluence based on the current design basis source terms is 1.11×10^{13} n/cm^2 for 340 years of waste emplacement (BSC 2003f, Table 6.4-1, p. 50). The cumulative gamma dose to the ground support material (stainless steel 316) is 69.1 mega-rads for 340 years of waste emplacement (BSC 2003f, Table 6.4-4, p. 55).

6.3 EMPLACEMENT DRIFT GROUND SUPPORT COMPONENTS

The ground support in the repository emplacement drifts will be friction-type rock bolts and perforated steel sheets (Assumption 5.4). In order to evaluate the longevity of ground support materials, it is essential to understand these two types of ground support components.

6.3.1 Friction-type Rock Bolts

Friction-type, or friction-anchored, rock bolts represent the most recent development in rock reinforcement techniques. Two friction anchored rock bolts are available, the Split Set and the Swellex (see Figure 4). For both types of rock bolt system, the frictional resistance to sliding, (for the Swellex combined with interlocking) is generated by a radial force against the borehole wall over the whole length of the bolt. Friction anchored rock bolts are the only type of bolts where the load of the rock is transferred to the reinforcing element directly without any necessary auxiliary such as mechanical locking devices or grouting agents (Stillborg 1994, p. 12)

6.3.1.1 Split Sets

Split Sets, sometimes called Split Set friction rock stabilizers, were introduced commercially in 1997. Now many millions are in use in more than 50 countries on seven continents around the world. The Split Set stabilizer system has only two parts – a tube and a bearing plate, as shown in Figure 4a. The high-strength steel tube has a slot along its length; one end is tapered for easy insertion, and the other has a welded ring flange to hold the plate (International Rollforms, p. 2).

With the bearing plate in place, the tube is driven into a slightly small hole, using the same standard percussion drill when made the hole. As the tube slides into place, its full-length slot narrows; the tube exerts radial pressure against the rock over its full contact length. Plate loading is generated immediately. The result is a tight grip, which actually grows stronger with time and ground movement (International Rollforms, p. 2).

In addition to its easy and fast installation (it usually takes less than a minute) and giving immediate support after installation, Split Set also has the following advantages: a) no special equipment needed, b) no mixing of grout, thus no waiting for grout to set, c) low labor and material cost, d) no need of torquing or retorquing, thus no maintenance cost (International Rollforms, p. 9).

However, due to its thin tube configuration with whole-length slot, there are some disadvantages, which are: a) borehole diameter is crucial in the prevention of failure during installation and in the provision of the intended holding force, especially when boreholes are not straight or cannot be made with adequate dimension, b) the steel tube is thin and sensitive to corrosion both at its inside and outside surfaces, and c) the holding capacity is relatively low, for example, 6 to 10 tons for upper range (i.e., for SS-46 Split Set) (International Rollforms, p. 9)

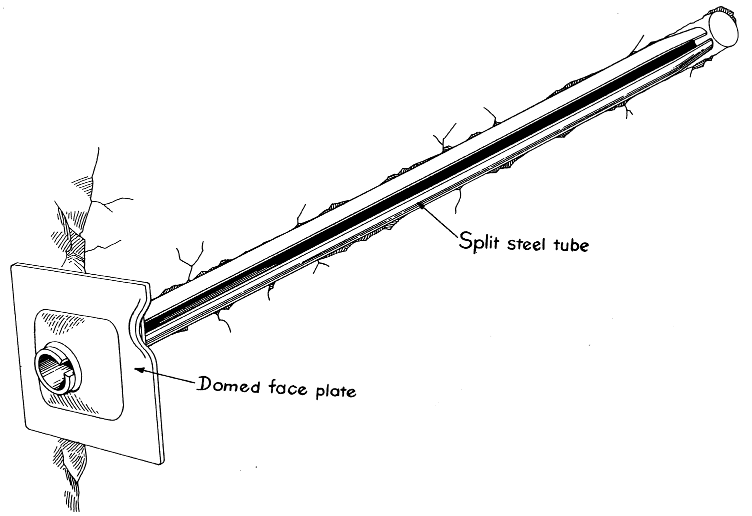
6.3.1.2 Swellex Bolts

The Swellex rock bolting system has gained worldwide acceptance since its introduction about twenty years ago. Today, the Swellex bolts are in use at mines and construction sites worldwide.

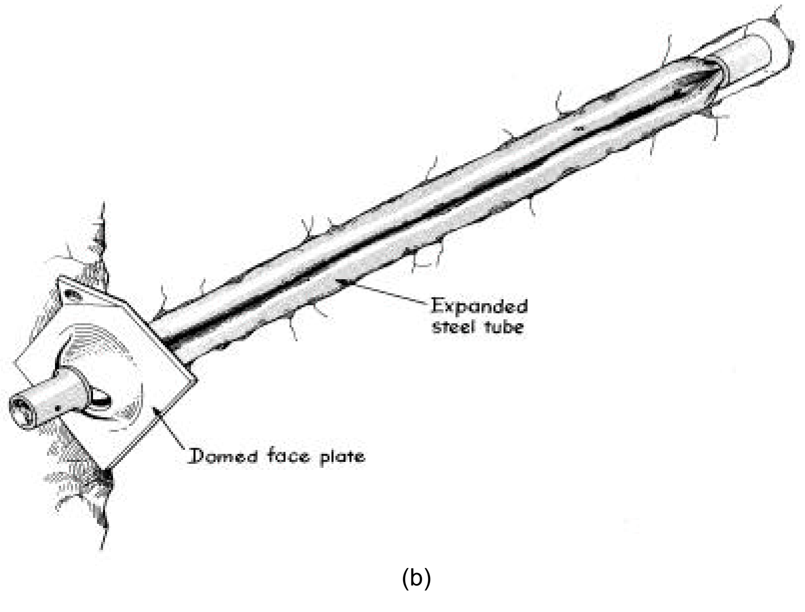
The Swellex bolt system consists of rock bolts made from circular steel tube, which has been folded to reduce its diameter, and a high pressure water pump. The Swellex rock bolts are placed in a drilled hole and expanded by high-pressure water. During the expansion process, the Swellex bolt compacts the material surrounding the hole and adapts its shape to fit the irregularities of the borehole. A combination of frictional and mechanical interlock is generated throughout the entire bolt length, reinforcing and increasing the load-bearing strength of the rock surrounding the drill hole. The load of the rock is transferred to the Swellex bolt directly without any necessary auxiliaries such as mechanical locking devices or grouting agents, the quality of which is difficult to control (Atlas Copco, p. 3 of Swellex catalog).

The installation procedure of Swellex bolt is easy and acts as a quality assurance control. First, put the bushing head of the bolt into the chuck and insert the bolt in the borehole. Then, start pumping the water into the tube through a connection at the lower sleeve. This causes the tube to swell in the hole. When the preset pressure has been reached the mechanical interlock with the rock is established and the pump stops automatically (Atlas Copco, p. 3 of Swellex catalog; Peng 1986, p. 230).

The Swellex bolts have almost the same advantages as those of Split Sets due to the similar friction mechanism and tubing configuration, see Section 6.3.1.1. Furthermore, the Swellex bolts have additional advantages, which are: a) borehole condition and dimension are not crucial for installation so it can be used in a variety of ground condition, b) the holding capacity is higher than that of Split Set, e.g., 10 metric tons for standard Swellex and 20 metric tons for Super Swellex, (Stillborg 1994, p. 14) and the steel tube is generally subject to corrosion from water contacting the outside surface instead of both sides.



(a)



(b)

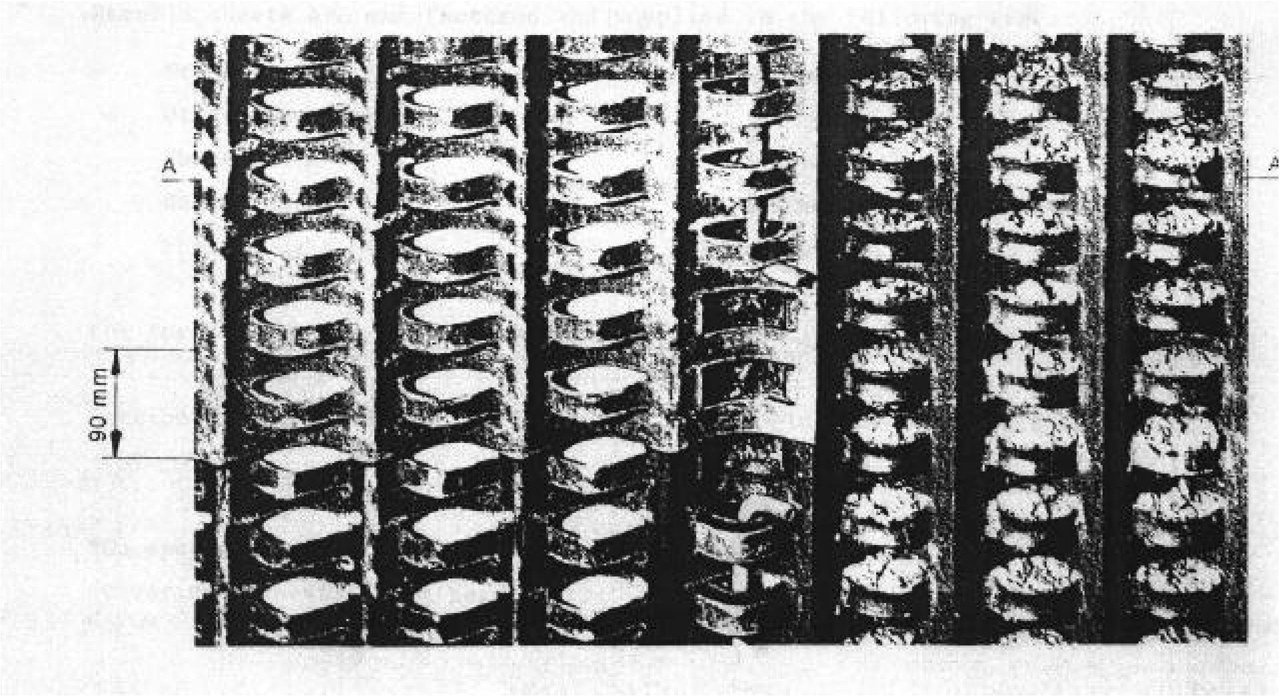
Source: Stillborg 1994, pp. 13 and 14

Figure 4. Friction Anchored Rock Bolts: (a) Split Set; (b) Swellex

6.3.2 Perforated Steel Sheets

The reason of using perforated steel sheets to be installed against emplacement drift wall comes from the concept that it is necessary, particularly in lithophysal rocks, to provide a continuous confinement to the rock surface along the tunnel to prevent raveling of the surface which could lead to slow, progressive failure. The perforated sheets provide both flexural strength and allow air circulation for rock dry-out, or reduce the relative humidity between the steel sheets and rock, which is important for preventing or minimizing the corrosion of steel.

The perforated steel sheets (often called Bernold sheets after a Swiss company that manufactures them) (see Figure 5) could be manufactured in such a size that a few sheets would cover the entire 240° peripheral coverage around a given tunnel section (see Figure 1). The sheets would also be pre-stamped with holes for rock bolts and depressions to accommodate the rock bolt plates. The holes stamped in sheet will be sized to prevent small rocks from falling through while still air circulation. Installation would be done using a modified rock bolter to automate the lifting and installation of the Bernold-type sheets which would be held in place by hydraulic jams while bolt installation taking place. The bolt plates would be installed on the exterior of the sheet, which would be pulled tightly into contact with the rock surface as the bolts are installed.



Source: Duan and Board 2003, p. 12

Figure 5. Bernold-type Perforated Steel Sheet

6.3.3 Candidate Ground Support Materials for Emplacement Drifts

In order to make a proper selection of suitable ground support materials, it is important to know the service life in which these materials will be functional and understand under what kind of environment they will be subjected to during the service life.

The design criterion for waste retrieval time is up to 50 years after initial waste emplacement (Section 4.2.3) whereas a minimum of 75 years with no or minimal maintenance is required (Section 4.2.4). Currently, a service life of 100 years is being considered as the basis for selecting the ground support materials in emplacement drifts.

The most important environmental conditions in emplacement drifts related to longevity of steel are presented in Section 6.2. Among the important environmental conditions affecting steel corrosion, which include temperature, relative humidity (RH), and water chemistry, RH is the most important 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 corrosion increases noticeably. Depending on the relative humidity condition of the environment, the corrosion of steel can be categorized as dry oxidation, humid-air corrosion, and aqueous corrosion (CRWMS M&O 1998, pp. 3-5 to 3-7).

During the early development of candidate materials for the steel to be used as the ground support, carbon steel, galvanized steel, and stainless steel were considered. However, galvanized steel will not be considered further for the emplacement drifts following reasons: a) the long-term behavior of the zinc coating under high temperature is not known, b) the surface coating would be likely damaged for friction-type rock bolts as well as Bernold-type steel sheets at various locations in contact with drift wall.

Recently, a corrosion evaluation of steel components in emplacement drifts has been performed. Steel ground support components made by carbon steel, high-strength low-alloy (HSLA) steel, and stainless steel were evaluated against corrosion (BSC 2003a). It is, therefore, adequate to consider them as candidate ground support materials for emplacement drifts.

The chemical compositions and material properties for the carbon steel, HSLA steel and stainless steel are to be followed by the following representative ASTM specifications:

Carbon Steel:	ASTM A 36
HSLA Steel:	ASTM A 242 and A 588
Stainless Steel:	ASTM A 240 and A 276

6.4 LONGEVITY OF STEEL GROUND SUPPORT COMPONENTS

The longevity of steel ground support materials in emplacement drifts will be evaluated in the following conditions: effects of elevated temperature, radiation, and the most important factor, the corrosion of steel components.

Steel components to be considered for emplacement drift ground control include:

- Friction-type rock bolts, i.e., Split Sets and/or Swellex bolts
- Bernold-type perforated steel sheets

Candidate steel ground support materials, i.e., carbon steel, HSLA steel, and stainless steel are considered in this evaluation.

6.4.1 Temperature Effect on Mechanical Properties

In this section, effects on mechanical properties of steel materials under moderately elevated temperatures are discussed.

6.4.1.1 Strength and Modulus of Elasticity

The yield point of structural steel (including carbon steel and HSLA steel) at room temperature (i.e., about 20 °C) and elevated temperatures such as 430 °C and 540 °C are presented in Section 4.1.1. It 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 (Section 4.1.1). By interpolation, the calculated values at 200 °C (the maximum allowable temperature during post-closure), 96 °C (the maximum allowable temperature during preclosure) (see Section 4.2.6), and 70 °C (the calculated approximately highest preclosure temperature based on continuous ventilation) (see Section 6.2.1) are about 91, 96, and 98 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 about 172 GPa (25,000 ksi) at 480 °C (Section 4.1.6), or 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 198 GPa (28,710 ksi) at 200, 96, and 70 °C, respectively, which decrease about 5, 2.5, and 1 percent, respectively, in comparison with the value at 20 °C.

Based on these data, it is likely that the effect of moderately elevated temperature on the strength and modulus of elasticity of structural steel (including carbon steel and HSLA steel) components is negligible (i.e., 2 and 1 percent decrease) for the predicted maximum temperature of about 70 °C, insignificant (i.e., 4 and 2.5 percent decrease) for the maximum temperature in the emplacement drift during the preclosure (i.e., 96 °C), and very small (i.e., 9 and 5 percent decrease) for the maximum temperature of 200 °C during post-closure.

Most stainless steels, particularly, the austenitic types such as 316, are used extensively for elevated-temperature (i.e., above 370 °C) applications (ASM International 1990, pp. 861 and 930). It is expected that for the temperature range from up to 70 °C to 200 °C, the temperature effect on mechanical properties of stainless steel is insignificant.

6.4.1.2 Toughness and Ductility

Toughness is the ability of a metal to absorb energy and deform plastically before fracturing. A measure of toughness is notch toughness, which is measured (in joules) by impact testing. Toughness generally decreases as the strength, hardness, and carbon content of the steel increase (ASM International 1990, p. 739, Fig. 9). The change in notch toughness (in terms of impact energy) for carbon steel with 0.11- and 0.80-percent carbon at temperatures of 70, 100, and 200 °C is presented in Section 4.1.2. With temperatures at 70 °C, 100 °C and 200°C, the notch toughness (in terms of impact energy) of a steel with 0.11-percent carbon is about 25, 20 and 6 times that of a steel with 0.80-percent carbon (Section 4.1.2). In other words, the difference in toughness of carbon steel is large between lower and higher carbon content for the lower temperature level, such as up to 70 °C. The 0.80-percent carbon steel exhibits the least ductility of the carbon steels whereas the 0.11-percent carbon steel the highest. For the maximum toughness and ductility, the carbon content should be kept as low as possible, consistent with strength requirements.

Ductility and toughness of most stainless steels are higher than the same properties of carbon steels (ASM International 1990, p. 853). For the temperature level expected in emplacement drifts during the preclosure period, which is low compared with many stainless steel at high temperatures, the effect of temperature on toughness and ductility of stainless steel is expected to be insignificant.

6.4.2 Thermal Properties

The properties needed to characterize the thermal and thermomechanical behavior of steel include thermal expansion, thermal conductivity, and specific heat. These properties are discussed in this section.

6.4.2.1 Thermal Expansion Coefficient

Structural steels (i.e., carbon steels and HSLA steel) have a coefficient of thermal expansion that varies from about 11.24×10^{-6}/°C at 25 °C to 11.52×10^{-6}/°C at 70 °C, 11.71×10^{-6}/°C at 100 °C and 12.32×10^{-6}/°C at 200 °C (Section 4.1.3). The thermal expansion coefficients for TSw2 tuff for near-field considerations vary from 7.50×10^{-6}/°C at 25-50 °C to 8.80×10^{-6}/°C at 50-75 °C, 9.06×10^{-6}/°C at 75-100 °C, and 13.77×10^{-6}/°C at 175-200 °C (Section 4.1.3). The differences in thermal expansion coefficients between TSw2 tuff and carbon steel are about 3.74×10^{-6}/°C at 25 °C, and about 2.72×10^{-6}/°C, 2.65×10^{-6}/°C and 1.45×10^{-6}/°C at 70, 100, and 200 °C, respectively. These data show that the thermal expansion coefficients of carbon steel are higher than those of the TSw2 tuff for the temperature range expected during the preclosure, i.e., up to 96 °C. Only at temperature range of 175-200 °C, the thermal coefficient of TSw2 tuff is slightly higher than that of carbon steel. This condition is beneficial to the friction-type rock bolts proposed for the ground support system in emplacement drifts, because friction-type rock bolts use whole-length contact to anchor the bolts and will have further contact with the borehole due to this differential thermal expansion.

The mean thermal expansion coefficients of the stainless steel 316 is 15.9 x 10^{-6}/°C at 0 °C to 100 °C and 16.2 x 10^{-6}/°C at 0 °C to 315 °C (Section 4.1.3). They are higher than those of carbon steel. Moreover, the thermal expansion coefficients of stainless steel are higher than those of TSw2 tuff for the entire temperature ranges from preclosure through post-closure, i.e., up to 200 °C. The differences between them range from about 7.4 x 10^{-6}/°C at 0-100 °C to 2.43 x 10^{-6}/°C at 0-200 °C. It is more advantageous to use stainless steel than carbon steel in terms of full-length anchoring mechanism for friction-type rock bolts due to this larger differential thermal expansion.

6.4.2.2 Thermal Conductivity and Specific Heat

The thermal conductivity of carbon steel (grade 1025) for temperatures at 0 °C, 100 °C and 200 °C are 51.9, 51.1 and 49 W/m·K, respectively. The mean specific heat of carbon steel (grade 1025) for temperatures of 50 °C to 100 °C and 150 °C to 200 °C are 486 and 519 J/kg·K, respectively (Section 4.1.4).

The thermal conductivity of stainless steel 316 for temperatures at 100 °C is 16.2 W/m·K. The specific heat of stainless steel 316 is 500 J/kg·K (Section 4.1.4).

The data indicates that the thermal conductivity of stainless steel 316 is lower than that of carbon steel whereas the specific heat of the former is very close to the latter. In addition, for temperature levels expected to be at emplacement drifts, the impacts of temperature on thermal conductivity and specific heat of carbon steel and stainless steel are insignificant.

6.4.3 Radiation Effect

The cumulative neutron fluence is important for determining property changes in metallic materials. The cumulative fast neutron fluence based on the current design basis source terms is 1.11 x 10^{13} n/cm^2 for 340 years of waste emplacement (see Section 6.2.4). 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 (ASM International 1990, p. 659, Figure 7). Therefore, the effect of neutron radiation on mechanical property of carbon steel is insignificant. This neutron fluence level (i.e., 1.11 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 (Etherington 1958, p. 10-107). Hence, there is no radiation effect on carbon steel or stainless steel 316.

The cumulative gamma dose to the ground support material for stainless steel 316 at 340 years of waste emplacement is about 70 mega-rads (see Section 6.2.4). Gamma radiation at this level is not expected to produce any effects on stainless steel 316 (BSC 2003f, p. 55).

It can be concluded that the cumulative neutron fluence and gamma dose are far too small to cause any appreciable mechanical damage to carbon steel or stainless steel over the maximum 300-year preclosure period.

6.4.4 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 emplacement drifts, i.e., friction-type rock bolts (including Split Sets and Swellex bolts) and Bernold-type steel sheets.

The simplest and most effective corrosion control practice is selection of a suitable metal or alloy for the service time in a particular environment. The design criterion for waste retrieval time is up to 50 years after initial waste emplacement (Section 4.2.3) whereas a minimum of 75 years with no or minimal maintenance is required (Section 4.2.4). For corrosion evaluation, a service life of 100 years is being considered as the basis for selecting the ground support materials in emplacement drifts.

Among the important environmental conditions affecting steel corrosion, which include temperature, relative humidity, and water chemistry, RH is probably the most important 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.

As discussed in Section 6.2.2, the RH inside the emplacement drifts during the preclosure is expected to be very low due to continuous ventilation. However, the RH deep inside the bolt holes will be high, especially near the end of bolt hole, which will cause rock bolts susceptible to humid-air or aqueous corrosion. For the Bernold-type perforated steel sheets to be installed against the drift wall, although the RH of ventilated air contacting the inside surface of steel sheets is very low, the RH between the outside surface of sheets and drift wall may be higher and susceptible to either humid-air corrosion or aqueous corrosion at some localized points.

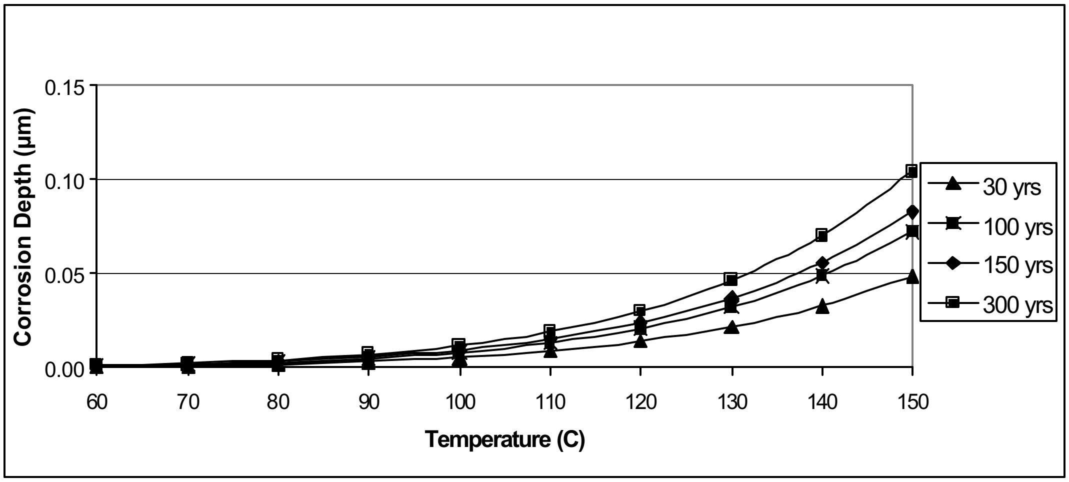
In this section, dry oxidation, humid-air corrosion, aqueous corrosion, pitting and crevice corrosion, stress corrosion cracking, hydrogen embrittlement, and microbiologically influenced corrosion of steel ground support components are evaluated. In this section, a period of 100 years is considered as the basis for corrosion evaluation.

6.4.4.1 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 (CRWMS M&O 1998, 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* (BSC 2003a). Figure 6 shows the estimated penetration depths of dry oxidation for carbon steel (BSC 2003a, Figure 3, p. 18). As shown on Figure 6, the estimated corrosion depths under dry oxidation condition for carbon steel are very small; approximately 0.01 μm at 100 °C, and 0.1 μm at 150 °C for a period of 100 years. Therefore, the impact of dry oxidation on the performance of carbon steel is insignificant.

High resistance to oxidation of stainless steel is generally associated with the formation of chromic oxide, Cr_2O_3 (Sedriks 1996, p. 389). For stainless steel, the oxidation rate is negligible for temperature below about 760 °C (1400 °F) (Fontana 1986, Table 11-5, p. 526). Therefore, the impact of dry oxidation on the performance of stainless steel is considered negligible.

Therefore, neither rock bolts nor perforated sheets made of carbon steel or stainless steel will fail due to corrosion by dry oxidation.



Source: BSC 2003a, Fig. 3, p. 18

Figure 6. Estimated Penetration Depths of Dry Oxidation for Carbon Steel

6.4.4.2 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 (CRWMS M&O 1998, pp. 3-6 to 3-7 and Fig. 3-2).

In the waste package degradation study, it was indicated that hygroscopic salts might be deposited on drip shield and waste package outer surfaces by seepage water and episodic water flow, as well as by aerosols and dusts introduced in the ventilation air. The deliquescence points of these salts determine the RH at which humid-air corrosion commences (CRWMS M&O 2000a, p. 1-10). The deliquescence points can cover a broad range. For example, the deliquescence point of sodium nitrate varies from 50 percent RH at the boiling point of the saturated solution to 73 percent RH at 30 ^{o}C. The deliquescence point for magnesium chloride increases from 22 percent RH at 100 ^{o}C to 32 percent RH at 30 ^{o}C. The deliquescence point for calcium chloride at the boiling point (sea level) is about 15 percent (BSC 2001f, pp. 7-16 to 7-17). 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 portion 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 6.2.2, the relative humidity inside the bolt hole is high, especially at the deeper portion, 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 bolt hole, 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 (McCright 1998). Although the major purpose of these tests was to investigate the corrosion behavior of waste package materials, the 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 (McCright 1998, Table 2.2-9). The average of these four values is 40 μm/year. It should be noted 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).

Table 2 presents the total corrosion depth 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 5.5 (i.e., if the total corrosion depth of any steel member exceeds one-tenth of its thickness, the steel member would fail), all steel ground support components including Split Set (2.3 mm thick), Swellex bolt (2 to 3 mm thick), perforated steel sheets (up to 3 mm thick), and bearing plates (4 mm thick) (see Table 1 in Section 4.1.5) made of carbon steel will fail due to humid-air corrosion after 30 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 (ASM International 1987, Table 2, p. 532), of which the average corrosion rate is 2.3 μm/year. By assuming 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 5.5), the following conclusions are made: a) for Swellex bolts, the Super Swellex bolt will not fail for service life up to 100 years, standard Swellex (i.e., EXL Swellex) bolt and bearing plate will fail after about 75 years, b) Split Sets will fail after about 50 years, and 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 within 75 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

A series of experimental studies have been conducted for stainless steel 316 under various environments. The average atmospheric corrosion rate from 22 measurements for stainless steel 316 under various environments is 0.006 µm/year (Gdowski and Bullen 1988, Table 2, p. 16). By assuming 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, neither rock bolts or perforated sheets 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: a) ground support components made of carbon steel will fail after service life of 30 years, b) only the Super Swellex bolt made of HSLA steel 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.

6.4.4.3 Aqueous Corrosion

The aqueous condition is equivalent to “immersion” or “bulk water” condition and it was stated that dripping conditions are required to achieve such a thick water film (CRWMS M&O 1998, p. 3-7). The conditions for aqueous corrosion to occur are either water from seepage or dripping, or RH above the deliquescence point of hygroscopic salts in the water. 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 steel sheets and drift wall or between friction bolts and bolt holes.

The estimated penetration depth of carbon steel due to aqueous corrosion was presented in Section 6.3.3 of BSC 2003a. Table 5 shows the single-sided corrosion penetration depth for a time period of 10 to 100 years with temperatures ranging from 60 to 150 °C, calculated based on the Equation 2, p. 23 of BSC 2003a. As can be seen from Table 5, the estimated corrosion depths under aqueous corrosion condition are much greater compared with those of dry oxidation case (see Figure 6). For a period of 10 years, the estimated corrosion depths range from 1 to 4 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 10 years of service.

Corrosion rates in the range of about 65 to 125 μm/year were reported for low-alloy steels fully immersed in seawater (ASM International 1987, p. 543). With this range of corrosion rate, all steel components in Table 1 would fail within 10 years. Although the environmental conditions in emplacement drifts are not so severe as that in the ocean, this result does show that HSLA steels such as ASTM A 242 or A 588 or similar ones may not be suitable to resist aqueous corrosion for required service life of up to 100 years.

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) (Gdowski and Bullen 1988, 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 the higher rate, i.e., 1.25 μm/year for conservatism, the corrosion depth for 100 years is 125 μm. Comparing this value with 10% of

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

T (°C)	**10 years**	**30 years**	**50 years**	**75 years**	**100 years**
60	1	2	3	4	4
70	2	3	4	5	5
80	2	4	5	6	7
90	3	5	6	7	9
100	4	6	8	9	11
110	4	7	9	11	13
120	5	9	11	14	16
130	6	11	13	16	19
140	8	13	16	19	22
150	9	15	19	23	26

those thickness data in Table 1, all steel ground components made of stainless steel 316 will not fail due to aqueous corrosion in 100 years.

It is clear that both carbon steel and HSLA steel will fail due to aqueous corrosion within 10 years whereas stainless steel 316 will not fail for 100 years of service life.

6.4.4.4 Pitting and Crevice Corrosion

Pitting and crevice corrosions are localized forms of attack that result in relatively rapid penetration at small discrete areas. Pits are often quite small at the surface and easily hidden by apparently inoffensive corrosion products. Similarly, localized attack is usually shielded from view within crevices created on metal parts under deposits or between metal and other metal or nonmetal parts. Thus both pitting and crevice corrosion often remain undetected until leaks result from penetration of the wall thickness. Both are insidious and unpredictable and often share similar growth processes (Jones 1996, p. 199).

Stainless steel alloys in general are more susceptible to both crevice and pitting corrosion than plain carbon steel. The reason for that is due to the disruption of the normally protective stainless steel passivation film by chlorine ions (U.S. Bureau of Mines 1987, 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 prevent susceptible pitting and crevice corrosion, stainless steel 316 is considered. This material is less susceptible to localized corrosion (LC) 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 (Gdowski and Bullen 1988, p. vii).

As discussed in previous sections, the corrosion rate for general corrosion under aqueous conditions is much higher compared with those of dry oxidation and humid-air corrosion. For general corrosion with a pitting factor of four (see Stahl et al. 1995, p. 674), the corrosion rate is four times of that for general aqueous corrosion. Consequently, all carbon steel components would fail in a very short period.

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 (ASM 1994, 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 will not fail at 100 years except perforated steel sheet with 1.5 mm thickness, which will fail after about 90 years of service. Note that perforated steel sheets with 2 to 3 mm in thickness, not the thinner one, are currently considered for design. The result clearly indicates stainless steel 316's superior performance against pitting corrosion.

The crevice corrosion rate based on a weight loss of 8.96 mg/cm^2 for stainless steel 316 exposed in seawater for 4.25 years was calculated to be 0.0026 mm/year based on stainless steel 316 density of 8.0 g/cm^3 (ASM International 1990, p. 871). The weight loss of 8.96 mg/cm^2 for stainless steel 316 is derived from Figure 5.10, p. 190 of Sedriks (1996). By assuming this penetration rate for crevice corrosion and for conservatism no decay in rate with time, the penetration depths for 50, 75, and 100 years are calculated to be 0.13, 0.195 and 0.26 mm, respectively. By comparing these values with 10% of thickness data in Table 1, all steel components except 1.5 mm thick steel sheet will not fail in 75 years but only the Super Swellex bolt and face plate will not fail for a service life of 100 years.

It should be mentioned that the corrosion rates for stainless steel 316 discussed previously were mainly obtained from ambient atmospheric and ocean type temperatures, which do not cover the potential effects of higher temperatures on general and localized corrosion. Based on YMP corrosion studies on structural stainless steel using cyclic polarization of aqueous solutions, the differences between values of corrosion potential (E_{corr}) and critical potential ($E_{critical}$) decrease very slightly from 20 ^{o}C to 80 ^{o}C and more significantly for temperature above 90 ^{o}C (see data for SCW and SAW cases in DTN: LL991210305924.105). As discussed in Section 6.2.1, the peak temperature in the emplacement drifts with forced ventilation of 15 m^3/s is about 70 ^{o}C during the preclosure period. Therefore, the potential effect of higher temperature on general and localized corrosion for stainless steel 316 is insignificant.

6.4.4.5 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 (Fontana 1986, p. 109). SCC of carbon steel was evaluated in Section 6.3.5 of BSC 2003a. It was stated that SCC is not expected to occur to fully-grouted rock bolts since the tensile stress induced in rock bolt is lower than the critical tensile stress level to initiate cracks. For the current ground support design, it is also expected that SCC will probably not occur to friction-type rock bolts due to the similar stress level.

Most alloys susceptible to cracking will begin cracking at least as low as 100 ^{o}C (Fontana 1986, p. 118). For austenitic stainless steel 316, the temperature to initiate cracking is above 100 ^{o}C, as shown in Fig. 3-64 of Fontana (1986, p. 119). As discussed in Section 6.2.1, the maximum drift wall temperature in the ventilated emplacement drift is about 70 ^{o}C and the temperature is 10 to 20 ^{o}C lower for rock mass 1 to 3 m inside the drift wall. It is also noted that in order to have SSC to occur to stainless steel, it must have an aqueous environment containing chloride, which is not expected to exist for friction-type rock bolts at emplacement drifts during the preclosure period.

Therefore, based on the stress level, temperature and ground water conditions, it is expected that SCC will probably not occur to friction-type rock bolts during the preclosure.

6.4.4.6 Hydrogen Embrittlement

Exact mechanism for all instances of hydrogen embrittlement have 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 (U.S. Bureau of Mines 1987, Appendix 2, p. 15).

Failure analysis was performed on rock bolts that failed in service at the WIPP site. The rock bolt material was an AISI 1040 grade plain carbon steel as called for in ASTM F 432. 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 (Lucas 1984, 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 7.9 (Assumption 5.3), 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. Therefore, the potential impact of hydrogen embrittlement on friction-type rock bolts is minimum or insignificant. For rock bolts made of stainless steels, since ductility and toughness of most stainless steels are higher than the same properties of carbon steels, the impact of hydrogen embrittlement is considered insignificant or negligible.

6.4.4.7 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). Therefore, all microbial influenced redox mineral transformations are possible in a Yucca Mountain repository (CRWMS M&O 2000b, Sec. 6.3.6, p. 55).

Over time, the repository environment will have environmental conditions that will favor certain bacteria over others (i.e., thermophiles over mesophiles or acidophiles over neutrophiles). However, microbes should be able to grow and produce their metabolic byproducts when the temperature is <120°C and the water activity is > 0.90 (i.e., RH > 90%), (CRWMS M&O 2000b, Sec. 6.3.6, pp. 55 and 56). As discussed in Sections 6.2.1 and 6.2.2, the temperature in the emplacement drifts is lower than about 70°C whereas the RH in the drifts is very low, i.e., much lower than 90%, the potential impact for MIC on steel supports will be insignificant below a RH of 90%. However, for rock bolts deep inside of bolt holes, the RH values may be higher than 90% (see Section 6.2.2), 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 (DTN: LL991203505924.094). It is assumed that MIC on stainless steel 316 will have the same effect on stainless steel 304. Based on these corrosion rates, carbon steel components with thickness data shown in Table 1 will fail within 100 years whereas the ground support components made of stainless steel 316 will not fail in 100 years. Therefore, the MIC effect on stainless steel 316 is insignificant.

6.4.5 Discussion

It should be pointed out that an accurate estimate of the longevity of steel ground support components within the emplacement drift is complicated because there is no precedent data from similar ground support components under similar environmental conditions. The evaluation presented in this calculation is made based on corrosion resistance available and assumptions presented in Section 5. Further work needs to be conducted to ensure that mechanical requirement on stress, fabrication concern, and cost impact are all taken into consideration.

6.5 UNCERTAINTIES

As discussed in Section 6.4.4, the most important factor that controls the longevity of steel ground support is corrosion. The uncertainty in corrosion evaluation of steel ground support components in emplacement drifts is mainly associated with the estimated corrosion rates, which depends primarily on relative humidity of the environment.

The relative humidity in the emplacement drifts has been discussed in detail in Section 6.2.2. The in-drift relative humidity was estimated to be about 10 percent or lower based on continuous ventilation. However, deliquescence points of hygroscopic salts caused by seepage water as well as by dusts may have a lower RH than that present in emplacement drifts. In contrast, the relative humidity near the end of bolt holes is expected to be greater than 90%. Depending on the level of relative humidity, corrosion rates based on different corrosion modes have been estimated. Although there are uncertainties existing with these RH values, the selection of adequate steel ground support materials is made based on the highest corrosion rate, i.e., rate for aqueous corrosion as well as pitting and crevice corrosion, which are essentially for the 100% RH condition. Moreover, the estimated corrosion rates are generally based on the longest exposure period available and assumed to be constant without decay over time. Furthermore, the corrosion rates were measured in environments that are more severe than that to be expected in the emplacement drifts. Therefore, a conservative approach has been adopted to minimize the uncertainties that may exist in estimating the relative humidity as well as corrosion rates.

The effects of temperature due to heat generated from waste packages on mechanical and thermal properties of steel components are also evaluated in this calculation. Although the highest drift wall temperature during the preclosure is estimated to be about 70 ^{o}C based on a most recent ventilation model and analysis (see Section 6.2.1), temperatures ranging from room temperature up to 100 ^{o}C and 200 ^{o}C are used in evaluating their impacts on the mechanical and thermal properties of steel components. Since the maximum allowable drift wall temperatures during preclosure and post-closure are 96 ^{o}C and 200 ^{o}C, respectively (Section 4.2.6), the results of using these upper-bound temperatures in evaluating the material properties are considered conservative. Consequently, the associated uncertainties on mechanical and thermal behavior are minimized.

The impact of radiation on mechanical properties of steel is also evaluated (Section 6.4.3). The cumulative neutron fluence and gamma dose due to waste package radiation are far too small to cause any appreciable mechanical damage to carbon steel or stainless steel over the maximum 300-year preclosure period. Since the level of estimated cumulative neutron fluence and gamma dose is too low (i.e., more than several orders of magnitude lower) compared with the threshold value that may initiate mechanical property damage, the uncertainty associated with radiation impact is minimized.

7. SUMMARY AND CONCLUSIONS

The longevity of emplacement drift ground support materials during the preclosure period has been evaluated in this calculation. The method, approach, and the results are presented in this calculation. It should be noted that 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 for LA progresses, the information will be updated as necessary.

The outputs are reasonable compared to the input. The results are suitable for the intended use. However, it should be pointed out that the conclusions made in this calculation are preliminary in nature, 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, summary of this calculation including conclusions is presented below.

7.1 EMPLACEMENT DRIFT ENVIRONMENTAL CONDITIONS

- The most important environmental conditions in emplacement drifts related to longevity of ground support materials (i.e., temperature, relative humidity, water chemistry, and radiation) have been identified and discussed.
- The repository design is to ensure that the maximum emplacement drift wall temperature does not exceed 96 °C during preclosure operations, nor exceed 200 °C during post-closure. The maximum drift wall temperature will be about 70 °C and will occur at the early time of waste emplacement and near the exhaust end of each emplacement drift.
- The in-drift relative humidity was calculated to be about 10 percent or lower based on continuous ventilation. However, hygroscopic salts might be deposited on the surfaces of ground support components by seepage water as well as by dusts introduced in the ventilation air. The deliquescence points of these salts may have a lower RH than that present in emplacement drifts.
- The relative humidity inside the bolt holes is high, especially at the deeper portion near the end of bolt holes, where the RH value is expected to be greater than 90%.
- The highest mean total percolation flux at the repository horizon under present-day condition at Yucca Mountain is 15 mm/year. The most important characteristics from the infiltrating water related to steel corrosion are chloride, sulfate, bicarbonate, and pH, the corresponding average concentration of which are 48, 56, and 352 mg/l, and 7.9, respectively.
- The cumulative fast neutron fluence from the waste package radiation is 1.11×10^{13} n/cm^2 at 340 years of waste emplacement whereas the cumulative gamma dose to the ground support material (stainless steel 316) is 69.1 mega-rads for the same period.

7.2 EMPLACEMENT DRIFT GROUND SUPPORT COMPONENTS

- The ground support system for emplacement drifts consist of friction-type rock bolts such as Split Sets and/or Super Swellex bolts and Bernold-type perforated steel sheets.

- Candidate materials including carbon steel, HSLA steel, and stainless steel are considered in this evaluation.

7.3 LONGEVITY OF STEEL GROUND SUPPORT COMPONENTS

- The temperature effect on mechanical properties of steel has been addressed. It is expected that, for the temperature level expected in emplacement drifts during the preclosure period, the temperature effect on mechanical properties of carbon steel and stainless steel is insignificant.

- For maximum toughness and ductility, the carbon content of carbon steel should be kept as low as possible, consistent with strength requirements. For the temperature level expected in emplacement drifts during the preclosure period, the effect of temperature on toughness and ductility of stainless steel is insignificant.

- Thermal properties of steel, including thermal expansion coefficient, thermal conductivity, and specific heat, were discussed. Thermal expansion coefficient of stainless steel is higher than that of carbon steel. It is more advantageous to use stainless steel than carbon steel for friction-type rock bolts in terms of full-length anchoring mechanism. The impacts of temperature on thermal conductivity and specific heat of carbon steel and stainless steel are insignificant.

- The cumulative neutron fluence and gamma dose due to waste package radiation are far too small to cause any appreciable mechanical damage to carbon steel or stainless steel over the maximum 300-year preclosure period.

- The potential corrosion mechanisms that may be expected in the repository environment have been evaluated. These include dry oxidation, humid-air corrosion, aqueous corrosion, pitting/crevice corrosion, stress corrosion cracking, hydrogen embrittlement, and microbiologically influenced corrosion.

  - The impact of dry oxidation on the performance of carbon steel and stainless steel is insignificant or negligible.

  - For humid-air corrosion, ground support components made of carbon steel will fail after service life of 30 years whereas only the Super Swellex bolt made of HSLA steel will not fail for a service life of 100 years. Ground support components made of stainless steel 316 steel will not fail for a service life of 100 years.

- Carbon steel and HSLA steel will fail due to aqueous corrosion within 10 years whereas stainless steel 316 will not fail for 100 years of service life.

- Stainless steel 316 indicates superior performance against pitting and crevice corrosion. The potential effect of higher temperature on general and localized corrosion for stainless steel 316 is insignificant.

- Based on the stress level, temperature and ground water conditions, it is expected that SCC will probably not occur to friction-type rock bolts during the preclosure. The potential impact of hydrogen embrittlement on friction-type rock bolts is minimum or insignificant.

- The effect of microbiologically influenced corrosion is significant on carbon steel whereas it is insignificant on stainless steel 316.

7.4 RECOMMENDATION

Based on the previous discussions, for a service life of 100 years during the preclosure, both the friction-type rock bolts (Split Sets and/or Swellex bolts) and the perforated steel sheets need to be made of stainless steel, such as 316 (equivalent or better), from the viewpoint of corrosion control. This result confirms the current design on materials for rock bolts and perforated sheets in emplacement drifts (Duan and Board 2003, p. 10). Rock bolts and perforated steel sheets made of stainless steel with thickness of 3 mm will not fail due to corrosion for a service life of 100 years. Furthermore, Swellex bolts may perform better than Split Sets in terms of corrosion attack due to its tubing configuration. Among all friction-type rock bolts, Super Swellex bolts have the highest holding capacity, which is desirable from the viewpoint of structural stability. Moreover, the Super Swellex bolt has a larger tube thickness compared with others, which is also desirable from the viewpoint of minimizing the effects of corrosion.

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