OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT ANALYSIS/MODEL COVER SHEET

Complete Only Applicable Items

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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD

Complete Only Applicable Items

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CONTENTS

Page

CONTENTS (Continued)

Page

FIGURES

TABLES

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ACRONYMS AND ABBREVIATIONS

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
AREA	American Railway Engineering Association
ASTM	American Society for Testing and Materials
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operating Contractor
C_2S	Dicalcium silicate
C_3S	Tricalcium silicate
C_3A	Tricalcium aluminate
C_4AF	Tetracalcium aluminoferrite
C-S-H	calcium silicate hydrogel
DOE	U.S. Department of Energy
DTN	data tracking number
EDA	Enhanced Design Alternative
RH	Relative Humidity
MIC	microbiologically influenced corrosion
MTU	metric tons of uranium
SRB	sulfur-reducing bacteria
TBD	To Be Determined
TBV	To Be Verified
TBM	Tunnel Boring Machine
VA	Viability Assessment
W/C	water-cement
W/CM	water-cementitious material
WP	waste package

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1. PURPOSE

1.1 PURPOSE

The purpose of this analysis is to evaluate the factors affecting the longevity of emplacement drift ground support materials and to develop a basis for selection of materials for ground support that will function throughout the preclosure period. The Development Plan (DP) for this analysis is given in CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) (1999a).

1.2 SCOPE

The candidate materials for ground support are steel (carbon steel, ductile cast iron, galvanized steel, and stainless steel, etc.) and cement. Steel will mainly be used for steel sets, lagging, channels, rock bolts, and wire mesh. Cement usage is only considered in the case of grouted rock bolts. The candidate materials for the invert structure are steel and crushed rock ballast.

The materials shall be evaluated for the repository emplacement drift environment under a specific thermal loading condition based on the proposed License Application Design Selection (LADS) design.

The analysis consists of the following tasks:

- Identify factors affecting the longevity of ground control materials for use in emplacement drifts.
- Review existing documents concerning behavior of candidate ground control materials during the preclosure period. The major criteria to be considered for steel are mechanical and thermal properties, and durability, of which corrosion is the most important concern.
- Evaluate the available results and develop recommendations for material(s) to be used.

2. QUALITY ASSURANCE

This report was prepared in accordance with AP-3.10Q, *Analysis and Models*, and the *Development Plan* (CRWMS M&O 1999a). An activity evaluation (CRWMS M&O 1999b) performed in accordance with QAP-2-0, *Conduct of Activities*, has determined that this analysis is subject to requirements described in *the Quality Assurance Requirements and Description* (QARD) document (DOE 1998). The *Classification of Permanent Items*, QAP-2-3, evaluation entitled *Classification of the MGR Ground Control System* has identified the ground control system at emplacement drifts as Quality Level 2 (QL-2) (CRWMS M&O 1999c, p. 7 of 9, Table 1).

Since this technical report is subject to quality assurance controls, any existing and new to-be-verified (TBV) and to-be-determined (TBD) information will be tracked in accordance with AP-3.15Q, *Managing Technical Product Inputs*.

3. COMPUTER SOFTWARE AND MODEL USAGE

This analysis uses no software other than standard word processing and spreadsheet software. *Microsoft Excel 97* is a commercial spreadsheet program designed to assist in routine calculations. This software was used to perform support calculations and figure presentation in Sections 6.3.3.1 and 6.3.3.2. Documentation of software routines are in accordance with AP-SI.1Q, *Software Management*, Section 5.1.1.

4. INPUTS

4.1 DATA AND PARAMETERS

4.1.1 The areal mass loading (AML) is anticipated to be approximately 60 metric tons of uranium (MTU)/acre while maintaining flexibility within reasonable spans (Wilkins and Heath 1999, Enclosure 2, p. 4).

4.1.2 Reserved.

4.1.3 Reserved.

4.1.4 The highest average percolation rates for matrix and fracture flow in the repository are about 10 mm/year (DTN:MO9901YMP98020.001) (TBV-3311) and 25 mm/year (DTN:MO9901YMP98017.001) (TBV-3312), respectively.

4.1.5 The concentration of chloride, sulfate, bicarbonate as HCO_3^-, and pH of groundwater from Well J-13 are 7.8, 22, and 130 mg/l, and 7.6, respectively (DTN: MO9808RIB00027.004) (TBV-3313).

4.1.6 Strength and Modulus of Elasticity of Steel

The yield point of structural 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 modulus of elasticity of structural steel decreases from an initial value of 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).

4.1.7 Toughness and Ductility of Steel

At 200 °C the notch toughness 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 of a steel with 0.11-percent carbon is about 20 times that of a steel with 0.80-percent carbon (ASM International 1990, p. 739, Fig. 9).

4.1.8 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 11.71×10^{-6}/°C at 100 °C and 12.32×10^{-6}/°C at 200 °C (Merritt 1983, p. 9-67, Eq. 9-75). The thermal expansion coefficient of tuffs for TSw2 formation vary from 7.14×10^{-6}/°C at 25-50 °C to 9.07×10^{-6}/°C at 100-125 °C and 13.09×10^{-6}/°C at 175-200 °C (DTN:SN9510RIB00035.000) (TBV-3757).

4.1.9 Thermal Conductivity and Specific Heat of Steel

The thermal conductivity of carbon steel (grade 1025) for temperature 0 to 200 °C range from 51.9 to 49.0 W/m·K (ASM International 1990, p. 197). The specific heat of carbon steel (grade 1025) for temperature 50 to 200 °C range from 486 to 519 J/kg·K (ASM International 1990, p. 198).

4.1.10 Typical Thickness Data for the Steel Ground Support Components

Typical thickness data for the steel ground support components are shown in Table 1 with source (i.e., reference) of data listed in the table.

Table 1. Typical Thickness Data for the Steel Ground Support Components

Type	Dimension	Thickness (mm)	Remark	Source of Data
Steel Set	W 6 x 20	6.35	Web Thickness	AISC 1995, p. 1-32
	W 8 x 31	7.94	Web Thickness	AISC 1995, p. 1-32
Steel Invert	W 8 x 48	9.53	Web Thickness	AISC 1995, p. 1-32
	W 8 x 67	14.29	Web Thickness	AISC 1995, p. 1-32
	W 12 x 40	7.94	Web Thickness	AISC 1995, p. 1-28
	W 12 x 65	9.53	Web Thickness	AISC 1995, p. 1-28
Rock Bolt	Hollow Bar	10.85	Williams bolt B7X	WFEC 1997, p. 8
	Steel tube	2.29	For Split Set bolt	Peng 1986, p. 228
Bearing Plate	--	9.53	For commonly used bolts	Peng 1986, p. 174
	--	12.7	For Williams bolt R7S	WFEC 1997, p. 38
Wire Mesh	#5 gage	5.26	Wire diameter	AISC 1995, p. 6-2
	#1 gage	7.19	Wire diameter	AISC 1995, p. 6-2
Steel Channel	C 8 x 11.5	6.35	Web thickness	AISC 1995, p. 1-40
Steel Panel	--	6.35	Steel plate thickness	AISC 1995, p. 1-107

4.2 CRITERIA

Appropriate criteria or requirements governing the development of the subject document are presented in this section. The major sources for these criteria are from *Ground Control System Description Document* (GCSDD) (CRWMS M&O 1998a), and *Direction to Transition to Enhanced Design Alternative II* (Wilkins and Heath 1999).

4.2.1 The ground support system provides structural support for the subsurface repository opening (CRWMS M&O 1998a, Section 1.1.1).

4.2.2 The ground support system shall use durable, non-combustible, and heat resistant materials having acceptable long-term effects on the ability of the engineered barrier system to assure waste isolation, including post closure conditions (CRWMS M&O 1998a, Section 1.2.2.1.1).

4.2.3 The ground support in the repository will be carbon steel (steel sets and/or rock bolts and mesh) with granular ballast in the invert. Cementitious grout will be used to anchor the rock bolts. The amount of grout should be kept to a minimum while affording satisfactory performance of the rock bolts. The ground support shall be maintained during the preclosure period (Wilkins and Heath 1999, Enclosure 2, p. 2).

4.2.4 A carbon steel frame will be used to construct the invert, and a granular material will be used as ballast. Criteria for selection of ballast material will include ability to control pH and considerations of thermal, hydrological, and geochemical consequences of available materials. Candidate materials include crushed limestone or marble (Wilkins and Heath 1999, Enclosure 2, p. 2).

4.2.5 Each drift segment in the repository will be ventilated during preclosure, which for base case analyses should be assumed to be 50 years. The ventilation system shall be designed to remove at least 70% of the heat generated by the waste packages during preclosure. The ventilation flow rate may vary with time in order to meet thermal performance requirements (Wilkins and Heath 1999, Enclosure 2, p. 3).

4.2.6 The repository will be capable of closure at 50 years; however the design parameters should not preclude longer operation. For planning purposes, an extended operational period of 100 years should be evaluated (Wilkins and Heath 1999, Enclosure 2, p. 4).

4.2.7 The emplacement drift spacing shall be 81 meters – drift center to center (Wilkins and Heath 1999, Enclosure 2, p. 1).

4.2.8 The diameter of the waste emplacement drifts is 5.5 meter (Wilkins and Heath 1999, Enclosure 2, p. 1).

4.3 CODES AND STANDARDS

Codes and standards applicable to this analysis for longevity of emplacement drift ground support materials are listed in the following:

4.3.1 American Institute of Steel Construction (AISC)

Manual of Steel Construction – Allowable Stress Design, 9th Edition, 1995.

4.3.2 American Society for Testing and Materials (ASTM)

ASTM A 36/ A 36M-97a	*Standard Specification for Carbon Structural Steel*, 1998
ASTM A 82-97	*Standard Specification for Steel Wire, Plain, for Concrete Reinforcement*, 1997
ASTM A 185-97	*Standard Specification for Steel Welded Wire Fabric, Plain, for Concrete Reinforcement*, 1997

ASTM A 572/ A 572M-99	*Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*, 1999
ASTM C 88-99a	*Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate*, 1999
ASTM C 117-95	*Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing*, 1995
ASTM C 127-88 (Reapproved 1993)	*Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate*, 1998
ASTM C 131-96	*Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, 1998
ASTM C 142-98	*Standard Test Method for Clay Lumps and Friable Particles in Aggregate*, 1998
ASTM C 150-97a	*Standard Specification for Portland Cement*, 1998
ASTM C 494-92	*Standard Specification for Chemical Admixtures for Concrete*, 1992
ASTM C 535-96	*Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, 1998
ASTM C 845-96	*Standard Specification for Expansive Hydraulic Cement*, 1996
ASTM C 1240-99	*Standard Specification for Silica Fume for Use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout*, 1999
ASTM D 4791-95	*Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate*, 1995
ASTM F 432-95	*Standard Specification for Roof and Rock Bolts and Accessories*, 1995

4.3.3 American Concrete Institute (ACI)

ACI 201.2R-92	*Guide to Durable Concrete*, 1992
ACI 223-98	*Standard Practice for the Use of Shrinkage – Compensating Concrete*, 1998

4.3.4 American Railway Engineering Association (AREA)

Manual for Railway Engineering, Volume 1, Track, 1997.

5. ASSUMPTIONS

The following assumptions were made in order to perform the analysis.

5.1 It is assumed that the water chemistry from J-13 water well is similar to that of water entering the repository horizon (TBD-3941) (used in Section 6.1.4).

Rationale: J-13 well water has been extracted from TSw2 in the saturated zone, east of Yucca Mountain, so its composition should be indicative of the composition of groundwater at the TSw2 repository horizon. Although J-13 water is from the saturated rocks below the repository, it is a reasonable assumption in absence of better estimations regarding the water chemistry in the repository horizon.

5.2 No human entry in emplacement drifts containing waste packages is planned (CRWMS M&O 1999d, p. 34) (TBV-1015) (used in Section 6.2.1.1).

5.3 It is assumed that the relative humidity (RH) values for dry oxidation, humid-air corrosion, and aqueous corrosion for carbon steel are less than 60 percent, 60 to 80 percent, and 85 to 100 percent, respectively (CRWMS M&O 1998b, pp. 3-5 to 3-7) (TBV-3938) (used in Section 6.3.3).

5.4 It is assumed that no measurable degradation of concrete and cement grout will be predicted below radiation dose of 1×10^{11} rads (TBV-3939) (used in Section 6.4.3.6).

Rationale: The threshold value of 1×10^{11} rads is based on results on concrete (CRWMS M&O 1996, p. C-15). Since the components of cement grout are similar to those of concrete, it is assumed that the same value for concrete will be applicable to cement grout.

5.5 It is assumed that the relative humidity (RH) in the emplacement drifts ranges from 1 to 40% during the preclosure period (CRWMS M&O 1998a, page 18 of 24) (TBV-3940) (used in Sections 6.1.2, and 6.3.3.2).

6. ANALYSIS/MODEL

The methodology used in this analysis is to evaluate the factors affecting longevity of emplacement drift ground support materials during the preclosure period. By reviewing existing documents concerning performance of candidate ground support materials and evaluating their behaviors under emplacement drift environment, a basis for selection of materials for ground support is provided.

6.1 EMPLACEMENT DRIFT ENVIRONMENTAL CONDITIONS

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

6.1.1 Temperature

For an unventilated emplacement drift, upon waste emplacement, emplacement drifts will experience increases in temperature from the heat output from the waste packages. The drift wall temperatures will increase due to thermal radiation from the waste packages. Natural convection by air is considered to have very limited effect on the heating process in the drifts and, therefore, is neglected (CRWMS M&O 1998d, p. 61 of 140). Within the rock mass, heat flow will occur by conduction due to the thermal gradient between the high-temperature drift wall and the low-temperature rock further away from the drift.

The drift wall temperatures depend on the waste package (WP) assembly configuration, WP spacing, drift spacing and diameter and ventilation. Based on a thermal load of 60 MTU/acre (Section 4.1.1) and 21 PWR waste package for 5.5 m drift diameter (Section 4.2.8) and 81 m drift spacing (Section 4.2.7) under an unventilated scenario, the emplacement drift wall temperature will be above 150 °C for at least 300 years following waste emplacement and remain above boiling for more than two thousand years (CRWMS M&O 1999f, Page IV-15 of IV-27).

Based on the Enhanced Design Alternative (EDA) II design, continuous ventilation rates of 2, 5, and 10 m^3/s per emplacement drift were considered in the thermal calculations (CRWMS M&O 1999e, p. 5-11). The temperature distribution for continuous ventilation with air quantity of 10 m^3/s shows that the drift wall temperature will increase from about 70 °C at 1 year to a peak at about 85 °C at 20 years and, then, decrease to about 55 °C at 100 years, and 50 °C at 150 years following waste emplacement (CRWMS M&O 1999f, Page IV-14 of IV-27). The wall temperatures in the emplacement drifts will be below boiling during preclosure. For ventilation with an air quantity of 2 m^3/s for 50 years, the drift wall temperature will be above boiling for about 50 years following waste emplacement with peak at about 180 °C at 20 years and would probably stay above boiling even if ventilation were continued beyond 50 years (see Page IV-7 of IV-27 of CRWMS M&O 1999f). For ventilation with an air quantity of 5 m^3/s for 50 years, the drift wall temperature will be above boiling for about 50 years following waste emplacement and would probably drop below boiling if ventilation were continued beyond 50 years (see Page IV-8 of IV-27 of CRWMS M&O 1999f).

The above temperature distributions illustrate the temperature profiles at the emplacement drift wall during preclosure with continuous ventilation of 2 to 10 m^3/s. It clearly indicates that the temperatures at the emplacement drift wall will be above boiling for most of the time during the preclosure period for ventilation rates of 2 and 5 m^3/s. The temperatures at the emplacement drift wall will be below boiling during the preclosure period for ventilation rates of 10 m^3/s based on EDA II design. If the waste stream condition and other conditions change, the temperatures at drift wall will also be affected. Since the ventilation system shall be designed to remove at least 70% of the heat generated by the waste packages during preclosure (Section 4.2.5), it may be necessary to use continuous ventilation of at least 10 m^3/s to achieve this requirement. Therefore, the temperatures at the emplacement drift wall will be below boiling during the preclosure period.

6.1.2 Relative Humidity

The relative humidity (RH) in an emplacement drift varies with location and time. It 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. 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 based on the requirements in EDA II, the RH will be relatively low. For example, based on a recent study on repository ventilation for an assumed airflow of 1.0 m^3/s and a water influx of 60 mm/year at thermal loading of 85 MTU/acre, the highest RH predicted for a 150-year time frame is 21.98 percent (CRWMS M&O 1999g, p. VIII-1 of VIII-1).

Since the highest percolation rate in the repository horizon will be about 35 mm/year (see Section 6.1.4), which is smaller than 60 mm/year in the previous ventilation study, the RH would be smaller. However, since the thermal loading level is lower, i.e., 60 MTU/acre (Section 4.1.1) and ventilation rate will probably be higher than 1.0 m^3/s, the actual RH can not be determined without detailed analysis. It should be noted that the RH in the emplacement drifts will be between 1 to 40 percent during the preclosure period (Assumption 5.5).

It should be indicated that the above statement for RH is applicable for steel sets, rock bolt heads, bearing plates, wire mesh, and invert materials that are exposed to the ventilation air. With regard to the drill holes for rock bolts, the relative humidity before cement grout injection should be similar to that within the drift. After the cement grout has been injected and hardened, most of the pores in the hardened grout will be partially filled with water. Any cracks or fractures encountered along the length of the drill hole are expected to be blocked by a grout layer with very low permeability.

6.1.3 Radiation

Radiation hazards from the waste packages will come from different types of radiation including alpha-particles, beta-particles, neutrons, and photons (gamma- and x-rays). The primary radiation from the waste package is neutron and gamma radiation because the alpha and beta radiation are stopped by the disposal container (CRWMS M&O 1996, p. C-9). Gamma radiation can strike electrons from the outward orbits of the atoms it contacts whereas neutrons interact with nucleii.

According to *MGDS Subsurface Radiation Shielding Analysis* (CRWMS M&O 1997a, p. 99 of 105), for 10-year old, 21-PWR spent fuel assemblies at 48,086 MWD/MTU burnup with a 4.2 percent initial enrichment, the combined cumulative radiation doses for neutron and gamma at a concrete lining surface 100 and 150 years after initial emplacement of waste are 1.857 $x10^6$ and 1.935 $x10^6$ rems, respectively. It is expected that the cumulative radiation dose at the drift wall is at the same level as that for a concrete lining. It should be pointed out that the dose unit of rems was cited from the quoted reference (CRWMS M&O 1997a, p. 99 of 105), the adequate dose unit for material should be in rads.

For normal conditions, the in-drift radiation field on the WP surface immediately after waste emplacement is about 40 rem/hr, dropping to less than 1 rem/hr at 90 years after emplacement (CRWMS M&O 1997a, p. 96 of 105). As a result, the materials used in the emplacement drifts will receive the most radiation dose early in the preclosure period. For example, for a 150 year period, the cumulative dose reaches 40 percent at 10 years after emplacement, and 83 percent at 50 years after emplacement (CRWMS M&O 1997a, p. 99 of 105).

It should be pointed out that the cumulative radiation doses and rates in the above discussions are estimated values made for that specific condition. The change in the WP design with thinner walls for EDA II design would increase the corresponding radiation fields. Such increase is not expected to have any significant impact on the ground support material.

6.1.4 Ground Water Characteristics at Repository Horizon

The repository horizon is located in a zone of the unsaturated rock within Yucca Mountain. There are two potential pathways for groundwater flow in the unsaturated zone at Yucca Mountain. The first is matrix flow, or the flux of groundwater through the interconnected pores of the rock mass. The second is fracture flow, or the flux of groundwater 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 assumed to be the only natural source of groundwater in the unsaturated zone in the Yucca Mountain area. Based on the updated data, the highest average percolation rates for matrix and fracture flow in the repository are about 10 mm/year (DTN:MO9901YMP98020.001) (TBV-3311) and 25 mm/year (DTN:MO9901YMP98017.001) (TBV-3312) (Section 4.1.4), respectively; hence, the highest percolation rate is about 35 mm/year. Fault zones may also be important pathways for groundwater flow. However, the repository is designed to avoid faulted areas. Hydration water from the cement grout for fully grouted rock bolts could be lost at temperatures above boiling but the amount should be of a very small magnitude since a low water/cementitious material ratio is to be used.

In assessing the effect of the chemistry of the ground water on the longevity of ground support components, it is assumed that the water chemistry from the J-13 water well is similar to that in the repository horizon (Assumption 5.1). Although J-13 water is from the saturated rocks below the repository, it is a reasonable assumption in absence of better estimations regarding the water chemistry in the repository horizon. The most important characteristics from ground water related to steel corrosion and cement grout longevity are Cl^-, SO_4^{2-}, HCO_3^-, and pH, the corresponding values of which from J-13 well water are 7.8, 22, 130 mg/l, and 7.6, respectively (DTN: MO9808RIB00027.004) (TBV-3313) (Section 4.1.5).

6.2 EMPLACEMENT DRIFT GROUND SUPPORT COMPONENTS

In accordance with the EDA II design, the ground support in the repository emplacement drifts will be steel sets and/or rock bolts and mesh (Wilkins and Health 1999). With regard to these two major ground support systems, two alternatives for rock bolt systems and four alternatives for steel set lining systems were considered in a ground support evaluation study (CRWMS M&O 1998c, p. 11). They are (a) rock bolts, mesh and channel, (b) rock bolts and shotcrete, (c) steel sets and steel channel lagging, (d) steel sets and wire mesh, (e) steel sets and steel panel lagging, and (f) steel sets and shotcrete. Of these six alternatives, ground support systems with the shotcrete option will not be considered further for two major reasons: a large amount of cementitious materials would need to be used and high thermal stress may be induced in the shotcrete and induce cracks. Based on EDA II design, cementitious materials will only be used for grout to anchor the rock bolts and the amount of grout should be kept to a minimum while affording satisfactory performance of the rock bolts (Wilkins and Health 1999). Among the steel set lining systems, although the steel sets with wire mesh receives one of the lowest ratings on undesirable characteristics (CRWMS M&O 1998c, p. 72), no distinction is to be made in this study in terms of material longevity. In this section, only rock bolts and steel sets will be discussed. The discussion of inverts will be presented in Section 6.5.

6.2.1 Rock Bolt System

A pattern rock bolt system, with welded wire fabric and steel channels, has been successfully used in portions of the 7.6-meter-diameter main loop tunnel in the Exploratory Study Facility (ESF). A third of this tunnel was excavated in rock of the proposed repository block, TSw2 unit (CRWMS M&O 1998d, p. 72 of 140). Although the ESF tunnels have not been subjected to the elevated temperatures expected to be present in the repository drifts and the bolts were of a temporary type, these tunnels provide an initial basis for developing a bolted support system for the repository. Welded wire mesh will usually be installed above the spring line, and arched steel channels used as continuous bearing plate to secure the mesh across the crown area. Supplemental bolting and mesh below the spring line may also be needed to prevent loose rock from raveling.

6.2.1.1 Rock Bolt Types

There are two basic types of rock bolts in terms of anchorage, those that are point-anchored (mainly mechanical bolts) and those that are fully grouted or full-column supported. The point-anchored bolts are mainly mechanically anchored tensioned bolts whereas fully grouted bolts can be either tensioned or untensioned. Although mechanical bolts are very common in underground mining operations, there are many instances of bolt tension decreasing with time because the anchoring mechanism is by tension. Therefore, mechanical anchors are generally retested periodically to determine if slippage has occurred. Since no human entry is planned in emplacement drifts while waste packages are present (Assumption 5.2), entry to the repository emplacement drifts will be limited to off-normal conditions. Access to the emplacement drifts would require blast cooling and removal of the waste packages prior to entry, involving considerable time and effort. Hence, mechanical anchors will not be considered further.

Full-column supported bolts develop their support capacities from the friction between the steel tubes and the rock. Split Set and Swellex bolts are the main types used in underground support. However, because of their thin-walled construction and large surface area, they are more susceptible than conventional bolts to damage by corrosion. For this reason, they are not recommended for long-term use. Fully grouted bolts use either resin or cement as grouting material (see further discussion in Section 6.2.1.3), with the former commonly used in the mining industry whereas the latter is generally used for civil construction.

6.2.1.2 Characteristics of Fully Grouted Rock Bolts

In general, fully grouted resin bolts have the following advantages (Peng 1986, p. 217):

- Virtually guaranteed anchorage under normal conditions.
- Resistance to both vertical and lateral movements.
- Capability to seal wet holes and exclude air, thereby reducing corrosion of the bolt assembly and weathering of the rock.
- Grout remains effective even with damage to the bolt head, bearing plate, or rock at the collar of the hole.
- Capability to absorb blast vibrations without bleed-off of the bolt load.
- Excellent performance with regard to anchorage creep.

It is expected that fully cement-grouted bolts have similar advantages because the reinforcing mechanism is similar. However, it should be pointed out that the above advantages apply to normal underground operations. For high temperature conditions in an emplacement drift environment, overstress may be induced in the anchor point, bolt steel, bearing plate, or other components, which needs further investigation.

6.2.1.3 Grout Types

The two main types of grouts for anchoring bolts are resin and cement. Although resin grouts have been widely used in the mining industry, there are some disadvantages to this type of material in the proposed repository environment. Firstly, most epoxy and polyester resins are suspected of (a) undergoing creep in elevated temperature environment, and (b) experiencing a marked reduction in strength (Leedy and Watters 1994, p. 692) under these conditions. At temperature of 100°C, the reduction in grout strength for polymer resin is 40 percent (Leedy and Watters 1994, p. 692). At temperatures approaching 200 °C, polymer resins that are epoxy or polymer based have essentially zero strength (Leedy and Watters 1994, p. 692). Another major drawback with resin grouts is that they are of an organic nature, which may favor microbiological activity; therefore, these grouts are not desirable from the long-term postclosure performance viewpoint.

On the other hand, cement grouts only have a slight strength reduction at the elevated temperatures expected in the emplacement drift environment (Leedy and Watters 1994, p. 692) (see further discussion in Section 6.4.2.1.)

Because the cement grouts have favorable characteristics compared with resin grouts as described above, the Repository Subsurface Design Department is currently considering fully cement grouted bolts as the candidate rock bolt system.

6.2.2 Steel Sets

As indicated in Section 6.2, three configurations of steel set ground support are considered in this study. They are steel sets with channel lagging, steel sets with wire mesh, and steel sets with panel lagging. A detailed discussion regarding these three support systems is presented in *Ground Support Alternatives Evaluation for Emplacement Drifts* (CRWMS M&O 1998c, Sections 5.6 to 5.8).

These three types of steel set ground support comprise the proposed all-steel lining for emplacement drift support. The steel sets with heavy wire mesh or channel lagging is installed in a single-pass operation immediately behind the Tunnel Boring Machine (TBM). For the steel set and panel configuration, it is installed in a two-pass operation. Steel sets are erected at a uniform spacing along the tunnel axis, and then bolted together using tie rods to form a continuous structure along the length of tunnel. The detailed installation process for these three types of ground support is provided in the above mentioned report (CRWMS M&O 1998c, Sections 5.6 to 5.8).

6.2.3 Candidate Materials for Emplacement Drift

During the early development of candidate materials for steel as the ground support, carbon steel, galvanized steel, and stainless steel were considered. However, based on the *Direction to Transition to Enhanced Design Alternative II* (Wilkins and Heath 1999, Enclosure 2, p. 2), the ground support will be carbon steel (steel sets and/or rock bolts and mesh) with granular ballast in the invert. Galvanized steel and stainless steel will not be considered further for the following reasons:

Galvanized steel is considered to protect against steel corrosion in many applications. However, zinc may react with cementitious materials to produce hydrogen gas, which is not desirable in the emplacement drifts. If rock bolts were made with galvanized steel, they could react with the cement grout to generate hydrogen gas, which would form bubbles in the grout. This is also not desirable. Moreover, the long-term behavior of this coating under high temperature is not known. Therefore, it is not advisable to apply protective coatings of galvanizing steel to the steel ground support in the emplacement drifts.

Stainless steel is resistant to corrosion over a wide range of water chemistry. However, stainless steel is not the solution to all corrosion problems. Depending on its chemical composition and the temperature and chemistry of the environment, it can be subjected to chloride pitting, crevice corrosion and stress corrosion cracking, including hydrogen embrittlement. Stainless steel may not be adequate for all situations. Especially, the cost of stainless steel is about three to five times that of the conventional carbon steel, depending on the quantity needed. As will be explained below, the corrosion of carbon steel is not expected to be a potential problem for steel ground support under expected environmental conditions; therefore, stainless steel will not be considered for emplacement drift ground support in this study.

For ground support made with carbon steel, the following ASTM specifications are proposed:

Steel sets:	A 36 or A 572
Rock bolts:	F 432
Steel wire mesh:	A 185 and A 82.

For cement grout to be used with rock bolts, the following specifications are proposed:

Cement:	C 845 for expansive hydraulic cement
Silica fume:	C 1240
Superplasticizer:	C 494.

For crushed rock ballast, crushed limestone or marble are selected as candidate materials based on the Direction to Transition to Enhanced Design Alternative II (Wilkins and Heath 1999, Enclose 2, p. 2). Crushed tuff is also considered as a candidate material for the invert because it will be compatible with host rock.

6.3 LONGEVITY OF STEEL

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

- Structural steel sets (also referred to as steel rings or ribs)
- Rock bolts (including bearing plates and washers)
- Steel mesh (welded wire fabric or chain link mesh), channels, straps, and panels
- Steel invert

Only carbon steel components will be considered in this study.

6.3.1 Temperature Effect on Mechanical Properties

In this section, changes in the mechanical properties of steel materials under elevated temperatures will be briefly discussed.

6.3.1.1 Strength and Modulus of Elasticity

The yield point of structural 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 (Section 4.1.6). By interpolation, the calculated values at 200 °C and at 100 °C are about 91 and 96 percent, respectively, of that at 20 °C. The modulus of elasticity of structural steel decreases from an initial value of 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. Assuming the modulus of elasticity of carbon steel is linearly related to the temperature and using the above mentioned values, the modulus of elasticity will be 189 GPa (27,400 ksi) at 200 °C and 195 GPa (28,300 ksi) at 100 °C, decreases which are about 5 percent and 2.5 percent, respectively, in comparison with the value at 20 °C.

The AISC document (AISC 1995, p. 6-3) also notes that the yield strength of carbon steel at 430 °C is approximately 77 percent of room-temperature strength; at 540 °C, yield strength is 63 percent of room temperature strength. Creep is not observed in these steels until temperatures are above 370 °C (ASM International 1990, p. 622).

Based on these data, it is quite likely that the effect of elevated temperature on the strength and modulus of elasticity of carbon steel components is insignificant (i.e., 4 percent decrease) if the maximum temperature in the emplacement drift is 100 °C and very small (i.e., 9 percent decrease) if maximum temperature is 200 °C.

6.3.1.2 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 are increased (ASM International 1990, p. 739, Fig. 9). At 200 °C the notch toughness 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 of a steel with 0.11-percent carbon is about 20 times that of a steel with 0.80-percent carbon (Section 4.1.7). The 0.80-percent carbon steel exhibits the least ductility of the carbon steels. For maximum toughness and ductility, the carbon content should be kept as low as possible, consistent with strength requirements (ASM International 1990, p. 739, Fig. 9).

Steel components manufactured based on the standard specification included in the American Society for Testing and Materials ASTM A 36-97a, *Standard Specification for Carbon Structural Steel*, or A 572-99, *Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*, and F 432-95, *Standard Specification for Roof and Rock Bolts and Accessories*, are expected to perform satisfactorily in the anticipated repository environment. Further study and tests are needed to determine the proper compositions of carbon steel to be used as ground support material in the emplacement drift environment.

6.3.2 Thermal Properties

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

6.3.2.1 Thermal Expansion Coefficient

Structural steels (i.e., carbon steels) have a coefficient of thermal expansion that varies from about 11.24 x 10^{-6}/°C at 25 °C to 11.71 x 10^{-6}/°C at 100 °C and 12.32 x 10^{-6}/°C at 200 °C (Section 4.1.8). The thermal expansion coefficient for TSw2 tuff for near-field considerations is shown to vary from 7.14 x 10^{-6}/°C at 25-50 °C to 9.07 x 10^{-6}/°C at 100-125 °C and 13.09 x 10^{-6}/°C at 175-200 °C (Section 4.1.8). These data show that the differences in expansion coefficients between tuff and steel decrease from about 4.1 x 10^{-6}/°C at 25 °C, to about 2.64 x 10^{-6}/°C and 0.77 x 10^{-6}/°C at 100 and 200 °C, respectively. Because the thermal expansion coefficients for carbon steel and for tuff are not very different and the rate of repository heating is expected to be slow at temperatures up to boiling, the effects of temperature on differential thermal expansion are anticipated to be minor during the preclosure period.

6.3.2.2 Thermal Conductivity and Specific Heat

The average thermal conductivity of carbon steel (grade 1025) for temperature 0 to 200 °C is 50.67 W/m·K, based on values ranging from 51.9 to 49.0 W/m·K (Section 4.1.9), with higher values for lower temperatures. The average specific heat of carbon steel (grade 1025) for temperature 50 to 200 °C is 502.5 J/kg·K, based on values ranging from 486 to 519 J/kg·K (Section 4.1.9) with higher values for higher temperatures. Based on these data, for temperatures below boiling at emplacement drift wall, the impacts of temperature on thermal conductivity and specific heat of carbon steel are insignificant.

It should be noted that the grade and specification of the carbon steel to be used in emplacement drifts has not been determined for the proposed repository. The grade 1025 carbon steel is used here to only illustrate the relative values of the parameter of interest and how these values vary with temperature. Further studies need to be conducted to determine the proper grade and specification of the carbon steel to be used for the ground support components.

6.3.3 Assessment of Corrosion

One of the most important processes that control the longevity of steel ground support is corrosion. The assessment of corrosion in this section applies to all steel ground support components, which include steel sets, steel wire mesh, channel lagging, steel panels, rock bolts, bearing plates, steel invert, etc.

The corrosion of steel ground support materials will depend on the properties of the steel materials and the environment in which the ground supports are installed. In this study, only carbon steel will be discussed, based on the requirements in Direction to Transition to Enhanced Design Alternative II (Section 4.2.3). Although the important environmental conditions affecting steel corrosion include temperature, RH, water chemistry, and oxygen partial pressure, only temperature and RH will be considered in the evaluation of corrosion potential at emplacement drift environment. The impact of water chemistry on steel corrosion potential is expected to be insignificant because of: 1) the amount of percolation is very small (Section 4.1.4), 2) neither pitting nor crevice corrosion is expected to occur since the Cl^- content in the groundwater is very low (Section 4.1.5), and 3) the pH value in the groundwater is 7.6 (Section 4.1.5), i.e., nearly neutral, which will minimize the corrosion potential of steel. Even if some higher Cl^- concentrations or pH excursions may occur, all liquid water will be carried away by the high amount of ventilation. The impact of oxygen partial pressure is likely to be insignificant during the preclosure period due to continuous ventilation.

The RH is generally expressed as the percentage ratio of the water vapor pressure in the atmosphere compared with that which would saturate the atmosphere at the same temperature. It is a very important 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 in the emplacement drifts can be categorized as dry oxidation, humid-air corrosion, and aqueous corrosion (CRWMS M&O 1998b, pp. 3-5 to 3-7). The corresponding RH values for these three types of corrosion are generally considered to be in the following ranges: less than 60 percent, 60 to 80 percent, and 85 to 100 percent, respectively (Assumption 5.3). The aqueous condition is equivalent to "immersion" or "bulk water" (CRWMS M&O 1998b, p. 3-7), which is not expected to occur in emplacement drifts during the preclosure period, based on the EDA II design, in which mobilized water (if any) will drain through the pillars rather than through the emplacement drifts (CRWMS M&O 1999e, p. v). In addition, due to the very high volume of ventilation required to remove 70 percent of heat generated by waste package (Section 4.2.5), the percolation water will be carried away by the high amount of ventilation. Therefore, aqueous corrosion will not be considered in this study.

6.3.3.1 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 60 percent). An empirical equation has been derived for the penetration depth of carbon steel due to this type of corrosion as follows (Stahl et al. 1995):

$$P = 178{,}700 \times t^{0.33} \times e^{-6870/T}, \qquad (1)$$

where P is penetration depth in microns, t is time in years and T is temperature in degrees Kelvin.

Table 2 shows the corrosion penetration depth for time period of 50 to 150 years with temperatures ranging from 60 to 200 °C, calculated based on Equation 1. Figure 1 presents the results based on Table 2. As can be seen from Table 2 and Figure 1, the estimated corrosion

Table 2. Estimated Penetration Depths of Dry Oxidation for Carbon Steel (μm)

T (°C)	50 years	100 years	150 years
60	0.001	0.001	0.001
70	0.001	0.002	0.002
80	0.002	0.003	0.003
90	0.004	0.005	0.006
100	0.007	0.008	0.009
110	0.011	0.013	0.015
120	0.017	0.021	0.024
130	0.026	0.032	0.037
140	0.039	0.049	0.056
150	0.057	0.072	0.083
160	0.084	0.105	0.120
170	0.120	0.150	0.172
180	0.168	0.212	0.242
190	0.234	0.294	0.336
200	0.320	0.402	0.460

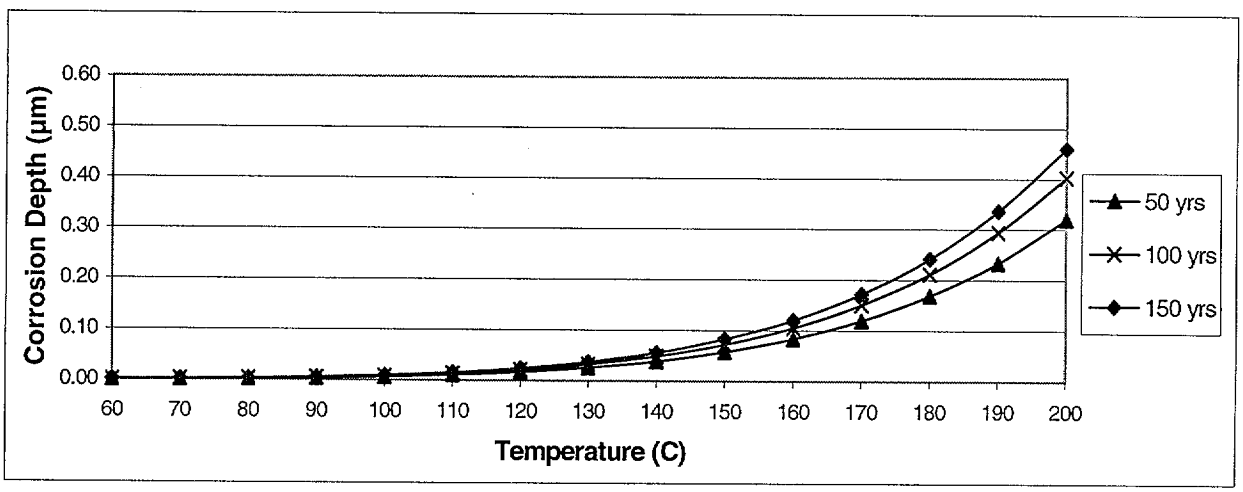

Figure 1. Estimated Penetration Depths of Carbon Steel for Dry Oxidation

depths under dry oxidation condition are very small; less than 0.01 μm at 100 °C, less than 0.1 μm at 150 °C and less than 0.5 μm at 200 °C for a period of 150 years. The impact of dry oxidation on performance of steel ground support components such as steel sets and rock bolts should be insignificant during the preclosure period of the repository.

6.3.3.2 Humid-Air Corrosion

In general, humid-air corrosion of steel occurs under RH of 60 to 80 percent. The lower limit of this range is much higher than the expected RH (no greater than 40 percent) in the ventilated emplacement drifts during the preclosure period (Assumption 5.5). 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. Because the emplacement drifts will be continuously ventilated, significant amounts of dust will not be present in the drifts. However, in some localized areas of the repository oxides and salts may accumulate on the surface of some steel components by precipitation of these salts from the evaporation of ground water from the host rock due to elevated temperatures generated from waste packages. Therefore, although quite improbable, conditions for humid-air corrosion in some localizied areas are possible in the drifts during the preclosure period.

Corrosion depths of steel ground support components under humid-air conditions were broadly approximated using experimental result 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) were 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 A516 and cast carbon steel. The test environments closest to the emplacement drift condition are at the vapor phase of SDW (simulated dilute well J-13 at 10x concentration) solution with temperatures of 60 °C and 90 °C. The one-year corrosion rates (μm/year) for the test results from the two materials under these two temperature conditions are 27, 37, and 56, 39, 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). However, for emplacement drifts under ventilated condition, the RH will be at most about 40 percent (see Section 6.1.2), which is below the lower limit for humid-air corrosion (see Section 6.3.3). Although the corrosion rate below RH of 60 percent is believed to be very small, compared with that above 60 percent, the actual rate can not be determined without testing. For illustrative purpose, reduction factors of 100, 10, and 5, i.e., one-hundredth, one-tenth, and one-fifth, of the corrosion rate with RH above 60 percent (i.e., 40 μm/year) are used to plot the corrosion depths for Corrosion Rates A, B, and C as shown in Figure 2 (note that the total corrosion depth for steel exposed to air is two times of that shown in the figure). By comparing Figure 2 and Figure 1, it is very clear that the corrosion depth based on humid-air conditions is much greater than that from dry oxidation.

Table 1 shows some typical thickness data of some steel ground support components (Section 4.1.10). By comparing the thickness data in this table with the corrosion depths depicted from Figure 2, the impact of corrosion on the support components can be derived. For example, if for each component 10 percent loss of its thickness is the maximum allowance before its strength is compromised, the following results can be made: (1) For Rate A: None will fail for 150-yr period. (2) For Rate B: All components except Split Set would not fail for 50 years. However, for a time period of 100 years, all of components except W 8x48, W 8x67, and W 12x65 steel invert, Williams bolt and bearing plates, would probably fail due to insufficient thickness. (3) For Rate C: All of components except W 8x48, W 8x67, and W 12x65 steel invert, Williams bolt and bearing plates, would probably fail for 50 years and all components will fail for a 100-yr period.

It should be emphasized that the above discussions are made merely to illustrate the impact of corrosion on structural components without detailed structural analysis. However, the illustrative example does show the need for systematic studies and tests to accurately estimate the probable humid-air corrosion rate and to investigate the potential of this type of corrosion in the repository.

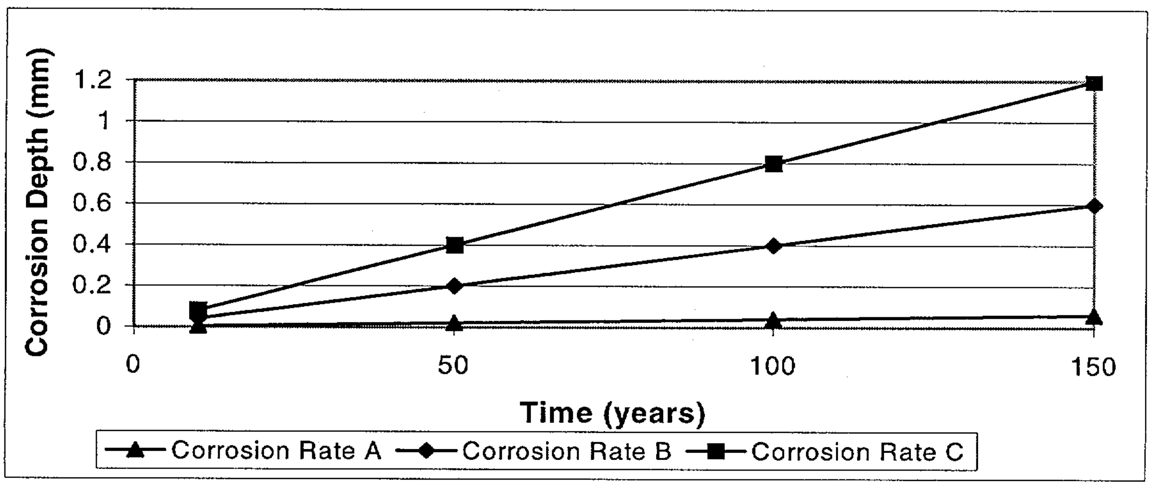

Figure 2. Illustrative Example of Humid-Air Corrosion Depths for Carbon Steel

6.3.4 Biological Effect

In aqueous, oxygen-free, reduced environments, the lifetime of steel and iron material is diminished by sulfur-reducing bacteria (SRB), which require the availability of sulfate, an electron acceptor, and a carbon source (CRWMS M&O 1996, p. C-10). Although the deleterious effects of SRB have been demonstrated in both laboratory and natural settings, the special conditions required for SRB to corrode steel do not exist at the Yucca Mountain repository.

The presence of oxygen, low RH, and elevated temperatures creates an environment hostile to SRB. In the absence of the specialized environment required for SRB metabolism, the corrosion of steel by SRB is not expected to occur.

The potential for microbiologically influenced corrosion (MIC) is related to bacteria and fungal growth, which is controlled by the availability of nutrients, water, and electron acceptors. All of these conditions must be available to have the potential for MIC. For the current ground support design, concrete lining is not considered. Cementitious grout will be used to anchor the rock bolts and its amount will be kept to a minimum (Section 4.2.3). Since superplasticizer is planned to be used in the cement grout, and thus may become the supply of nutrients for microbial activity, by minimizing the amount of cement grout the supply of nutrients will be significantly reduced. Most importantly, the potential for MIC is greatly affected by the presence or absence of water. Since the emplacement drifts are expected to be dry and low in RH (no greater than 40 percent) during the preclosure, the potential for MIC for steel sets will not be present (CRWMS M&O 1998b, Section 3.3.4). For steel bolts in the rock bolt system, since the bolt will be sealed by a grout with very low permeability (see Section 6.4.1), the water flow into the grout will be either blocked or substantially reduced; thus, the potential of MIC in bolts is insignificant.

6.3.5 Radiation Effect

Generally, the only type of radiation emanating from the waste packages that may affect steel is the neutron field, as gamma radiation has no known significant effect upon the structural properties of steel (CRWMS M&O 1996, p. C-9).

Because the estimated neutron fluence over the service life of the underground facilities is less than 2.2×10^{20} n/m^2 (considering a 100-year service life), the increase in the ductile-brittle transition temperature is not expected to be more than 0.6 °K (0.8 °K for a 144-year service life) (CRWMS M&O 1996, p. C-10). Neglecting the decay in neutron radiation, the increase in the ductile-brittle transition temperature is not expected to be more than 0.9 °K for a 150-year service life. It should be noted that these values are very conservative because shielding from the waste package walls, decay of radioactivity, and geometric divergence are not considered. Furthermore, the transition temperature change is a function of the type of steel and how it is welded.

As it was pointed out in Section 6.1.3, the radiation fields based on waste package design in EDA II will change from VA. Although such a change is not expected to have a significant impact on the steel ground support material, because the expected change in the brittle-ductile transition temperature may be very small, further investigation on the effect of radiation on steel properties due to the change in WP design is needed. It should also be pointed out that the radiation effect is further reduced for the steel rock bolts, which are installed inside the rock mass and, therefore, shielded from radiation by the rock mass (see Section 6.4.4.6).

In summary, the impact of effect of neutron irradiation on steel should be minimal or insignificant during the preclosure period.

6.3.6 Longevity of Steel Ground Support Elements

Based on the above discussions regarding the longevity of the steel ground support components under the expected environment, i.e., elevated temperature (ranging from about 55 °C to above the boiling point of water) and low RH (lower than 40 percent), the potential for corrosion of steel sets and other steel components such as wire mesh, channels, panels, nut and bolts for fastening lagging to steel sets, etc., is not anticipated to be significant enough to compromise their structural integrity.

Steel corrosion in mines is usually caused by sulfuric acid generated by the oxidation of ore-bearing and pyritic sulfide phases. This type of aggressive corrosion is not expected in the waste emplacement drifts since no sulfides have been observed in the repository host formation. Per Section 6.3.4, the potential for MIC in steel sets will not be present and the potential of MIC in steel bolts of the rock bolt system is insignificant. Per Section 6.3.5, the effect of radiation on steel will be likely insignificant. In addition, the impacts on mechanical properties including strength, modulus of elasticity, toughness, and ductility of steel due to elevated temperatures are minimal since the maximum temperature at emplacement drift during the preclosure period will be boiling for EDA II design (see Section 6.1.1), which is not high enough to cause significant change in the mechanical properties at ambient conditions.

The above conclusion also applies to rock bolts heads and bearing plates, which are made with carbon steel materials. For the majority portion of the rock bolt, which is encapsulated by cement grout and inside the rock mass, i.e., not exposed directly to the air, the corrosion potential is reduced even further.

Based on the empirical corrosion rate for carbon steel under dry oxidation, the maximum corrosion depth for temperatures up to 200 °C for a 150-year period is less than 0.5 μm, which is negligible. Although this dry environment may prevail during the preclosure period, there may be some localized conditions where humid-air corrosion may occur, especially for such a large repository area and a long operational period. Due to the length of time that the steel ground support components must remain functional, it would be prudent to design steel sets, rock bolts, mesh, straps, and lagging with allowance of some amount of material loss. In this situation, systematic studies and tests as recommended at the end of Section 6.3.3.2 should be completed to accurately estimate the corrosion depths in humid-air conditions and used in selecting the material types and thickness.

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. However, based on the above discussions, the steel ground support components can be designed to be functional and durable during the preclosure period for a service life of up to 150 years, with adequate type, size (thickness), material composition, and method of installation.

6.4 LONGEVITY OF CEMENT GROUT

As discussed in Sections 6.2.1.2 and 6.2.1.3, fully cement-grouted rock bolts, which would perform superior to other types of rock bolts in the emplacement drift environment, are being considered as the candidate rock bolt system. This rock bolt system consists of several components made from two material types: 1) steel (steel bolts and accessories such as bearing plates, washers, and wire mesh) and 2) cement grout that fully grouts the steel bolt.

The issues associated with the longevity of the steel components of the rock bolt system have been discussed in Section 6.3. In this section, the issues associated with the longevity of cement grout are discussed (Section 6.4.3) after introduction of the desirable characteristics of cement grout and its components (Section 6.4.1) and mechanical and thermal properties of cement grout (Section 6.4.2).

The grout plays a significant role in determining the longevity of the rock bolt system; the integrity of the grout controls the steel bolt-grout-rock bounding capacity, prevents water percolation and steel bolt corrosion. The grout provides the overall protection to the steel bolt and borehole from damage and deterioration.

It should be pointed out that the degradation of cement grout under the elevated temperature condition in the repository and its interaction with groundwater, steel components of the rock bolt system and other engineered barrier components as well as with radionuclides and with the geosphere is a very complex phenomena. Many processes are coupled in a very complicated manner. To evaluate properly the behavior of cement grout under repository conditions there is a clear need for further systematic research work to improve our understanding of phenomena that may take place in the repository and to provide appropriate data to develop mechanistic and empirical models. Nevertheless, a basic knowledge of the characteristics of the cement grout components is necessary to understand the principal mechanisms that control the grout degradation and its interaction with other components of the rock bolt system. This will be examined first, then, factors affecting the longevity of cement grout. Finally, design considerations for grout in fully grouted rock bolts in terms of longevity will be addressed.

It should be noted that the potential effect of cementitious materials on long-term waste package performance during the postclosure period is not within the scope of this study and will not be included. However, due to the limited volume of cementitious materials and the corrosion resistance of the outer barrier material, no adverse effect on performance is expected.

6.4.1 Desirable Characteristics of Cement Grout and Its Components

Of particular importance to the proper functioning of fully grouted rock bolts in the emplacement drifts is the development of a suitable grout to act as a corrosion barrier for the steel bolt and to retain sufficient strength to maintain the rock reinforcement function with little or no maintenance for a period of up to 150 years. In addition, the grout should have acceptable low hydraulic conductivity, i.e., less than 10^{-12} m/s (Onofrei et al. 1992, p. 137), as well as physical and chemical compatibility with the host environment.

For cement-based grout to perform as a hydrological barrier, it must have a low hydraulic conductivity, be free of cracks, and not shrink under service conditions. Ability to perform over a long term period would require chemical stability under in-situ and expected future conditions and physical stability under combined stress conditions (in-situ and thermal) as well as low reactivity with the rock and groundwater.

6.4.1.1 Cement

Cements that exhibit expansion (called expansive cements) have found wide application in prestressed concrete, preventing cracks in concrete due to drying shrinkage, sealing fractures or cracks in rocks, and soil and rock anchoring installation. Because the expansive cement does not exhibit the normal shrinkage that occurs with regular portland cement, it was considered for grouts for the steel bolts in emplacement drifts.

A shrinkage-compensating cement was considered because this type of cement grout does not shrink like portland cement, thus producing a more complete encapsulation of the rock bolt. When it is used for grouting the rock bolts in the bolt hole, it will not shrink away from bolts or walls of hole after curing. This ensures the maintenance of an intact shroud of grout for enhanced corrosion protection and bonding. Note that this type of cement grout falls in the category of expansive hydraulic cement (also referred to as shrinkage-compensating cement), which conforms to ASTM C 845-96.

Several types of expansive cements based on ettringite formation have been developed and are categorized as Type K, M, or S according to their expansive constituents. Based on ACI 223-98, *Standard Practice for the Use of Shrinkage – Compensating Concrete,* Section 1.4, expansive cement Type K is defined as a mixture of portland cement, anhydrous tetracalcium trialuminate sulfate ($C_4A_3\bar{S}$) (where $C = CaO$, $A = Al_2O_3$, and $\bar{S} = SO_3$), calcium sulfate ($CaSO_4$), and lime (CaO). The $C_4A_3\bar{S}$ is a constituent of a separately burned clinker interground with portland cement, or alternatively, formed simultaneously with portland cement clinker compounds during the burning process. Type M cement is a blend of portland cement, calcium-aluminate cement, and calcium sulfate. Type S cement is a portland cement containing a large computed tricalcium aluminate (C_3A) content and more calcium sulfate than usually found in portland cement (ACI 223-98, Section 1.4).

To produce ettringite, calcium sulfate is used as the source of sulfate ions, whereas different calcium aluminate phases may be used for supplying the aluminum ions. From among the various aluminate phases, tetracalcium trialuminate sulfate ($C_4A_3\bar{S}$) appears to be the most suitable source of aluminum ions for the expansive reaction. Most of this phase hydrates in the desirable time range of several hours to several days, after mixing with water. Therefore, Type K cement was considered as the candidate cement for the grout to be used in the rock bolt system. Type K cement is also the most commonly used expansive cement in the United States.

As stated in ACI 223-98, Section 2.1.2, 75 to 90 percent of shrinkage-compensating cements consist of the constituents of conventional portland cement, with added source of aluminate and calcium sulfate. For this reason, the oxide analysis on mill test reports does not differ substantially from the portland cements described in ASTM C 150 except for the larger amounts of sulfate (typically 4 to 7 percent total SO_3) and usually, but not always, a higher percentage of aluminate (typically 5 to 9 percent total Al_2O_3) (ACI 223). Table 3 (Kosmatka and Panarese 1994, p. 21) and Table 4 (Moore 1999) show a typical chemical and compound composition of portland cements and typical chemical analysis for Type E-1 (K) cement, respectively. The standard chemical and physical requirements of expansive cement based on ASTM C 845-96 are listed in Tables 5 and 6, respectively.

Table 3. Typical Chemical and Compound Composition of Portland Cements

Types of portland cement	Chemical composition, %						Compound composition, %			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	C_3S	C_2S	C_3A	C_4AF
Type I	20.9	5.2	2.3	64.4	2.8	2.9	55	19	10	7
Type II	21.7	4.7	3.6	63.6	2.9	2.4	51	24	6	11
Type III	21.3	5.1	2.3	64.9	3.0	3.1	56	19	10	7
Type IV	24.3	4.3	4.1	62.3	1.8	1.9	28	49	4	12
Type V	25.0	3.4	2.8	64.4	1.9	1.6	38	43	4	9

Table 4. Typical Chemical Analysis for Type E-1(K) Cement

Chemical Component	Composition, %
SiO_2	19.4
Al_2O_3	5.2
Fe_2O_3	2.8
CaO	61.9
MgO	1.4
SO_3	6.9
Loss on Ignition at 950 °C	1.1
Na_2O	0.10
K_2O	0.59
SrO	0.05
ZnO	0.02
TiO_2	0.28
P_2O_5	0.10
MnO_3	0.04

Table 5. Standard Chemical Requirements for Expansive Cement

Magnesium oxide (MgO), max	6.0 %
Insoluble residue, max	1.0 %
Loss on Ignition, max,	4.0 %

Table 6. Physical Requirements for Expansive Cement

Time of setting, min, minutes	75
Air content, max, vol %	12.0
Required expansion of mortar: 7-day expansion: min, % max, % 28-day percentage of 7-day expansion, max	 0.04 0.10 115
Compressive strength, min: 7-day, psi (MPa) 28-day, psi (MPa)	 2100 (14.7) 3500 (24.5)

6.4.1.2 Sand (or Fine Aggregate)

In the proposed cement grout, no sand or fine aggregate will be used. This is for ease of pumping, since the annular space between the bolt and hole wall is very small, i.e., about 3 to 10 mm. The presence of fine aggregate will not only separate or tear expensive pump components, but make it difficult to achieve the thixotropic properties of the cement grout, which are preferable for injecting through the hollow bolt and squeezing down along the bolt length.

6.4.1.3 Water

The mixture water used in the shrinkage-compensating cement grout should be of the same quality as that used in portland cement grout. But, the water requirement of shrinkage-compensating cement is greater than that of portland cement for a given consistency (ACI 223-98, Section 2.5.1). To ensure the high strength of the cement grout, a low W/CM ratio of about 0.4 to 0.6 is desirable. The use of a low W/CM ratio in a grout will maximize the density, and consequently minimize porosity and permeability, and may also favor autogeneous sealing (Onofrei et al. 1992, p. 135) of internal or interfacial fractures that could arise from physical disturbance (e.g., movement and stresses of the rock, drying, and shrinkage).

6.4.1.4 Silica Fume

The addition of silica fume to conventional concrete reduces workability, decreases air content, significantly reduces permeability, and increases compressive strength. Silica fume also enhances flexural strength and accelerates early-strength development. It dramatically decreases the rapid chloride permeability of shrinkage-compensating concrete made with Type K cement (Bayasi and Abifaher 1993, p. 9). The use of silica fume in Type K expansive cement helps minimize, and possibly prevent, the damage action of excessive expansion, while allowing the necessary expansion (Cohen et al. 1993, p. 29). The expansive cement mixed with silica fume expands at a higher rate during the early stage (first three days) than the cement mortar without silica fume, and the appropriate expansion at an earlier level is preferable because the cement grout is more able to heal itself (Cohen et al. 1993, p. 32).

Silica fume will be used in the cement grout to increase the strength and to reduce the permeability of the grout. An appropriate amount of silica fume; i.e., about 5 to 10 percent by weight of cement, will be used. Condensed silica fume, also known as silica fume or micro-silica, is a by-product of the manufacture of silicon, ferrosilicon, or the like, from quartz and carbon in electric arc furnaces (Day 1995, p. 235). The silicon dioxide (SiO_2) content can vary from 70 to 96 percent, increasing in percentage as the amount of silicon increases in the ferro silicon metal manufactured (Wolsiefer 1991, p. 2). Table 7 shows the required chemical composition for silica fume based on ASTM C 1240-99. Silica fume is a superfine material with a particle size of the order of 0.1 micron and a surface area of over 15,000 m^2/kg (a hundred times greater than cement or fly ash) (Day 1995, p. 235).

Table 7. Chemical Requirements for Silica Fume

SiO_2, min, %	85.0
Moisture Content, max, %	3.0
Loss on Ignition, max, %	6.0

6.4.1.5 High Range Water-Reducing Admixture

Since silica fume is proposed to be used as an admixture to the cement grout, an appropriate amount of high-range water reducer, i.e., superplasticizer, will be needed to increase the workability of the grout at a given W/CM ratio. One of the reasons for pursuing grout mixes with silica fume and superplasticizer is that they exhibit no measurable bleed. Grout mix that will bleed will poorly bound to the rock, which is not desirable.

High-range water reducers conforming to ASTM C 494-98a Type F or G generally reduce water content by 12 to 30 percent (Kosmatka and Panarese 1994, p. 67). By using superplasticizer, it is possible to increase concrete workability and not need any additional water. In addition to improving workability, superplasticizers provide other technical benefits such as: (a) production of a stable and dense hydrated cement paste, (b) production of a cement paste with very low porosity and permeability, and (c) production of significant increase in the density and durability of the cement grout, which provides a greater resistance to the penetration of aggressive agents and an improved service life.

There are basically three principal types of superplasticizers on the market: (1) lignosulfonate-based, (2) polycondensate of formaldehyde and melamine sulfonate (often referred to simply as melamine sulfonate), and (3) polycondensate of formaldehyde and naphthalene sulfonate (often referred to as naphthalene sulfonate) (Shah and Ahmad 1994, p. 8).

Of these three types of superplasticizers, the naphthalene superplasticizers have been in use longer than any of the others and are available under a great number of brand names. They are generally available as either calcium salts, or more commonly, sodium salts. The particular advantages of naphthalene superplasticizers, apart from their being slightly less expensive than the other types, appear to be that they make it easier to control the rheological properties of high strength concrete because of their slight retarding action (Shah and Ahmad 1994, p. 9).

There is no *a priori* way of determining the required superplasticizer dosage; it must be determined by a trial and error procedure. For the current study, a preliminary value of 1 percent naphthalene superplasticizer by total mass of cement plus silica fume is used. It should be pointed out that although the use of superplasticizers (organic admixtures) in the potential repository environment may cause other postclosure performance problems related to waste package corrosion and waste isolation, there are reasons showing that the impact of using superplasticizers in the cement grout in this aspect is insignificant: (1) the amount of cement to be used in the rock bolt system is much less than what would be used with that of concrete lining. The ratio of cement in the cement grout for rock bolts compared with that in concrete lining is 1.6 to 18.3 percent, based on a recent M&O study (CRWMS M&O 1999h, Page II-2 of

II-2); these values would be lower if the annulus between drill hole and bolt, and the hole lengths are reduced; (2) the organic admixtures from superplasticizers (especially long-chain types) in cement grout will probably not be used as nutrient supply for microbial activity (CRWMS M&O 1998e, p. 28 of 34).

It should be noted that the objective of this study is to evaluate the longevity of emplacement drift ground support materials. The final mix design of the cement grout is not within the scope of this study. Therefore, the above proportioning of the ingredients for cement grout is preliminary in nature. The actual proportioning of cement grout must be first calculated by following the proper procedure. Then, based on trial mixtures using a range of ingredient proportions, by evaluating their effects on strength, water requirements, time of set, and other important properties (e.g., permeability and coefficients of thermal expansion), the optimum proportions can be determined. In particular, the appropriate amount of silica fume and superplasticizer needs further investigation, as the durability and appropriate expansion of cement grout is affected by the amount of silica fume. Some water-reducing admixtures may be incompatible with shrinkage-compensating cement due to acceleration of the ettringite reaction which usually has the effect of decreasing expansion (ACI 223-98, Sec. 2.4.b).

6.4.2 Mechanical and Thermal Properties of Cement Grout

In this section, mechanical and thermal properties of cement grout in the emplacement drift environment are presented.

6.4.2.1 Mechanical Properties

The modulus of elasticity, flexural and compressive strength, and bond strength of shrinkage-compensating cement after expansion has completed are similar to those of portland cement because 75 to 90 percent of the former consists of the constituents of the latter, with added sources of aluminate and calcium sulfate (ACI 223-98, Sec. 2.1.2).

Compressive strengths of shrinkage-compensating cement, however, are at least comparable to portland cement manufactured from the same clinker and having the identical cement content. For example, depending on water/cement (W/C) ratios, the unconfined compressive strengths at 7 days are 4600 and 6700 psi at W/C of 0.44 and 0.40 respectively, and greater than 10,000 psi for W/C of about 0.38 (WFEC 1995, p.2).

In a recent M&O study on materials for emplacement drift ground support (CRWMS M&O 1997b, p. 68 of 74), it was concluded that for temperatures up to 200 °C (392°F), the compressive strength of concrete can be assumed to be reduced up to 30 percent compared with the ambient temperature strength for a 150-year service life. For temperatures up to 100 °C, the reduction in compressive strength will probably be reduced up to 10 to 20 percent compared with that at the ambient temperature. In the same report, it was concluded that for temperature of 200 °C (or 392°F), and prolonged periods of heating above 100 °C, it is reasonably conservative to assume that the modulus of elasticity of concrete may be reduced about 50 percent compared with the ambient temperature modulus of elasticity (CRWMS M&O 1997b, p. 68 of 74). For temperatures up to 100 °C, the reduction in elasticity values will probably be smaller.

In a recent laboratory testing on concrete properties at elevated temperatures, it was concluded that (1) the compressive strength of the concrete mixes investigated appeared to be relatively insensitive to temperature (nominally 10 percent degradation over the range 23 to 200 °C), at least for relative short aging periods, (2) the elastic moduli of the concretes tested were affected by temperature exposure even for short periods of time, with approximately a 30 percent reduction in modulus for exposure to temperatures of 105 °C and above (CRWMS M&O 1999i, p. 91).

Due to the lack of cement grout testing data at high temperatures for a long period, it is uncertain how much the reduction will be for strength and modulus of elasticity as compared to the values at ambient temperatures. Therefore, testing of cement grouts at elevated temperatures is recommended.

Data available on the creep characteristics of shrinkage-compensating concrete indicate that creep coefficients are within the same range as those of portland cement concrete of comparable quality (ACI 223-98, Sec. 2.5.4). There has been no observed difference between Poisson's ratio in shrinkage-compensating concrete and portland cement concrete (ACI 223-98, Sec. 2.5.5). It is reasonably to assume that grouts made with normal and shrinkage-compensating cement will behave similarly.

Based on the above discussion, it is expected that for room temperature conditions, the mechanical properties of expansive cement grout should be comparable to those of grouts made using conventional portland cement. The actual behavior of grout under elevated temperature may be somewhat different depending on the range of temperatures and moisture conditions in the repository. Further study and field testing of grout behavior at elevated temperatures, including longevity considerations, are necessary to confirm the above conclusions.

6.4.2.2 Thermal Properties

The most important thermal property of cement grout to be used in the repository is the thermal expansion coefficient. It should be pointed out that this property is a variable that depends on the W/CM ratio, age, and moisture content of the paste.

Although the coefficient of thermal expansion of shrinkage-compensating concrete is similar to that of corresponding portland cement concrete (ACI 223-98, Sec. 2.5.6), its value cannot be determined correctly without knowing details regarding its composition, age, and moisture content. It is desirable to design a cement grout such that the difference in thermal expansion coefficients between steel bolt, grout and host rock will be kept to minimum. Further research and testing are needed to determine the thermal properties of cement grouts to be used for the rock bolt system.

6.4.3 Factors Affecting Longevity of Cement Grout

The cement grout will play a significant role in determining the longevity of the fully grouted rock bolt system. In this section, factors affecting longevity of cement grout are evaluated.

6.4.3.1 Permeability

The permeability of cement grout plays an important role in durability because it controls the entry rate of moisture that may contain aggressive chemicals and the movement of water during heating. It should be noted that the term "permeability" used in this study is actually the coefficient of permeability, or hydraulic conductivity with units of m/s based on common concrete practice, rather than the strict definition of permeability, which has units of m^2. In a study on service life of concrete, it was concluded that concretes with low permeability are most likely to achieve service lives of around 500 years (Clifton and Knab 1989, p. 67). For the cement grout proposed to be used for the rock bolt system, it is expected that a service life of 150 years can be achieved if the permeability is less than 10^{-12} m/s. This value was considered as an acceptable hydraulic conductivity for cement grout to be used in a nuclear waste disposal facility in Canada (Onofrei et al. 1992, p.137). Due to its similar function for long-term performance, it is reasonable to use the same value for the current study.

Permeability, in turn, is strongly dependent on the W/CM ratio. As the W/CM ratio decreases, the porosity of the paste decreases and the cement becomes more impermeable. The W/CM ratio has a dual role to play in grout durability. A lower W/CM ratio increases the strength of grout and hence, improves its resistance to cracking from internal stresses that may be generated by adverse reactions. Adding silica fume to the cement will decrease the permeability further.

The permeability of mature hardened paste kept continuously moist ranges from 0.1 x 10^{-12} to 120 x 10^{-12} cm/s for W/C ratios ranging from 0.3 to 0.7 (Kosmatka and Panarese 1994, p. 8). A low-permeability grout requires a low W/CM ratio and an adequate moisture-curing period. In the proposed cement grout mix design, a low W/CM ratio in the range of 0.4 to 0.6 is proposed. Moreover, silica fume of 5 to 10 percent by weight of cementitious material and appropriate amount of superplasticizers are included in the design. The use of silica fume, superplasticizer and low W/CM ratio in the proposed grout design should produce a hardened cement grout with high density and strength and very low permeability.

6.4.3.2 Sulfate Resistance

The most widespread and common form of chemical attack to concrete is the action of sulfates. Naturally occurring sulfates of sodium, potassium, calcium, and magnesium are sometimes found in soils or dissolved in groundwater adjacent to concrete structures, and they can attack concrete or cement products. The consequences of sulfate attack include not only disruptive expansion and cracking, but also loss of strength of the concrete or cement grout due to the loss of cohesion in the hydrated cement paste and of adhesion between it and the aggregate particles.

Resistance of concrete to attacks by sulfate is related to the amount of cement in the concrete and the calculated amount of C_3A (tricalcium aluminate) in the cement. The resistance is enhanced for concrete with high cement content and for cement low in C_3A (Waddell 1984, p. 37). The use of silica fume, fly ash, and ground slag generally improves resistance of concrete to sulfate attack. Among these admixtures, silica fume provides excellent sulfate resistance, better than fly ash or ground slag in some studies (Kosmatka and Panarese 1994, p. 72).

Type II portland cement was selected in the ESF invert to provide increased resistance to sulfate attack (CRWMS M&O 1995, p. 59 of 300), which is conservative based on the SO_4^{2-} content of J-13 well water from the saturated zone below the repository horizon. In addition, the SO_4^{2-} content from J-13 well water is 22 mg/l (Section 4.1.5), which falls within the category of mild exposure for concrete subjected to sulfate attack, meaning special cement type is not needed for this exposure, based on Table 2.2.3 of ACI 201.2R-92, *Guide to Durable Concrete*. With conservative consideration, a 10 x concentration of SO_4^{2-} from J-13 well water, i.e., 220 mg/l, is under the category of moderate exposure based on this table. The recommended cement type for this exposure category is Type II cement, which is adequate to be used as the basis cement, from which the expansive cement Type K is manufactured. The expansive cement in the U.S. market is made with Type II cement, which is moderately sulfate resistant. In addition, the low W/CM ratio and silica fume to be used in the cement grout will provide further resistance to sulfate attack. Thus, if the proposed cement grout mix is used the effect of sulfate attack in the groundwater should be negligible.

6.4.3.3 Thermal Stability of Ettringite

As discussed in Section 6.4.1.1, ettringite formation is the basis of production of expansive cement. It is generally believed that ettringite is stable at room temperature. However, because of the many water molecules incorporated in its crystal structure, heating of ettringite may result in a progressive loss of water, or its decomposition. Since the cement grout will be subjected to elevated temperature conditions, the thermal stability of ettringite is very important to the longevity of cement grout for the rock bolt system.

The thermal stability of ettringite has been evaluated by many investigations but no systematic results have been reported. In one study, it was indicated that ettringite heated under dry conditions was stable at 65 °C, but partially decomposed at 93 °C (Klemm 1998, p. 28). In a moist environment, ettringite appeared not to show any significant change after one hour at 93 °C. It was also indicated that ettringite was decomposed at 130 to 150 °C in deionizing water. It was also believed that at temperatures between 50 and 80 °C, the ettringite formed by early hydration reactions is decomposed in the presence of alkali hydroxides (Klemm 1998, pp. 28 to 29).

It should be pointed out that even though ettringite may decompose at high temperature, the destruction of ettringite may not impact the strength of cement grout. It was indicated in one study that the destruction of ettringite at 100 °C did not appear to have detrimental effects on compressive strength or volume stability of any of the cement (3 percent C_3A) mixtures which contained 30 percent amounts of fly ash, granulated blast furnace slag and silica fume (Klemm 1998, p. 29). However, the percentage of ettringite in Type K cement is higher than in normal grout and concrete, therefore, the decomposition of ettringite may affect in higher degree the compressive strength of the grout.

It should be pointed out that the expansion of Type K cement will be completed in the first few days (Cohen et al. 1993, p. 34) after the cement grout is injected. From then on, the strength of the cement grout will mainly be controlled by C-S-H gel, which should not be impacted significantly by the elevated temperature. Since waste packages will not be emplaced in emplacement drifts until several months or later after ground support components have been installed, at that time the expansion process should have been completed, and the thermal stability of ettringite may not be a major concern. Nevertheless, from a longevity concern, further studies may need to be conducted to evaluate the stability of ettringite under the environmental conditions which are expected in the emplacement drift.

6.4.3.4 Carbonation

Carbonation of concrete is a process by which CO_2 from the air, in the presence of moisture, penetrates the concrete and reacts with the hydroxides, mostly calcium hydroxide, to form carbonates and water. Carbonation increases shrinkage on drying (prompting crack development) and lowers the alkalinity of concrete (Kosmatka and Panarese 1994, p. 72).

As stated by Mindess and Young (1981, pp. 496 to 497), hardened cement paste will react chemically with carbon dioxide. The amount present in the atmosphere (~0.04 percent) is sufficient to cause considerable reaction with cement paste over a long period of time. This is accompanied by shrinkage. The extent to which cement paste can react with carbon dioxide and, hence undergo carbonation shrinkage, is a function of relative humidity (RH) and is greatest around 50 percent RH. At high humidities, carbonation is low because the pores of concrete or cement paste are mostly filled with water and CO_2 cannot penetrate the paste very well. At very low humidity, an absence of water films is believed to lower the rate of carbonation (Mindess and Young 1981, pp. 496 to 497). Note that as was discussed in Section 6.1.2, the RH in emplacement drifts is expected to be less than 40 percent during the preclosure period.

The amount of carbonation is significantly increased in concrete or hardened cement paste with a high water-cement ratio, low cement content, short curing period, low strength, and highly permeable or porous paste. For the proposed cement grout mix design, however, all these factors liable for carbonation will not exist. Moreover, emplacement drifts are expected to be very dry with elevated temperatures for an extensive period of time. Of special note, the cement grout in the rock bolt system is located in an annular space within the rock mass, which will minimize the cement grout to be exposed to air containing CO_2 gas. In addition, the very small end surface area of the annular space is separated from the drift air by the bearing plate and is not exposed to air directly. Bolt holes may intersect some fractures in the rock mass, which may have ground water containing HCO_3^- with concentration of 130 mg/l (i.e., 0.013 percent) (Section 4.1.5). Note that this concentration is too low to cause considerable reaction with $Ca(OH)_2$ in the cement grout. In addition, since the permeability of the cement grout will be very low (see Section 6.4.4.1), the potential access of water to the cement paste will be minimal.

Since the $Ca(OH)_2$ content in the silica fume grout mixes will be less than that in the cement grout without silica fume and the development of a silica fume grout will have very low permeability, the carbonation effect will be insignificant. It is postulated that under this dry and elevated temperature environment, the effect of carbonation on the cement grout in terms of longevity will be minimal or insignificant during the preclosure period, resulting in no impact on longevity.

6.4.3.5 Biological Effect

The biological effect on cement grout for the rock bolt system is expected to be minimal, or insignificant during the preclosure period. The conditions in terms of oxygen, moisture content and nutrient supply are not expected to be favorable to the microorganisms associated with biodegradation of grout for the following reasons:

- Water percolation rate will be very low within the rock mass (see Section 4.1.4) adjacent to the emplacement drift wall.

- Water flow through any cracks or fractures that may be encountered along the length of drill hole will be either blocked or substantially reduced by the grout, which will have very low permeability (less than 10^{-10}cm/s) (see Section 6.4.3.1).

- Cement grout will be encapsulated within the rock mass and the grout will have a low W/CM ratio.

- The organic admixtures from superplasticizers (especially long-chain types) in cement grout will probably not be used as nutrient supply for microbial activity (see Section 6.4.1.5).

6.4.3.6 Effect of Radiation

As discussed in Section 6.1.3, the cumulative combined radiation doses for neutron and gamma radiation approach approximately 2 x10^6 rads in 100 to 150 years after waste emplacement based on VA design (CRWMS M&O 1997a, p. 99 of 105). This value is about five orders of magnitude below the approximate threshold of 1 x 10^{11} rads (Assumption 5.4), above which measurable degradation of concrete is predicted, thus the effect of radiation on the strength of concrete or hardened cement grout will be insignificant. Although the radiation dose due to the thin-walled waste package in EDA II design is increased, the cumulative dose will still be much lower than the threshold value for concrete/cement grout degradation. Moreover, for the case of fully grouted rock bolts, the cement grout is located inside the rock mass, which provides additional shielding from radiation. Thus, the impact of radiation on the cement grout is further reduced.

In summary, the effect of radiation on the longevity of cement grout during the preclosure period will be insignificant.

6.4.4 Design Considerations

The function of the grout within the fully grouted rock bolt system is complex. The grout must bind well with the steel bolt and with the rock mass and protect the steel components against corrosion in such a way that the rock bolt system will retain sufficient strength to maintain its rock reinforcement function with little or no maintenance for a period of up to 150 years. In addition, the grout should have physical and chemical compatibility with the host rock.

6.4.4.1 Corrosion

One of the functions of grout in the rock bolt system is to seal the drill hole to prevent corrosion of the bolt. As discussed in Sections 6.3.3 and 6.3.6, the potential for steel corrosion is insignificant for the emplacement drift environment under continuous ventilation. However, it should be pointed out that the integrity of the grout as a seal or barrier is very important. Since bolt drill holes may intersect fractures within the rock mass, there is potential for water percolating from these fractures and contacting the bolt if the encapsulating grout cracks under elevated temperature for a period of up to 150 years. The cracking of cement grouts may be caused by differential thermal expansion between rock bolt, grout, and rock, and this has the potential to cause failure of the bonds. The effective bond between the grout and host rock is also crucial to minimize water flow at the rock/grout interface, which could lead to corrosion of the bolt shank or bolt head.

It is, therefore, very important to investigate the bonding integrity of the cement grout with steel and its interaction with the host rock, i.e., tuff, under elevated temperatures to ensure its long-term performance to prevent the bolt corrosion.

6.4.4.2 Differential Thermal Expansion

Differential thermal expansion between rock bolt, grout, and rock has the potential to cause failure of the bonds. Although the differences in the thermal expansion coefficients between steel, cement, and welded tuff may be small and the thermal loading rate is low, the temperature change from about 25 °C (initial temperature at the emplacement drift) to the wall rock of 100 °C or higher may give rise to significant accumulative displacements. The combination of differential strain and a weakening grout bond due to time and temperature could significantly reduce the long-term capacity of the rock bolts. An approach to this potential problem has been suggested by analytical results that show that high axial bolt stress occurs near the head of the bolt. A debonded section, such as suggested by Leedy and Watters (1994, p. 693), along the bolt near the drift wall could eliminate the high stress but must be designed so it will not reduce the corrosion protection and support capacity. An alternative approach is to develop grouts that are much more stable at elevated temperature and have a thermal expansion coefficient sufficiently close to those of the bolt and the host rock.

6.4.4.3 Creep

The major advantage of fully grouted rock bolt system over mechanical bolts is its excellent performance with regard to anchorage creep at ambient temperature. However, there is a very little experimental data regarding the performance of grouted rock bolt systems under elevated temperatures.

Preliminary results from a 9-month in situ heater test indicated that the grout creep may be higher at elevated temperature than at ambient temperature. In this test, load cells were installed on pretensioned fully-grouted rock bolt system. Four bolts at the heated side showed an average of 3.45 percent load drop while the other four rock bolts, away from the heater at ambient temperature, showed an average of 1.37 percent decrease (CRWMS M&O 1997c, p. 5-27). It is possible that grout creep was responsible, although differential thermal expansion could have contributed as well. Since access to the repository emplacement drifts will be limited and the required service life is long, it is important to investigate this behavior with further analyses and field testing in the expected emplacement drift environment to further understand its performance.

6.5 LONGEVITY OF MATERIALS FOR EMPLACEMENT DRIFT INVERT

Invert materials will not be a component of the emplacement drift ground support. Note that steel inverts between steel sets are not part of ground support system. They will be completely independent regardless of the configuration. In this section, a brief discussion on this subject is presented.

6.5.1 Structural Steel

For this configuration the structural frames forming the invert will be anchored to the walls of the drift and will directly support the gantry rails and the waste packages. For this design, the crushed rock serves only as a filler material surrounding the structural steel supports.

6.5.1.1 Material

The structural steel will be carbon steel conforming to either ASTM A 36 or ASTM A 572.

6.5.1.2 Longevity

Preclosure longevity of the structural steel invert will depend on the corrosiveness of the environment during this period. For a discussion of the drift environment and the corrosiveness of carbon steel in this environment, see Section 6.3.3.

6.5.2 Crushed Rock

For this configuration the gantry rails will be supported on steel ties which will be supported on the crushed rock ballast in a manner similar to the rail support provided for railroad trains. Waste package supports will also be supported on steel spread footings directly supported by the crushed rock ballast. In this case, the crushed rock ballast serves as the structural bearing material rather than as simply a filler material.

6.5.2.1 Material

The candidate crushed rock material may be crushed marble or crushed limestone. Further investigation of crushed granite for its reaction to heating will be required because of the presence of mica and feldspar in its composition. Crushed tuff is also considered as candidate material for invert. Although it will be compatible with the host rock, it may have tendency to wick water towards the waste packages. Further investigation of water flow through crushed tuff is needed.

6.5.2.2 Longevity

The longevity of crushed rock is briefly presented in this section.

6.5.2.2.1 Crushed Rock Filler

For the invert configuration as described in Section 6.5.1, the longevity of the crushed rock ballast is not an issue because the crushed rock ballast functions only as a filler material, except if it weathers to smaller pieces, which may wick and increase moisture retention and promote corrosion of the steel in contact. Further investigation on water flow through crushed rock filler is needed.

6.5.2.2.2 Crushed Rock Structural Ballast

For the invert configuration described in Section 6.5.2, the crushed rock ballast must serve as a structural bearing material. In order for it to meet this function it must have the following: 1) proper quality, 2) proper gradation, and 3) proper compaction.

Proper Quality-The crushed rock structural ballast must be strong and durable. Recommendation for these attributes according to the American Railway Engineering Association (AREA) (AREA 1997, p. 1-2-12, Table 2-1) for limestone as a representative is given in the following.

1) Bulk Specific Gravity:	2.60 min. (ASTM C 127)
2) Absorption Percent:	2.0 max. (ASTM C 127)
3) Clay Lumps and Friable Particles:	0.5% max. (ASTM C 142)
4) Degradation:	30% max. (ASTM C 535 or C 131)
5) Soundness (Sodium Sulfate) 5 Cycles:	5.0% max. (ASTM C 88)
6) Flat and/or Elongated Particles:	5.0% max. (ASTM D 4791)
7) Percent Material Passing No. 200 Sieve:	1.0% max. (ASTM C 117)

Proper Gradation-As recommended by AREA (AREA 1997, Vol. 1, Table 2-2) the following gradation for Gradation Number 5, which is recommended as one of the yard ballast materials, should be one of the suitable gradations.

Sieve Size	% Passing
1 ½ in.	100
1 in.	90-100
¾ in.	40-75

½ in.	15-35
3/8 in.	0-15
No.4	0-5

Proper Compaction-The crushed rock invert materials should be compacted with roller vibration in a multiple lift operation. The compaction effort should be characterized in terms of the relative density properties.

Longevity of the Crushed Rock Invert-Given the proper quality and the proper gradation of the crushed rock invert, along with the proper compaction effort, the crushed rock invert should be able to function in the emplacement drifts during the preclosure period.

7. CONCLUSIONS

The factors affecting longevity of emplacement drift ground support materials during the preclosure period have been evaluated in this analysis, and a basis for selection of materials for this function has been developed. Based on the discussions in the previous sections, the following conclusions are made.

7.1 RECOMMENDED EMPLACEMENT DRIFT GROUND SUPPORT MATERIALS

- The ground support materials are steel sets and fully cement-grouted rock bolts.
- Both steel sets and steel rock bolts will be made from carbon steel.
- The candidate materials for emplacement drift invert are crushed limestone, marble, and tuff. Further investigation is needed to determine the final material.

7.2 LONGEVITY OF STEEL GROUND SUPPORT COMPONENTS

- Under the expected environment of elevated temperature (ranging from about 50 °C to up to boiling) and low RH (less than 40 percent), the corrosion potential under dry oxidation on steel sets and other steel components such as wire mesh, channels, panels, nut and bolts for fastening lagging to steel sets should be insignificant during the preclosure period.

- The humid-air corrosion of steel ground components is not expected to occur in the emplacement drifts during the preclosure period. However, it is possible that the potential of this type of corrosion may exist in some localized areas. Based on results of the corrosion test on corrosion-allowance materials from Lawrence Livermore National Laboratory, the impact of this type of corrosion on carbon steel ground support components was illustrated. It was indicated that some ground support components may fail in different periods, such as 50 and 100 years under humid-air condition if inadequate thickness of steel components is used. However, it should be emphasized that this conclusion is made on very simple assumption without any structural analysis. Systematic studies and tests are needed to investigate the potential of humid-air corrosion in the repository.

- The effect of expected temperatures and radiation on the mechanical properties of steel, including strength, modulus of elasticity, toughness and ductility, will be insignificant during the preclosure period. The potential for microbiologically influenced corrosion (MIC) will not likely be present in these environmental conditions.

- The above conclusions also apply to rock bolts, heads, and bearing plates, which are made with carbon steel materials. For the major portion of the rock bolt, which is encapsulated by cement grout of very low permeability and inside the rock mass, the corrosion potential is insignificant during the preclosure period.

- An accurate estimate of the longevity of steel ground support components within the emplacement drifts is complicated because there is no precedent data from similar ground support components under similar environmental conditions. However, based on the discussions in the previous sections, the steel ground support components are expected to be functional and durable during the preclosure period for a service life up to 150 years, if adequate types, sizes (thickness), and material composition are selected and proper methods of installation are utilized.

7.3 LONGEVITY OF CEMENT GROUT

- To ensure the proper function of the grout, i.e., to provide sufficient strength to maintain the rock reinforcement function and serve as a corrosion barrier for the rock bolt, it should have acceptable low hydraulic conductivity (or permeability), and resistance to attack by the environmental conditions.

- A potentially suitable candidate cement grout will consist of the following ingredients: Type K cement, silica fume, superplasticizer, and water, with no sand or fine aggregate. It should be pointed out that these candidate ingredients are preliminary in nature. Further study and testing are required to determine whether they are actually adequate and suitable in the repository environment.

- Factors affecting longevity of cement grout include permeability, sulfate resistance, thermal stability of ettringite, carbonation, biological effect, and radiation effect. It is expected that the proposed materials for cement grout can ensure the longevity of cement grout in the emplacement drift environment during the preclosure period. However, it is very important to conduct further study and testing to investigate the ettringite thermal stability when grout is exposed to elevated temperatures for a relatively long period.

- Due to the particular importance of grout in the rock bolt system, there may be a need to investigate the capability of other grout types, in addition to the expansive cement type, which may be used successfully in the fully grouted rock bolt system.

- There exists a need for further investigation with regard to corrosion, differential thermal expansion, and creep of a fully grouted rock bolt system. A thorough understanding of the mechanisms and performance of rock bolts in these areas will be essential to ensure the fulfillment of the rock bolt functions.

7.4 LONGEVITY OF MATERIALS FOR EMPLACEMENT DRIFT INVERT

- The longevity of invert materials for the preclosure period has been assessed for both steel invert and crushed rock ballast. The longevity of steel ground support discussed earlier should be applicable to steel invert during the preclosure period.

- The candidate crushed rock material for invert may be crushed marble, limestone or tuff. Further investigation of crushed granite for its reaction to heating will be required because of the presence of mica and feldspar in its composition. Crushed tuff is still under consideration. Although it will be compatible with the host rock, it may have tendency to wick water towards the waste packages. Further investigation of water flow through crushed tuff is needed.

- For the crushed rock ballast as a filler for steel, the longevity of the crushed rock ballast is not an issue because it functions only as a filler material, except if it weathers to smaller pieces, which may wick and increase moisture retention and promote corrosion of the steel in contact. Further investigation on water flow through crushed rock filler is needed.

- For the crushed rock ballast serving as a structural bearing material, the structural function and durability can be secured by following the American Society for Testing and Materials for proper quality, gradation, and compaction.

7.5 TBV/TBD IMPACT

- TBV-1015, which is about no human entry is planned in emplacement drifts while waste packages are present, is not expected to impact the results from this analysis.

- TBV-3311 and TBV-3312 are about highest average percolation rates for matrix and fracture flow, respectively, in the repository. Significant modifications to these data as a result of the qualification process are not anticipated, therefore, the resolution of these two TBVs is not expected to significantly impact the results presented in this analysis.

- TBV-3313 is about the concentration of chloride, sulfate, bicarbonate as HCO_3^-, and pH of groundwater from Well J-13. Since these input data are qualified with unconfirmed status, the confirmation of their status is, therefore, not anticipated to have significant impact on the results of this analysis.

- TBV-3757 is about thermal expansion coefficients for TSw2 tuff. The status of this input data is qualified with unconfirmed condition. Because the thermal expansion coefficients for carbon steel and for TSw2 tuff are not very different and the rate of repository heating is expected to be slow for temperatures up to boiling, the confirmation of this TBV is not anticipated to have significant impact on the results presented in this analysis.

- TBV-3938 is about the RH values for dry oxidation, humid-air corrosion, and aqueous corrosion of carbon steel. Significant modifications to these data as a result of the qualification process are not anticipated, therefore, the resolution of this TBV is not expected to significantly impact the results presented in this analysis.

- TBV-3939 is about the threshold value of no degradation for concrete and cement grout subjected to radiation. Since the expected radiation dose rate will be much smaller than the expected threshold value, the resolution of this TBV is not expected to significantly impact the results presented in this analysis.

- TBV-3940 is about the RH values in emplacement drifts during the preclosure period. Significant modifications to these data as a result of the qualification process are not anticipated, therefore, the resolution of this TBV is not expected to significantly impact the results presented in this analysis.

- TBD-3941 is about the assumption that the water chemistry from J-13 water well is similar to that of water entering the repository horizon. The resolution of this TBD may impact the results presented in this analysis.

7.6 UNCERTAINTIES AND RESTRICTIONS

It should be pointed out that the recommendations for ground support materials to be used in the emplacement drifts are preliminary in nature since no precedent testing of carbon steel and cement grout at the emplacement drift environment has been done in the past. Both the grade and specification of the carbon steel and the actual mix design for the cement grout to be used in the emplacement drifts have not been determined for the proposed repository. Therefore, outputs/conclusions from this analysis cannot be used as input into documents supporting procurement, fabrication, or construction nor used in verified design unless controlled in accordance with applicable procedures.

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9. ATTACHMENTS

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

1. Document Identifier No./Rev.:	Change:	Title:
ANL-EBS-GE-000003 REV 00	N/A	Longevity of Emplacement Drift Ground Support Materials

Input Document			4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	8. TBV Due To		
2a	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section					Unqual.	From Uncontrolled Source	Un-confirmed
1	ASM International 1990. *Properties and Selection: Irons, Steels, and High Performance Alloys*. Volume 1 of *Metals Handbook*. 10th Edition. Metals Park, Ohio: ASM International. TIC: 245666.	p. 622	N/A	6.3.1.1	Temperature limit of carbon steel, below which creep is not observed.	N/A	N/A	N/A	N/A
		p. 739, Fig. 9	N/A	6.3.1.2	Toughness generally decreases as strength and carbon content of steel increase. For maximum toughness and ductility, the carbon content should be kept as low as possible, consistent with strength requirements.	N/A	N/A	N/A	N/A
		p. 197	N/A	6.3.2.2	Thermal conductivities of carbon steel for temperatures of 0 to 200 °C	N/A	N/A	N/A	N/A
		p. 198	N/A	6.3.2.2	Specific heats of carbon steel for temperatures of 50 to 200°C	N/A	N/A	N/A	N/A
2	Bayasi, Z. and Abifaher, R. 1993. "Properties of Shrinkage-Compensating Silica-Fume Concrete Made with Type K Cement." *Mineral Admixtures.* Compilation 22. 7-9. Detroit, Michigan: American Concrete Institute. TIC: 245372.	p. 9	N/A	6.4.1.4	Silica fume decreases the rapid chloride permeability of shrinkage-compensating concrete made with Type K cement	N/A	N/A	N/A	N/A
3	Clifton, J.R. and Knab, L. I., 1989. *Service Life of Concrete.* NUREG/CR-5466. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 216355.	p. 67	N/A	6.4.3.1	Concrete with low permeability are most likely to achieve service life of around 500 years	N/A	N/A	N/A	N/A
4	Cohen M.D.; Olek J.; and Mather B. 1993. "Silica Fume Improves Expansive-Cement Concrete." *Mineral Admixtures.* Compilation 22, pp. 29 to 35. Detroit, Michigan: American Concrete Institute. TIC: 245372.	p. 32	N/A	6.4.1.4	Preferred time of expansion of expansive cement by adding silica fume	N/A	N/A	N/A	N/A

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5	CRWMS M&O 1995. *ESF Ground Support Design Analysis.* BABEE0000-01717-0200-00002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19960409.0355.	7.15.4.1, p. 59 of 300	N/A	6.4.3.2	Type II portland cement selected in the ESF invert to provide increased resistance to sulfate attack	N/A	N/A	N/A	N/A
6	CRWMS M&O 1996. *Repository.* Volume II *of Mined Geologic Disposal System Advanced Conceptual Design Report.* B00000000-01717-5705-00027 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19960826.0095.	C.2.2, p. C-9	N/A	6.1.3	The primary radiation from the waste package is neutron and gamma radiation because the alpha and beta radiation are stopped by the disposal container.	N/A	N/A	N/A	N/A
		C.2.3, p. C-10	N/A	6.3.4	In order for SRB to corrode steel , it requires the availability of sulfate, an electron acceptor, and a carbon source.	N/A	N/A	N/A	N/A
		C.2.2, p. C-9	N/A	6.3.5	Gamma radiation has no known significant effect upon the structural properties of steel.	N/A	N/A	N/A	N/A
		C.2.2, p. C-10	N/A	6.3.5	Increase in the ductile-brittle transition temperature for 100 and 144 years.	N/A	N/A	N/A	N/A
7	CRWMS M&O 1997a. *MGDS Subsurface Radiation Shielding Analysis.* BCAE00000-01717-0200-00001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19971204.0497.	7.7, p. 99 of 105	N/A	6.1.3; 6.4.3.6	Cumulative radiation doses for neutron and gamma at the concrete lining surface for 100 and 150 years.	N/A	N/A	N/A	N/A
8	CRWMS M&O 1997b. *Materials for Emplacement Drift Ground Support.* BCAA00000-01717-0200-00003 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19971029.0493.	8.2.1and 8.2.2, p. 68 of 74	N/A	6.4.2.1	Conservative assumption of compressive strength and modulus of elasticity of concrete at temperatures up to 200 °C.	N/A	N/A	N/A	N/A

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9	CRWMS M&O 1997c. *Single Heater Test Status Report*. BAB000000-01717-5700-00002 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980904.0202.	p. 5-27	N/A	6.4.4.3	Bolt load drop at high temperature may be due to creep based on single heater test	N/A	N/A	N/A	N/A
10	CRWMS M&O 1998a. *Ground Control System Description Document*. BCA000000-01717-1705-00011 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980825.0286.	1.1.1; 1.2.2.1.1	N/A	4.2	Ground support criteria	N/A	N/A	N/A	N/A
11	CRWMS M&O 1998b. *Waste Package Degradation Expert Elicitation Project*. Rev. 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980727.0002.	3.3.1	N/A	6.3.3	RH conditions for corrosion of carbon steel	N/A	N/A	N/A	N/A
		3.3.4	N/A	6.3.4	Potential of MIC will not be present until temperature < 100 ^{o}C & RH> 60%	N/A	N/A	N/A	N/A
12	CRWMS M&O 1998c. *Ground Support Alternatives Evaluation for Emplacement Drifts*. BCAA00000-01717-5705-00002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980930.0468.	p. 11	N/A	6.2	Ground support alternatives	N/A	N/A	N/A	N/A
		p. 72	N/A	6.2	Steel set with mesh receives one of the lowest ratings on undesirable characteristics.	N/A	N/A	N/A	N/A
		5.6 to 5.8	N/A	6.2.2	Steel set description	N/A	N/A	N/A	N/A
13	CRWMS M&O 1998d. *Repository Ground Support Analysis for Viability Assessment*. BCAA00000-01717-0200-00004 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980512.0714.	p. 72 of 140	N/A	6.2.1	A third of ESF tunnel was excavated in rock of the proposed repository block, TSw2 unit	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

1. Document Identifier No./Rev.:	Change:	Title:
ANL-EBS-GE-000003 REV 00	N/A	Longevity of Emplacement Drift Ground Support Materials

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14	CRWMS M&O 1998e. *Concrete Chemical Evolution.* BCAA00000-01717-5705-00003 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981207.0332.	6.5, p. 28 of 34	N/A	6.4.1.5	Organic admixtures from superplasticizers in cement grout will probably not be used as nutrient supply for microbial activity.	N/A	N/A	N/A	N/A
15	CRWMS M&O 1999a. *Longevity of Emplacement Drift Ground Support Materials.* TDP-EBS-GE-000003 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990826.0103.	---	N/A	1.1	Development plan	N/A	N/A	N/A	N/A
16	CRWMS M&O 1999b. *Ground Control - 99 (FY 99 WP # 12012383MD).* Activity Evaluation, March 29, 1999. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990407.0117.	---	N/A	2	Activity evaluation	N/A	N/A	N/A	N/A
17	CRWMS M&O 1999c. *Classification of the MGR Ground Control System.* ANL-GCS-SE-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990928.0217.	p. 7 of 9, Table 1	N/A	2	Quality of emplacement ground control system	N/A	N/A	N/A	N/A
18	CRWMS M&O 1999d. *Monitored Geologic Repository Project Description Document.* B00000000-01717-1705-00003 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990701.0328.	p. 34	TBV-1015	5.2; 6.2.1.1	No human entry planned in emplacement drifts containing waste packages	3	✓	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

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19	CRWMS M&O 1999e. *Enhanced Design Alternative II Report.* B00000000-01717-5705-00131 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990712.0194.	p. 5-11	N/A	6.1.1	Ventilation rates in EDA II design	N/A	N/A	N/A	N/A
		p. v	N/A	6.3.3	Mobilized water will drain through the pillars rather than through the emplacement drifts.	N/A	N/A	N/A	N/A
20	CRWMS M&O 1999f. *ANSYS Calculations in Support of Enhanced Design Alternatives.* B00000000-01717-0210-00074 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990218.0240.	p. IV-15 of IV-27	N/A	6.1.1	Temperatures at unventilated emplacement drift for 60 MTU/acre	N/A	N/A	N/A	N/A
		p. IV-14 of IV-27	N/A	6.1.1	Temperatures at ventilated (10 m^3/s) emplacement drift for 60 MTU/acre	N/A	N/A	N/A	N/A
		p. IV-7 of IV-27	N/A	6.1.1	Temperatures at ventilated (2 m^3/s) emplacement drift for 60 MTU/acre	N/A	N/A	N/A	N/A
		p. IV-8 of IV-27	N/A	6.1.1	Temperatures at ventilated (5 m^3/s) emplacement drift for 60 MTU/acre	N/A	N/A	N/A	N/A
21	CRWMS M&O 1999g. *Post Closure Open-Loop Natural Ventilation.* BCAD00000-01717-0210-00002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990806.0069.	p. VIII-1 of VIII-1	N/A	6.1.2	RH values for ventilation for an assumed airflow of 1.0 m^3/s and a water influx of 60 mm/year	N/A	N/A	N/A	N/A
22	CRWMS M&O 1999h. *Evaluation of Alternative Materials for Emplacement Drift Ground Control.* BCAA00000-01717-0200-00013 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990720.0198.	P. II-2 of II-2	N/A	6.4.1.5	The ratio of cement in the cement grout for rock bolts to that in concrete lining	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

1. Document Identifier No./Rev.:	Change:	Title:
ANL-EBS-GE-000003 REV 00	N/A	Longevity of Emplacement Drift Ground Support Materials

Input Document							8. TBV Due To		
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23	CRWMS M&O 1999i. *Progress Report for Laboratory Testing of Concrete Properties at Elevated Temperatures, Data Transmittal Number 1.* BA0000000-01717-5700-00021 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990317.0395.	p. 91	N/A	6.4.2.1	Compressive strength and elastic moduli of concrete tested at elevated temperatures	N/A	N/A	N/A	N/A
24	Day, K.W. 1995. *Concrete Mix Design, Quality Control and Specification.* London, England: E & F N SPON. TIC: 245446.	p. 235	N/A	6.4.1.4	Silica fume description	N/A	N/A	N/A	N/A
25	DOE (U.S. Department of Energy) 1998. *Quality Assurance Requirements and Description.* DOE/RW-0333P, Rev. 8. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19980601.0022.	---	N/A	2	Applicability of QARD	N/A	N/A	N/A	N/A
26	Klemm, W. A. 1998. *Ettringite and Oxyanion-Substituted Ettringites – Their Characterization and Applications in the Fixation of Heavy Metals: A Synthesis of the Literature.* Skokie, Illinois: Portland Cement Association. TIC: 245413.	pp. 28 to 29	N/A	6.4.3.3	Ettringite thermal stability	N/A	N/A	N/A	N/A
27	Kosmatka, S. H. and Panarese, W. C. 1994. *Design and Control of Concrete Mixtures.* Thirteenth Edition. Skokie, Illinois: Portland Cement Association. TIC: 242269.	p. 21, Table 2-4	N/A	6.4.1.1, Table. 3	Typical Chemical and Compound Composition of Portland Cements	N/A	N/A	N/A	N/A
		p. 67	N/A	6.4.1.5	High-range water reducers generally reduce water content by 12 to 30 percent	N/A	N/A	N/A	N/A
		p. 8	N/A	6.4.3.1	The permeability of mature hardened paste	N/A	N/A	N/A	N/A
		p. 72	N/A	6.4.3.2	Silica fume provides excellent	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

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					sulfate resistance.				
		p. 72	N/A	6.4.3.4	Silica fume reduces carbonation.	N/A	N/A	N/A	N/A
28	Leedy, W.T. and Watters, R.J. 1994. "Assessment of Rock Bolt Systems for Underground Waste Storage." *High Level Radioactive Waste Management, Proceedings of the Fifth Annual International Conference, Las Vegas, Nevada, May 22-26, 1994*, 691-695. La Grange Park, Illinois: American Nuclear Society. TIC: 241944.	p. 692	N/A	6.2.1.3	Most epoxy and polyester resins are suspected of (a) undergoing creep in elevated temperature environment, and (b) experiencing a marked reduction in strength.	N/A	N/A	N/A	N/A
		p. 693	N/A	6.4.4.2	Debonded full column bolt system	N/A	N/A	N/A	N/A
29	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.19981222.0137.	---	N/A	6.3.3.2	Corrosion tests at Lawrence Livermore National Laboratory	N/A	N/A	N/A	N/A
		2.2.6, Table 2.2-9	N/A	6.3.3.2	Corrosion rates based on tests of carbon steel at Lawrence Livermore National Laboratory	N/A	N/A	N/A	N/A
30	Merritt, F. S. 1983. *Standard Handbook for Civil Engineers*, 3rd Ed. New York, New York: McGraw-Hill. TIC: 206892.	p. 9-67	N/A	6.3.1.1	Temperature effect on yield point and modulus of elasticity of carbon steel	N/A	N/A	N/A	N/A
		p. 9-67, Eq. 9-75	N/A	6.3.2.1	Thermal expansion coefficient of steel calculated based on equation	N/A	N/A	N/A	N/A
31	Mindess, S. and Young, J. F. 1981. *Concrete*. Englewood Cliffs, New Jersey: Prentice-Hall. TIC: 242878.	pp. 496 to 497	N/A	6.4.3.4	Effect of RH on carbonation rate	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

1. Document Identifier No./Rev.: ANL-EBS-GE-000003 REV 00		Change: N/A	Title: Longevity of Emplacement Drift Ground Support Materials							
Input Document							8. TBV Due To			
	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section	4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	Unqual.	From Uncontrolled Source	Un-confirmed
32	Moore, D. 1999. *Blue circle Expansive Cement Type E-1(k). Manufactured to ASTM C 845-96 Typical Chemical Analysis.* Marietta, Georgia: Blue Circle Cement. ACC: MOL.19990915.0362.	---	N/A	6.4.1.1	Typical chemical composition of Type E-1 (K) cement	N/A	N/A	N/A	N/A
33	Onofrei, M.; Gray, M.N.; Coons, W.E.; and Alcorn S. R. 1992. "High Performance Cement-based Grouts for Use in a Nuclear Waste Repository Facility." *Waste Management*, Vol. 12, pp. 133-154. New York, New York: Pergamon Press. TIC: 245401.	Table 3, p. 137	N/A	6.4.1; 6.4.3.1	Desired characteristics of cement grout	N/A	N/A	N/A	N/A
		p. 135	N/A	6.4.1.3	Effect of low W/CM ratios on cement grout properties	N/A	N/A	N/A	N/A
34	Peng, S.S. 1986. *Coal Mine Ground Control.* Second Edition. New York, New York: John Wiley & Sons. TIC: 243435.	p. 217	N/A	6.2.1.2	Advantages of fully grouted resin bolts	N/A	N/A	N/A	N/A
		p. 228	N/A	Table 1	Thickness of Split Set tube	N/A	N/A	N/A	N/A
		p. 174	N/A	Table 1	Thickness of bearing plate for rock bolts	N/A	N/A	N/A	N/A
35	Shah, S.P. and Ahmad, S. H., eds. 1994. *High Performance Concrete: Properties and Applications.* New York, New York: McGraw-Hill. TIC: 241054.	p.8	N/A	6.4.1.5	Types of superplasticizers	N/A	N/A	N/A	N/A
		p. 9	N/A	6.4.1.5	Advantages of naphthalene superplasticizers	N/A	N/A	N/A	N/A
36	Stahl, D.A.; 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.	---	N/A	6.3.3.1	Empirical equation of penetration depth for carbon steel under dry oxidation	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

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ANL-EBS-GE-000003 REV 00	N/A	Longevity of Emplacement Drift Ground Support Materials

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37	Waddell, J. J. 1984. *Concrete Manual.* Pages 3-4, 31-35, 37-38, and 54. Whittier, California: International Conference of Building Officials. TIC: 240632.	p. 37	N/A	6.4.3.2	Effect of C_3A content on resistance of concrete to sulfate attack.	N/A	N/A	N/A	N/A
38	WFEC (Williams Form Engineering Corp.) 1995. *Wil-X-Cement Grout*, No. S5Z. Grand Rapids, Michigan: Williams Form Engineering Corp. TIC: 245371.	p. 2	N/A	6.4.2.1	Relationship between strength of cement grout and W/C	N/A	N/A	N/A	N/A
39	WFEC 1997. *Rock Anchor Systems*, No. 397. Grand Rapids, Michigan: Williams Form Engineering Corp. TIC: 245370.	p. 8	N/A	Table 1	Williams bolt hollow bar thickness	N/A	N/A	N/A	N/A
		p. 38	N/A	Table 1	Williams bolt bearing plate thickness	N/A	N/A	N/A	N/A
40	Wilkins, D.R. and Heath, C.A. 1999. "Direction to Transition to Enhanced Design Alternative II." Letter from Dr. D.R. Wilkins and C.A. Heath (CRWMS M&O) to Distribution, June 15, 1999, LV.NS.JLY.06/99-026, with enclosures, "Strategy for Baselining EDA II Requirements" and "Guidelines for Implementation of EDA II." ACC: MOL.19990622.0126; MOL.19990622.0127; MOL.19990622.0128.	---	N/A	4.1	Design parameters for areal mass loading	N/A	N/A	N/A	N/A
		---	N/A	4.2	Design criteria for ground support materials for emplacement drifts, ventilation during preclosure, repository closure time, emplacement drift spacing, and drift diameter	N/A	N/A	N/A	N/A
		---	N/A	6.2.3, 6.3.3	Emplacement drift ground support materials	N/A	N/A	N/A	N/A
		---	N/A	6.3.4	Cementitious grout will be used for the rock bolts	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

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41	Wolsiefer, Sr., J.T. 1991. "Silica Fume Concrete: A Solution to Steel Reinforcement Corrosion in Concrete." *2nd CANMET/ACI International Conference on Durability of Concrete, August 1991, Montreal, Canada.* SP 126-28. Detroit, Michigan: American Concrete Institute. TIC: 245402.	p. 2	Reference only	6.4.1.4	The silicon dioxide content in silica fume	N/A	N/A	N/A	N/A
42	ACI 201.2R-92. 1992. *Guide to Durable Concrete*. Detroit, Michigan: American Concrete Institute. TIC: 241421.	Table 2.2.3	N/A	6.4.3.2	Exposure categories for concrete subjected to sulfate attack	N/A	N/A	N/A	N/A
43	ACI 223-98. 1998. *Standard Practice for the Use of Shrinkage – Compensating Concrete*. Farmington Hills, Michigan: American Concrete Institute. TIC: 245440.	1.4	N/A	6.4.1.1	Definition of expansive cement	N/A	N/A	N/A	N/A
		2.1.2	N/A	6.4.1.1; 6.4.2.1	Compositions of shrinkage-compensating cement	N/A	N/A	N/A	N/A
		2.5.1	N/A	6.4.1.3	Water requirement of shrinkage-compensating cement	N/A	N/A	N/A	N/A
		2.4	N/A	6.4.1.5	Some water-reducing admixtures may be incompatible with shrinkage-compensating cement	N/A	N/A	N/A	N/A
		2.5.4; 2.5.5; 2.5.6	N/A	6.4.2.1; 6.4.2.2	Creep, Poisson's ratio, and thermal expansion coefficient of shrinkage-compensating cement concrete	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

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ANL-EBS-GE-000003 REV 00	N/A	Longevity of Emplacement Drift Ground Support Materials

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44	AISC (American Institute of Steel Construction) 1995. *Manual of Steel Construction - Allowable Stress Design.* 9th Edition. Chicago, Illinois: American Institute of Steel Construction. TIC: 240772.	p. 6-3	N/A	6.3.1.1	Yield strength of elevated-temperature carbon steel	N/A	N/A	N/A	N/A
		p. 1-32	N/A	Table 1	Web thicknesses of W 6x20, 8x31, 8x48, & 8x67	N/A	N/A	N/A	N/A
		p. 1-28	N/A	Table 1	Web thickness of W 12x40 & W12x65	N/A	N/A	N/A	N/A
		p. 6-2	N/A	Table 1	Thickness for wire gages # 1 and 5	N/A	N/A	N/A	N/A
		p. 1-40	N/A	Table 1	Web thickness of C8x11.5	N/A	N/A	N/A	N/A
		p. 1-107	N/A	Table 1	Steel plate thickness	N/A	N/A	N/A	N/A
45	AREA (American Railway Engineering Association) 1997. *Manual for Railway Engineering.* Volume 1. Washington, D.C.: American Railway Engineering Association. TIC: 233847.	Table 2-1	N/A	6.5.2.2.2	Quality for crushed rock structural ballast	N/A	N/A	N/A	N/A
		Table 2-2	N/A	6.5.2.2.2	Gradation for crushed rock structural ballast	N/A	N/A	N/A	N/A
46	ASTM A 36/A 36M-97a. 1998. *Standard Specification for Carbon Structural Steel.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3, 6.3.1.2; 6.5.1.1	Standard specification for carbon structural steel	N/A	N/A	N/A	N/A
47	ASTM A 82-97. 1997. *Standard Specification for Steel Wire, Plain, for Concrete Reinforcement.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3	Standard specification for steel wire	N/A	N/A	N/A	N/A
48	ASTM A 185-97. 1997. *Standard Specification for Steel Welded Wire Fabric, Plain, for Concrete Reinforcement.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3	Standard specification for steel welded wire fabric	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

1. Document Identifier No./Rev.: ANL-EBS-GE-000003 REV 00		Change: N/A	Title: Longevity of Emplacement Drift Ground Support Materials						
Input Document							8. TBV Due To		
	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section	4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	Unqual.	From Uncontrolled Source	Un-confirmed
49	ASTM A 572/A 572M-99. 1999. *Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3; 6.3.1.2; 6.5.1.1	Standard specification for high-strength low-alloy steel	N/A	N/A	N/A	N/A
50	ASTM C 88-99a. 1999. *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.5.2.2.2	Standard test method for soundness of aggregates by use of Sodium Sulfate or Magnesium Sulfate	N/A	N/A	N/A	N/A
51	ASTM C 117-95. 1995. *Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.5.2.2.2	Standard test method for materials finer than 75-μm (No. 200) sieve in mineral aggregates by washing	N/A	N/A	N/A	N/A
52	ASTM C 127-88 (Reapproved 1993). 1998. *Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.5.2.2.2	Standard test method for specific gravity and absorption of coarse aggregate	N/A	N/A	N/A	N/A
53	ASTM C 131-96. 1998. *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.5.2.2.2	Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles Machine	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

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54	ASTM C 142-98. 1998. *Standard Test Method for Clay Lumps and Friable Particles in Aggregate*. Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.5.2.2.2	Standard test method for clay lumps and friable particles in aggregate	N/A	N/A	N/A	N/A
55	ASTM C 150-97a. 1998. *Standard Specification for Portland Cement*. Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3; 6.4.1.1	Standard specification for portland cement	N/A	N/A	N/A	N/A
56	ASTM C 494-92. 1992. *Standard Specification for Chemical Admixtures for Concrete*. Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3; 6.4.1.5	Standard specification for chemical admixtures for concrete	N/A	N/A	N/A	N/A
57	ASTM C 535-96. 1998. *Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.5.2.2.2	Standard test method for resistance to degradation of large-size coarse aggregate by abrasion and impact in the Los Angeles Machine	N/A	N/A	N/A	N/A
58	ASTM C 845-96. 1996. *Standard Specification for Expansive Hydraulic Cement*. Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3; 6.4.1.1; Tables 5 and 6	Standard specification for expansive hydraulic cement	N/A	N/A	N/A	N/A

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

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Input Document			4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	8. TBV Due To		
	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section					Unqual.	From Uncontrolled Source	Un-confirmed
59	ASTM C 1240-99. 1999. *Standard Specification for Silica Fume for Use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3; 6.4.1.4; Table 7	Standard specification for silica fume for use in hydraulic-cement concrete and mortar	N/A	N/A	N/A	N/A
60	ASTM D 4791-95. 1995. *Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.5.2.2.2	Standard test method for flat particles, elongated particles, or flat and elongated particles in coarse aggregate	N/A	N/A	N/A	N/A
61	ASTM F 432-95. 1995. *Standard Specification for Roof and Rock Bolts and Accessories.* Philadelphia, Pennsylvania: American Society for Testing and Materials. Readily available.	---	N/A	6.2.3; 6.3.1.2	Standard specification for roof and rock bolts and accessories	N/A	N/A	N/A	N/A
62	MO9901YMP98020.001. Matrix Flux at Repository for QB.OUT. Submittal date: 01/05/1999.	---	TBV-3311	6.1.4	Matrix percolation flux at repository	2	✓	N/A	N/A
63	MO9901YMP98017.001. Fracture Flux at Repository for QB.OUT. Submittal date: 01/05/1999.	---	TBV-3312	6.1.4	Fracture percolation flux at repository	2	✓	N/A	N/A
64	MO9808RIB00027.004. Geochemical Characteristics: Saturated Zone Ground-Water Chemistry. Submittal date: 08/24/1998.	---	TBV-3313	6.1.4	Concentration of chloride, sulfate, bicarbonate as HCO_3^-, and pH of groundwater from Well J-13	2	N/A	N/A	✓
65	SN9510RIB00035.000. RIB Item #35/Rev0: Geologic Characteristics: Rock Thermal Expansion. Submittal date: 09/19/1995.	---	TBV-3757	4.1.8	Thermal expansion coefficients of tuff for TSw2 formation	2	N/A	N/A	✓

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DOCUMENT INPUT REFERENCE SHEET

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66	Initial use	---	TBD-3941	5.1, 6.1.4	Assumption that the water chemistry from J-13 water well is similar to that of water entering the repository horizon	2	N/A	N/A	N/A
67	Initial use	---	TBV-3938	5.3, 6.3.3	Assumption that the relative humidity (RH) values for dry oxidation, humid-air corrosion, and aqueous corrosion for carbon steel are less than 60 percent, 60 to 80 percent, and 85 to 100 percent, respectively	2	✓	N/A	N/A
68	Initial use	---	TBV-3939	5.4, 6.4.3.6	Assumption that no measurable degradation of concrete and cement grout will be predicted below radiation dose of 1×10^{11} rads	2	✓	N/A	N/A
69	Initial use	---	TBV-3940	5.5, 6.1.2, 6.4.3.6	Assumption that the relative humidity (RH) in the emplacement drifts ranges from 1 to 40% during the preclosure period	2	✓	N/A	N/A