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EVALUATION OF POTENTIAL IMPACTS OF OFF-NORMAL TEMPERATURES ON INACCESSIBLE NONEMPLACEMENT OPENINGS

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EVALUATION OF POTENTIAL IMPACTS OF OFF-NORMAL TEMPERATURES ON NONEMPLACEMENT OPENINGS

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CHANGE HISTORY

Revision Number	Interim Change No.	Date	Description of Change
00A		03/23/2007	Initial issue.

CONTENTS

Page

FIGURES

TABLES

ACRONYMS

ACI	American Concrete Institute
BSC	Bechtel SAIC Company, LLC
DST	Drift Scale Test
DOE	U.S. Department of Energy
DST	Drift Scale Test
DTN	Data Tracking Number
FLAC	Fast Lagrangian Analysis of Continua
LA	License Application
QARD	Quality Assurance Requirements and Description
SCM	Software Configuration Management
STN	Software Tracking Number
TDMS	Technical Data Management System

1. INTRODUCTION

The purpose of this informal study is to evaluate potential impacts of the maximum off-normal temperatures on inaccessible nonemplacement openings: exhaust mains and exhaust shafts of the repository.

The current ground support design for these openings considers only the normal operation scenario in which the ventilation system will function as designed, thus controlling the emplacement drift wall temperature below the boiling point and resulting in cooler temperatures for nonemplacement openings. However, an off-normal thermal condition would occur should the ventilation system get interrupted or shut down due to system failure or the airway become blocked due to unexpected rockfalls in either emplacement drifts, intake mains, or exhaust mains. As a result, temperatures at these affected openings may rise far beyond normal operation levels, depending upon how rapidly the ventilation can be restored. Because of high radiation and hot temperature, any attempt to perform unexpected repair or maintenance on ground support in these openings is difficult. Therefore, an engineering evaluation of off-normal thermal conditions and resulting thermomechanical responses of both surrounding rock and ground support is needed to address the adequacy and longevity of the ground support system. Furthermore, this study will form the basis for consideration of design risk and risk management pertaining to this subject.

It must be pointed out that massive rockfalls in any opening have been numerically demonstrated to be unlikely scenarios during the preclosure unless seismic events far beyond the design basis are imposed on the underground openings.

2. SCOPE

This informal study considers only the preclosure period and focuses on addressing the following two specific concerns:

- How likely is it for the maximum off-normal temperatures to reach 177 ^{o}C in these openings?
- What would happen to the ground support and surrounding rock should the temperatures reach 177 ^{o}C?

The target temperature of 177 ^{o}C is considered here because it is the temperature limit under which concrete or shotcrete, when used for ground support, can function for accident or any other short term period (ACI 349-01[DIRS 158833]).

3. QUALITY ASSURANCE

This informal study was prepared in accordance with *Engineering Studies,* EG-PRO-3DP-G04B-00016, Rev. 3. The results of this study are to be used as part of the basis for addressing potential impacts of the maximum off-normal temperatures on nonemplacement openings. The repository openings and their ground support involved in this study are classified as non-Safety Category, i.e., not important to safety and not important to waste isolation (BSC 2005 [DIRS 175539], A-11). Therefore, this engineering study is not subject to requirements of the *Quality Assurance Requirements and Description* (QARD) (DOE 2006 [DIRS 177092]) and *Quality Management Directive* (BSC 2006a [DIRS 177655]).

4. USE OF COMPUTER SOFTWARE

FLAC Version 4.0 (STN: 10167-4.0-00) is a two-dimensional explicit finite difference code which simulates the behavior of structures built of soil, rock, or other materials subjected to static, dynamic, and thermally-induced loads (Itasca 2002 [DIRS 160331]). Modeled materials respond to applied forces or boundary restraints according to prescribed linear or non-linear stress/strain laws and undergo plastic flow when a limiting yield condition is reached. FLAC is based upon a Lagrangian scheme that is well suited for large deflections and has been used primarily for analysis and design in mine engineering and underground construction. The explicit time-marching solution of the full equations of motion, including inertial terms, permits the analysis of progressive failure and collapse. A detailed discussion on the general features and fields of the FLAC computer software applications is presented in the user's manual (Itasca 2002 [DIRS 160331]).

The thermomechanical provision of FLAC was used in this study. The validation test cases of Test 1, Test 3, Test 4, Test 5, and Test 7 documented in *the Software Implementation Report for FLAC Version 4.0* (BSC 2002 [DIRS 168820], Table 2) support the software application in this study.

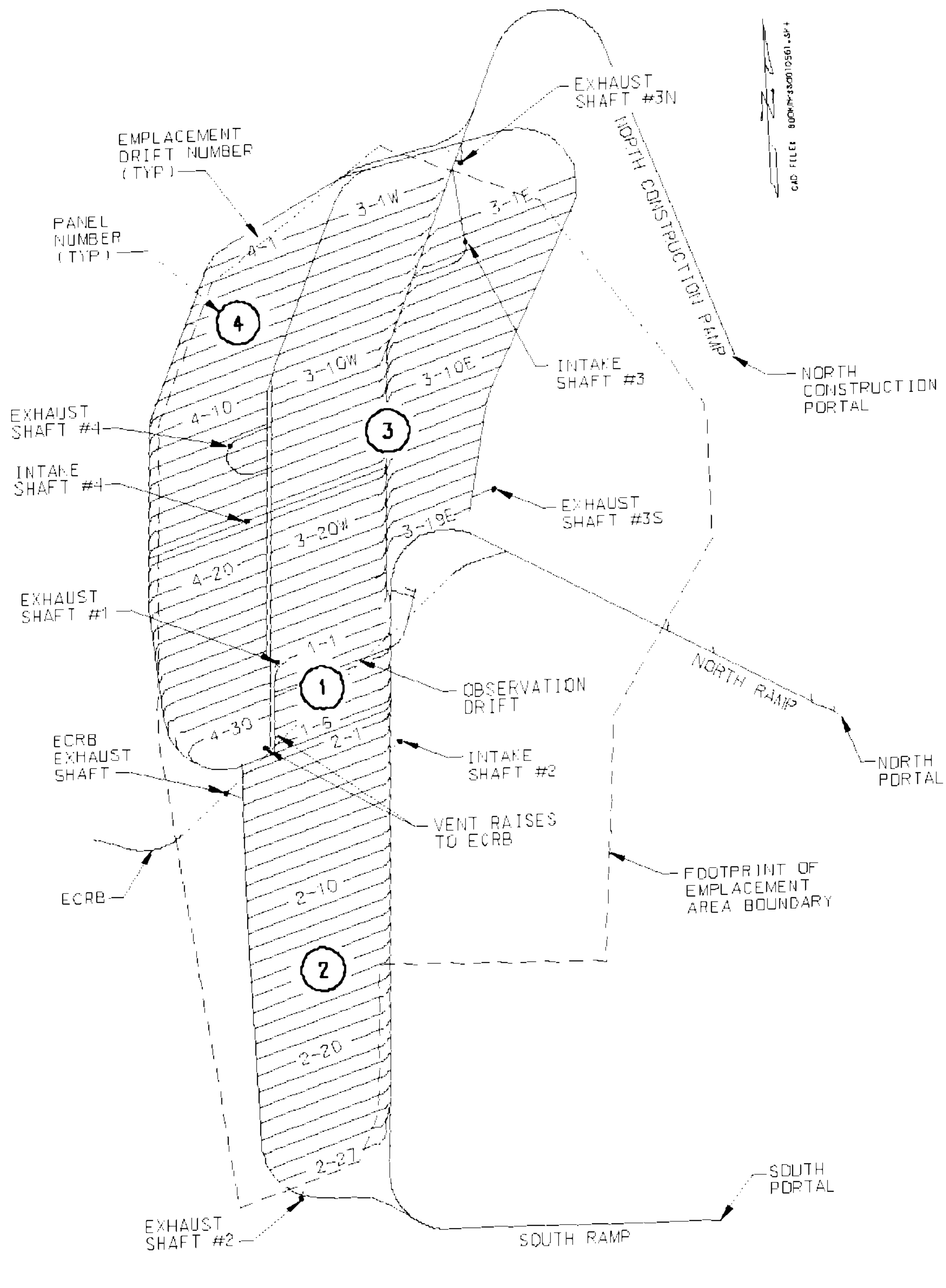
FLAC Version 4.0 [DIRS 161953] was obtained from the Software Configuration Management (SCM) in accordance with the IT-PRO-0011 procedure. FLAC is installed and run on stand-alone PC with Windows 2000/NT 4.0 operating systems. FLAC Version 4.0 is qualified for use in design in accordance with the IT-PRO-0011 procedure. The software was appropriate for the applications used in this study and used only within the range of validation as specified in the software qualification documentation.

Other computer software programs used in this study include Microsoft® Word 2000 and Microsoft® Excel. These programs are Level 2 controlled software that are commercially available and are not required to be qualified per IT-PRO-0011, *Software Management*.

5. INPUT PARAMETERS

Input parameters for this study include thermal and mechanical properties of the rock mass surrounding the openings to be evaluated. In addition, parameters such as drift dimensions, in situ stress field, and thermal loads need to be defined. These parameters exist either in the Technical Data Management System (TDMS) tracked by Data Tracking Numbers (DTNs) or in ground support design calculations including *Subsurface Geotechnical Parameters Report* (BSC 2007b DIRS [178693]). Input parameters used in this study are presented in this section.

As illustrated in Figure 5-1, the exhaust mains are approximately perpendicular to emplacement drifts and exhaust shafts are generally located close to exhaust mains. Due to close proximity, the exhaust mains between panels 4 and 3W would experience temperatures closer to those in the emplacement drifts. Similarly, the bottom portion of a typical exhaust shaft will experience temperatures similar to the exhaust mains. Therefore, analyzing exhaust mains will provide the information sufficient for evaluating exhaust shafts. Figure 5-2 shows that exhaust mains are primarily located in the lithophysal rock unit with the exception of Panels 2 and 3E where the small portion of exhaust mains are located in the nonlithophysal rock unit. The ground support system for exhaust mains consists of fully grouted rockbolts with welded wire fabric for both the lithophysal and nonlithophysal rock units. In addition, shotcrete will be applied at the intersections between exhaust mains and emplacement drifts.



Source: BSC 2006b [DIRS 178323], Figure 10.

Figure 5-1. Current Underground Layout Configuration

Note: This figure is slightly different from the current layout and is for illustration only. The red color represents the lithophysal rock and the green color indicates the nonlithophysal rock exposed at the repository host horizon.

Figure 5-2. Underground Layout and Geological Units by Panel

5.1 Lithophysal Rock Mass Mechanical Properties

Table 5-1 lists the lithophysal rock mass mechanical properties used in this study. These properties are the same as those used in non-emplacement drift ground support calculations.

Table 5-1. Rock Mass Mechanical Properties for Lithophysal Rock

Rock Mass Competency Measure	Rock Mass Category	1	5
	Lithophysal Porosity	25% - 30%	<10%
Elastic Deformation Properties	Modulus of Elasticity (E)	1.92 GPa	19.71 GPa
	Poisson's Ratio (υ)	0.22	0.22
$2G = E/(1 + \upsilon)$	Bulk Modulus (K)	1.14 GPa	11.73 GPa
$3K = E/(1 - 2\upsilon)$	Shear Modulus (G)	0.79 GPa	8.08 GPa
Strength Parameters	Cohesion (c)	2.07 MPa	6.21 MPa
	Friction Angle (ϕ)	45^{o}	45^{o}
$C_o = 2c\text{Cos}(\phi)/(1-\text{Sin}(\phi))$	Unconfined Compressive Strength (C_o)	10 MPa	30 MPa

Source: BSC 2004b [DIRS 168178], Table 4-1.

5.2 Nonlithophysal Rock Mass Mechanical Properties

The nonlithophysal rock mass mechanical properties used in this study are presented in Table 5-2. These properties are the same as those used in non-emplacement drift ground support calculations.

Table 5-2. Rock Mass Mechanical Properties for Nonlithophysal Rock

Rock Mass Competency Measure	Rock Mass Category	1	5
	Rock Mass Quality (Q)	2.05	12.58
Elastic Deformation Properties	Elastic Modulus (E)	10.25 GPa	26.18 GPa
$2G = E/(1 + \upsilon)$	Poisson's Ratio (υ)	0.19	0.19
$3K = E/(1 - 2\upsilon)$	Bulk Modulus (K)	5.51 GPa	14.08 GPa
	Shear Modulus (G)	4.31 GPa	11.00 GPa
Strength Parameters	Cohesion (c)	7.60 MPa	11.75 MPa
$C_o = 2c\text{Cos}(\phi)/(1 - \text{Sin}(\phi))$	Friction Angle (ϕ)	40.15^{o}	46.66^{o}
	Unconfined Compressive Strength (C_o)	32.71 MPa	59.14 MPa

Source: BSC 2004b [DIRS 168178], Table 4-2.

5.3 Rock Mass Thermal Properties

Table 5-3 lists rock mass thermal properties for both lithophysal and nonlithophysal rock units used in this study.

Table 5-3. Thermal Properties of Lithophysal and Nonlithophysal Units

Litho-Stratigraphic Unit	Thermal Conductivity (W/m·K)		Specific Heat (J/kg·K)		
	Wet	Dry	25 - 94°C	95 - 114°C	115 - 325°C
Tptpmn	2.07	1.42	910	3000	990
Tptpll	1.89	1.28	930	3300	990

Temperature Range (°C)	Coefficient of Thermal Expansion (10^{-6}/°C)
25 - 50	7.50
50 - 75	8.80
75 - 100	9.06
100 - 125	9.80
125 - 150	10.61
150 - 175	11.83
175 - 200	13.77
200 - 225	17.27

Source: BSC 2004a [DIRS 170292], Tables 3-2 and 3-3.

5.4 Drift Wall Temperature Responses

Off-normal temperature profiles for the exhaust mains are taken from the calculation of *Drift Wall Thermal Response to Loss of Ventilation* (BSC 2007a [DIRS 179893]). Table 5-4 presents a summary of the drift wall temperature responses. Note that Case 4C temperature files are used in this study for computing thermomechanical responses.

Table 5-4. Times to Reach Specified Temperatures on Drift Wall Surface

Thermal Loading (kW/m)	Simulation Case No.	Time at Loss of Ventilation (yr)	Time to Reach 177 °C After Loss of Ventilation (days)	Time to Reach 200 °C After Loss of Ventilation (days)
1.45	**Case 1A**	0.1	101	178
	Case 1B	0.5	88	163
	Case 1C	1.0	86	159
1.25	**Case 2A**	0.1	147	277
	Case 2B	0.5	130	298
	Case 2C	1.0	126	254
1.75	**Case 3A**	0.1	53	89
	Case 3B	0.5	46	78
	Case 3C	1.0	45	77
2.00	**Case 4A**	0.1	26	45
	Case 4B	0.5	23	39
	Case 4C	1.0	22	39

Source: BSC 2007a [DIRS 179893].

5.5 Ground support systems for the exhaust main consist of fully grouted bolts with heavy-duty welded wire fabric, whereas, fully grouted bolts and steel fiber-reinforced shotcrete are used at the intersection areas formed by exhaust mains and emplacement drifts. Table 5-5 lists the properties of ground support used in this study.

Table 5-5. Dimensions and Properties of Fully Grouted Rock Bolts and Shotcrete

Parameter	Value	Source and Remark
Diameter of Rock Bolt (m)	0.0254	Converted from a diameter of 1 inch (1 in $\times$ 0.0254 m/in = 0.0254 m)
Thickness of Grout Annulus (m)	0.00635	Converted from a thickness of 0.25 in (0.25 in $\times$ 0.0254 m/in = 0.00635 m)
Length of Rock Bolts (m)	3 - 5	3 m in typical non-emplacement drifts and increase up to 5 m in intersection area
Spacing between bolts and rows (m)	1.25	Spacing may be changed to 1.5 m if necessary
Perimeter of Rock Bolt (m)	0.08	Calculated: $p = \pi D = 3.1415 \times 0.0254 = 0.08$ m
Allowable Axial Force (kN)[a]	264	Based on the yield strength (force) of 264 kN (DSI, Dywidag threadbar [DIRS 166160])
Modulus of Elasticity of Steel (GPa)	200	AISC 1997, p. 1-117 (29,000 x1000/(145x 10^6))
Modulus of Elasticity of Grout (GPa)	14	Onofrei, et al. 1993, Figure 33, p. 60
Poisson's Ratio of Grout	0.25	Set to be the same as concrete (Merritt 1983, p. 6-8)
Grout Unconfined Compressive Strength (MPa)	90	Onofrei, et al. 1993, Figure 27b, p. 52
Bond Stiffness of Grout (N/m/m)	8.68×10^8	Calculated using Equation 3 of Ruest and Martin 2002
Bond Strength of Grout (cohesion) (N/m)	1.9×10^5[a] 3.0×10^5[b]	Based on recommendation by Hutchinson and Diederichs (1996, Figure 2.6.13 [DIRS 153305]). [a] for lith. tuff, [b] for non lith. tuff.
Thickness of Shotcrete (m)	0.1	Converted from a thickness of 4 in (4 in $\times$ 0.0254 m/in = 0.102 m)
Elastic Modulus *E* (GPa) for Shotcrete	29	Based on mean value in Sec. 1.7 of ACI 506R-90(95)
Poisson's Ratio ν for Shotcrete	0.25	Assumed same as concrete, Merritt (1983, p. 6-8)

5.6 A rock mass saturated bulk density of 2,410 kg/m^3 is used to estimate overburden and in situ stress state. This value is the mean saturated density for the rock unit of Tptpln (DTN: SNL02030193001.027) which is conservative for the purpose of this study.

5.7 The diameter of typical exhaust mains is 7.62 m.

6. ASSUMPTIONS

The following assumptions are made to facilitate the numerical modeling involved in this study.

6.1 Temperatures at the exhaust mains and exhaust shafts are generally lower than those at emplacement drifts. Due to lack of the information on expected off-normal temperatures in the vicinity of exhaust mains and exhaust shafts, this study uses the off-normal temperature profiles from emplacement drifts for exhaust mains and exhaust shafts. This is considered conservative in evaluating off-normal temperature impacts on subjected underground openings.

6.2 It is assumed that the maximum off-normal temperature to be reached in the subjected underground openings is 177°C (351°F). The subsurface ventilation system design shall take into account potential modes of off-normal system shutdowns and recoveries, such that the drift wall temperatures and air temperatures in the emplacement drifts and downstream airway openings and structures (exhaust mains, shaft and raise connecting drifts, exhaust shafts and raises, shaft and raise collars) do not reach levels that are detrimental to the integrity of structural and ground support components. The maximum temperature not to be exceeded during off-normal conditions for short duration is 177°C (351°F) (ACI 349-01 [DIRS 158833], Section A.4).

6.3 Only one episode of off-normal thermal loading is considered in this study. Considering that a 100-year preclosure period is a long time, more than one episode of normal and off-normal thermal cycles could be possible. However, peak temperature value dictates the maximum thermally-induced stresses in rock and ground support components. As long as the peak off-normal temperature is accounted for in thermomechanical computations, consideration of more episodes of off-normal scenarios is not expected to change the results. In addition, it is assumed that neither rock mass nor ground support system will be subjected to degradation due to multiple off-normal thermal cycles.

6.4 It is assumed that the average depth of repository host horizon is 400 m measured from the center of nonemplacement openings with the bounding horizontal-to-vertical stress ratios of 0.3 and 1.0.

6.5 Seismic loading is not considered in this study.

7. METHODOLOGY

This study deals with potential off-normal temperature scenarios during the 100-year preclosure period. To understand the complexity of the work scope outlined in Section 2, one must first gain insight into how heat transfers from emplaced waste packages to the surrounding rock with and without ventilation. As is mentioned in Section 1, it is a normal scenario with ventilation to function as designed. When ventilation is interrupted, the repository temperature will rise above the normal operation range and will become an off-normal scenario. This section begins with a brief narrative about how the rock surrounding an exhaust main will respond to the rise in temperature due to the heat emitted from waste packages in emplacement drifts, then proceeds to define the scope of numerical modeling, and ends with describing the numerical models involved in this study.

7.1 THERMOMECHANICAL CONSIDERATIONS

In brief, heat flow in a ventilated waste-emplaced drift occurs from the heat-generating waste package to the drift wall primarily by thermal radiation as a result of temperature differences between the WP surface and the drift wall, together with convective heat being transferred between the WP surface and the ventilating air, as well as between the drift wall and the air. Without ventilation (forced or natural), the convective heat transfer ceases. In the rock mass, heat flow occurs by conduction due to the thermal gradient between the high-temperature at the drift wall and the low temperature of the rock away from the drift. Therefore, the temperature of the rock surrounding exhaust mains and exhaust shafts is elevated through a combination of heat conduction in rock and convection between drift wall and exhaust air.

The rock mass surrounding the exhaust mains will respond to heating by thermal expansion which is affected both by the constraint due to the relatively cold rock farther away from the openings and by temperature-generated expansion from adjacent drifts, such as emplacement drifts. As a result, the constrained thermal expansion induces thermal stresses in the rock mass. The higher the rock mass modulus of elasticity, the greater the thermally-induced stresses.

Fully grouted rockbolts designed for exhaust mains will bond to rock to reinforce the rock mass along their length. There are two bonding interfaces for a fully grouted rockbolt: one between steel bar (bolt) and grout, and the other between the grout and rock. Either yielding of the steel bar or substantial breaking of one of the two interfaces along the bolt length will render a fully grouted bolt useless. When subjected to high thermal loading, the difference in coefficient of thermal expansion among steel bar, grout annulus, and rock may result in shear stress development at interfaces that can be high enough to break the bonds. When shotcrete is applied as a thin liner to the drift wall, thermally-induced stress will develop in the liner. Such a stress can be high enough to crack the liner.

In summary, adequate determination of thermomechanical responses of ground support systems and their surrounding rock is an important step toward evaluating the opening stability.

7.2 NUMERICAL MODELING

In order to deal with the complexity of the problem to be evaluated, a numerical modeling approach is adopted. Other methods, such as closed-form solutions and empirical approaches, are not readily available. The numerical modeling approach involves constructing a representative numerical model, applying proper boundary conditions, calculating static stress and displacement redistributions due to excavation of the openings, subjecting the model to thermal loads and computing thermally-induced stresses and displacements, and assessing the yielding or overstressing or failure of the rock and/or ground support by testing the resulting stresses (static + thermal) against appropriate failure criteria.

A quick count of major contributing parameters will help determine how intensive the numerical modeling effort will be. These parameters are listed in the following:

Repository host horizon rock type: Both nonlithopysal and lithophysal rock types will be considered.

Rock mass category: Both the least competent (category 1) and most competent (category 5) rock mass conditions are considered as bounding scenarios. Category 5 rock mass is considered because it results in the highest thermal stresses.

In situ stress: The vertical stress component is gravitational with the bounding horizontal-to-vertical stress ratio (Ko) of 0.3 and 1.0. The in situ stress field dictates the stress redistribution and concentration in the vicinity of the opening upon excavation. To evaluate the drift stability, excavation-induced stress redistributions corresponding to Ko = 0.3 and Ko = 1.0 are both needed to combine with thermally-induced stresses.

Ground support: For this study, three scenarios are modeled: unsupported drifts, drifts reinforced with fully grouted bolts, and drifts supported with fully grouted bolts and shotcrete. The unsupported scenario will provide the information of what is going to happen to the drift wall rock, as well as the information needed for deciding on the effective ground support. The other two scenarios will provide information of what would happen to ground support when an off-normal thermal condition arises.

Off-normal thermal scenario: Depending on the initial heat output of waste packages emplaced in a particular emplacement drift, the equivalent thermal line load varies from 1.45 (base case) to 2.0 (extreme case) kW/m. In this study, the off-normal temperature scenario is based on Case 4C of *Drift Wall Thermal Response to Loss of Ventilation* calculation (BSC 2007a [DIRS 179893]).

Therefore, a total of 24 computer runs are required to cover the combinations of the 5 key parameters listed above, that is, 2 (rock types) x 2 (Ko values) x 2 (rock mass categories) x 3 (ground support types) x 1 (off-normal temperature scenario) = 24. These 24 combinations are presented in Table 7-1.

Table 7-1. Modeling Scenarios Considered in the Study

Case No.	Rock Type		In Situ Stress Field		Rock Mass Category		Ground Support Type		
	Nonlith	Lith	Ko=0.3	Ko=1	1	5	Unsupported	Bolts	Bolts and Shotcrete
1	X		X		X		X		
2	X		X		X			X	
3	X		X		X				X
4	X		X			X	X		
5	X		X			X		X	
6	X		X			X			X
7	X			X	X		X		
8	X			X	X			X	
9	X			X	X				X
10	X			X		X	X		
11	X			X		X		X	
12	X			X		X			X
13		X	X		X		X		
14		X	X		X			X	
15		X	X		X				X
16		X	X			X	X		
17		X	X			X		X	
18		X	X			X			X
19		X		X	X		X		
20		X		X	X			X	
21		X		X	X				X
22		X		X		X	X		
23		X		X		X		X	
24		X		X		X			X

Note: The off-normal temperature scenario is based on Case 4C of *Drift Wall Thermal Response to Loss of Ventilation* calculation (BSC 2007a [DIRS 179893]).

7.3 DESCRIPTION OF NUMERICAL MODELS

As is mentioned in previous sections, the off-normal temperature profiles for this study are based on the calculation of *Drift Wall Thermal Response to Loss of Ventilation* (BSC 2007a [DIRS 179893]). The thermal numerical model used for the calculation is illustrated in Figure 7-1. The worst case off-normal temperature profile from this model is shown in Figure 7-2, which was obtained using a linear thermal load of 2.0 kW/m.

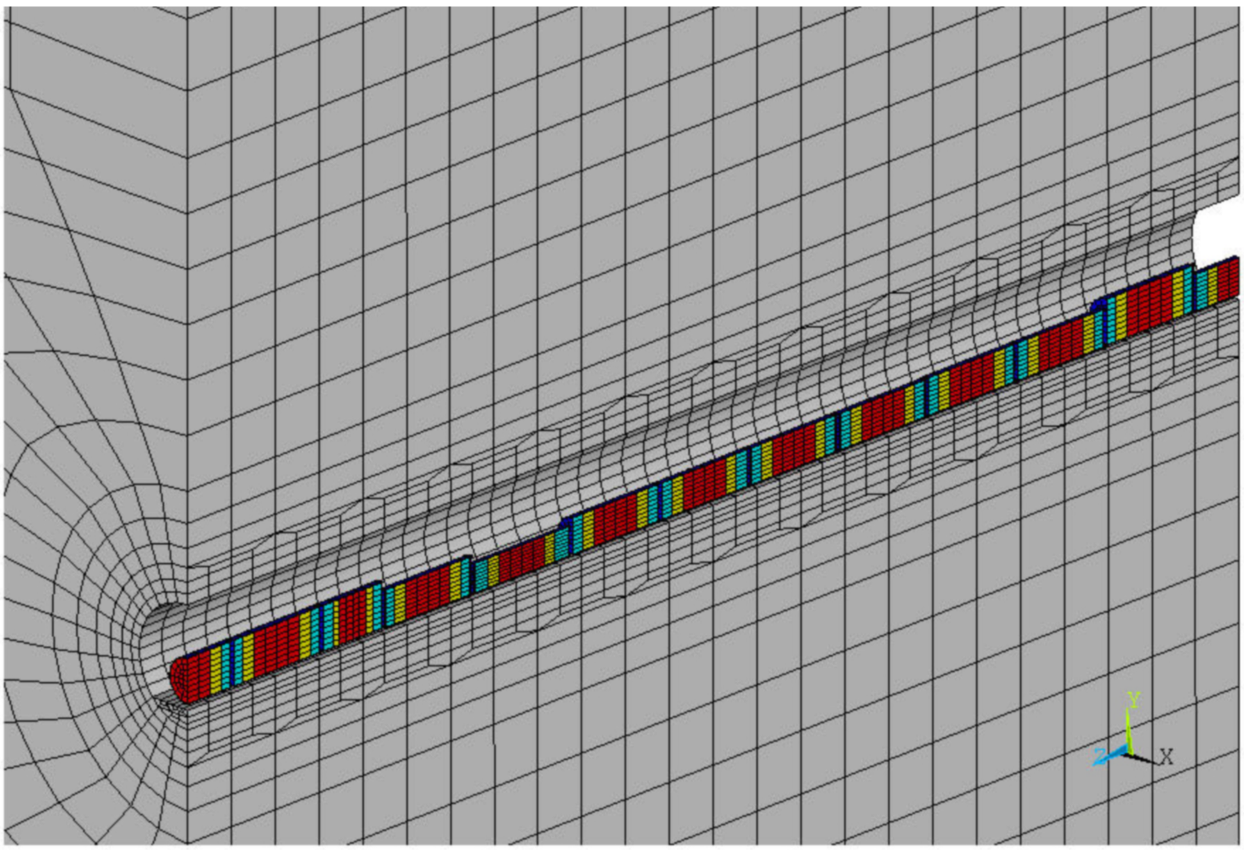
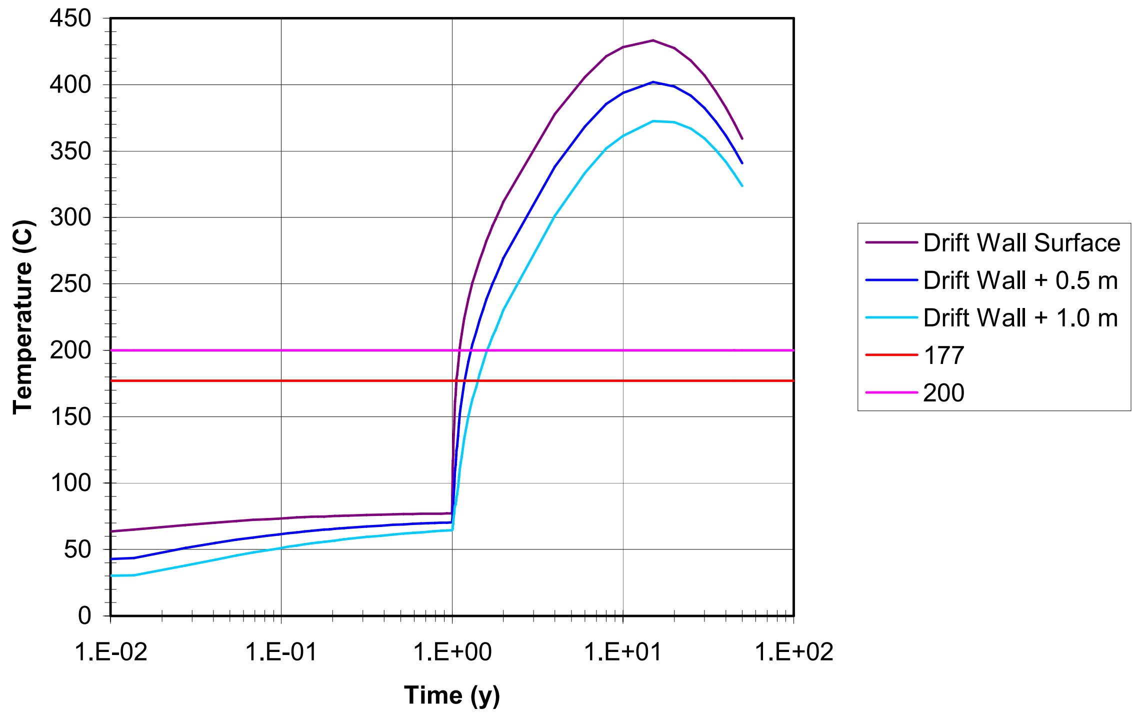
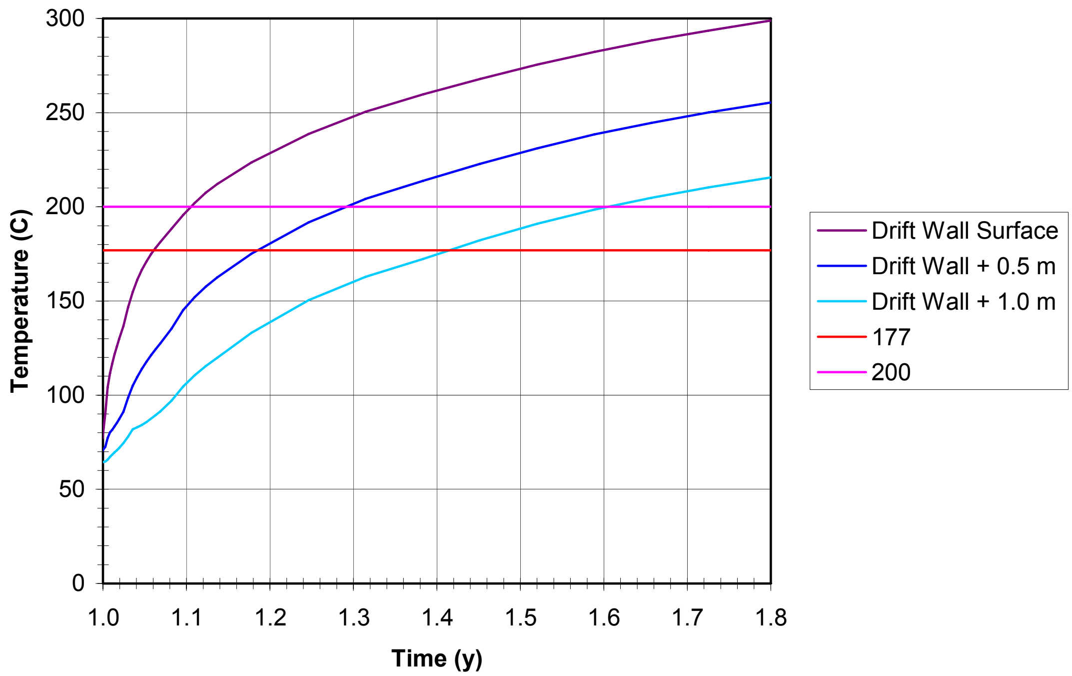


Figure 7-1. A Close-up of the Thermal Model Used to Generate the Off-Normal Temperature Profiles





Source: BSC 2007a [DIRS 179893].

Figure 7-2. Off-Normal Temperature Profiles Based on 2.0 kW/m Thermal Load

By exporting these temperature time histories to thermomechanical numerical models of an exhaust main opening, thermomechanical responses of the exhaust main are simulated using the finite difference code FLAC. Unlike the thermal model, there are no waste package combinations presented in the thermomechanical model. Furthermore, modeling a cross section of the exhaust main alone provides adequate numerical results that can be used to address other openings. The inaccessible nonemplacement openings include the intersections between emplacement drifts and exhaust mains, exhaust mains, and exhaust shafts. Figure 7-3 illustrates the FLAC model used for studying the thermomechanical responses of the exhaust main that is supported with bolts and shotcrete to the maximum off-normal temperatures. Fully grouted bolts are numerically represented by using cable elements while the 240-degree shotcrete arch is numerically represented by beam elements, representing one of the three ground support types listed in Table 7-1. By removing these cable and beam elements from this mesh, an unsupported exhaust main model can be obtained. Numerical removal of beam elements alone from the mesh will lead to an exhaust main model supported with bolts only. These numerical modeling approaches allow for quick consideration of all the three ground support types listed in Table 7-1.

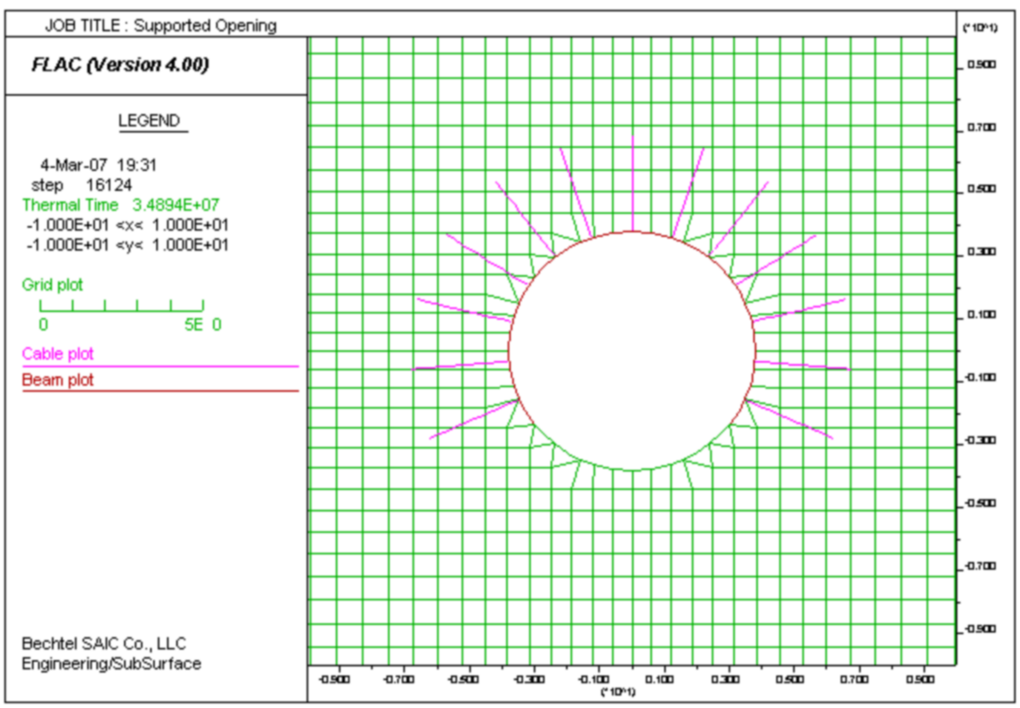


Figure 7-3. FLAC Model of Exhaust Mian Supported with Rock Bolts and Shotcrete

8. NUMERICAL MODELING RESULTS

Given that thermal loading for all 24 scenarios is the same, a straightforward measure of the off-normal temperature impacts on the exhaust main is to look at the extent of predicted overstressing regions or zones surrounding the exhaust main and safety margin within ground support. This section first presents numerical results for unsupported openings, followed by the thermomechanical responses of the supported opening by rockbolts and shotcrete.

8.1 UNSUPPORTED OPENINGS

Numerical simulation of the behavior of an unsupported opening will provide the information essential to understanding the potential failure mode of the opening, selecting the proper ground support system, and deciding on the optimal timing of ground support installation.

Computer modeling runs begin with the simulation of drift excavation under the in situ stress load. Stress redistribution and concentration will take place upon excavation, particularly surrounding the drift. Afterwards, the thermal loads in forms of temperature time histories, are imposed at model boundaries and thermally-induced stresses and displacements are calculated. The resulting stresses are evaluated against specified failure criteria to estimate the potential overstressing (yield) extent or safety margin.

Figure 8-1 illustrates the temperature distribution surrounding the opening. Because of the relatively short thermal time simulation (i.e., 1 year ventilation on and 39 day ventilation cut off), the heat has not been transferred deep into the rock prior to reaching the target temperature at the drift wall.

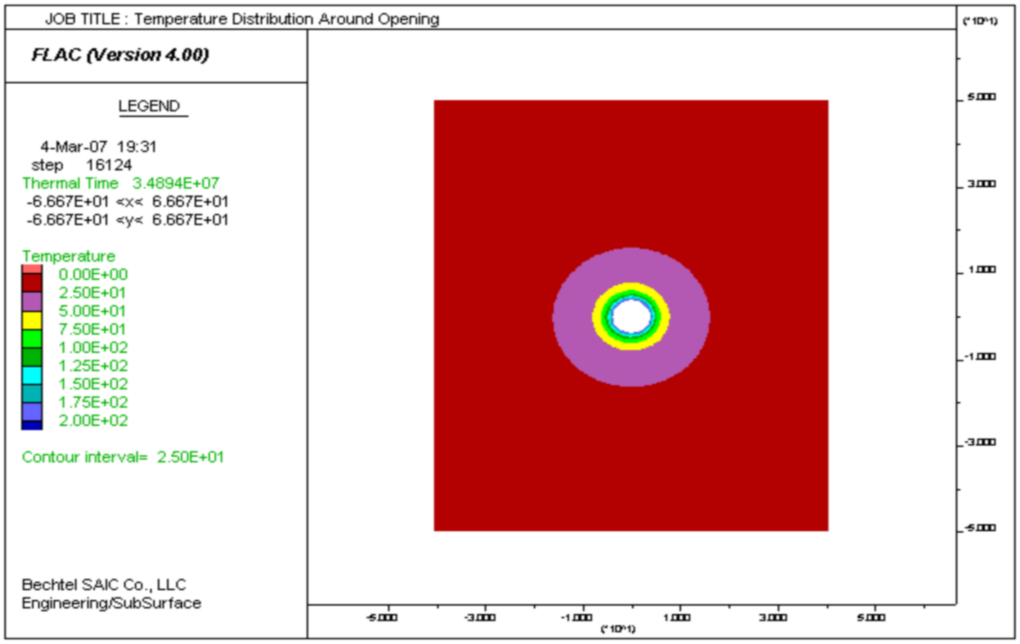


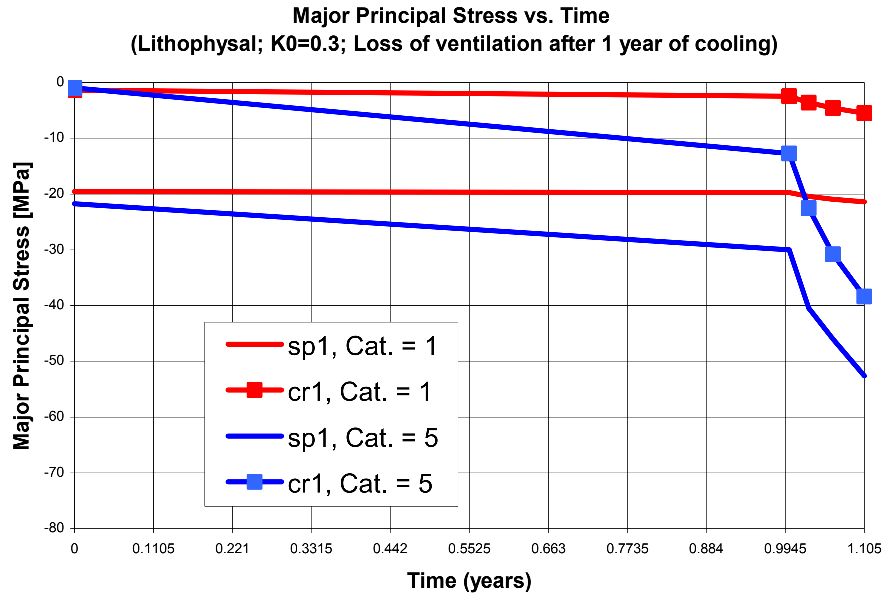
Figure 8-1. Simulated Off-Normal Temperature Distribution Surrounding the Opening

Figures 8-2 and 8-3 show time histories of major principal stresses at the crown and springline of the unsupported opening in both lithophysal and nonlithophysal rock, respectively. From these figures, the increase of major principal stresses near the crown and springline of the unsupported opening is observed with respect to the elapse of the thermal loading time. The major principal stress is in the circumferential direction while the minor principal stress in the radial direction. In these stress plots, a negative sign represents compressive and a positive sign represents tensile. During the normal operation scenario, when ventilation is on, the thermally-induced stress increases rather slowly as most of the heating emitted from the waste packages is carried out by the ventilation air. However, the rock stresses will build up rapidly when the ventilation is stopped. As seen in the thermal loading scenario, Case 4C of Table 5-4, with an ambient rock temperature of about 25 ^{o}C, it takes about 22 days for the drift wall temperature to reach 177 ^{o}C and an additional 17 days for the drift wall temperature to reach 200 ^{o}C.

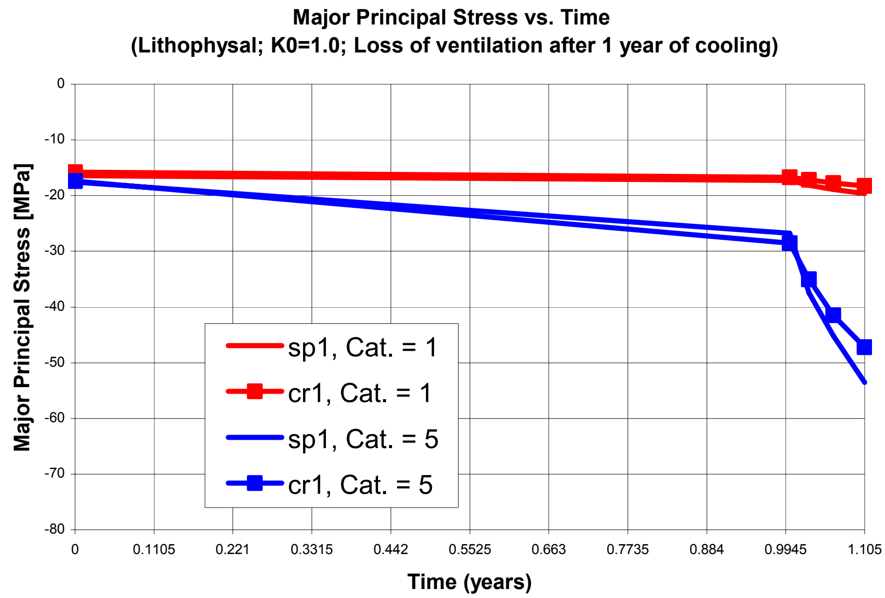
Time histories of the major principal stresses at the crown and springline shown in Figures 8-2 (a) and (b) are corresponding to the drift excavated in the lithophysal rock subjected to in situ and thermal loads with the K_o of 0.3 and 1.0, respectively. The time zero corresponds to the ambient condition (i.e., excavation-induced effect only). During the first year of ventilation, the maximum major principal stresses are shown to vary from about 2 to 20 MPa for category 1 rock and from about 13 to 30 MPa for category 5 rock. However, after the ventilation is shut down, the stresses increase rapidly, especially in category 5 rock mass. During this period, the maximum major principal stresses are expected to vary from about 5 to 21 MPa for category 1 rock and from about 38 to 53 MPa for category 5 rock.

Similarly, time histories of the major principal stresses at the crown and the springline shown in Figures 8-3 (a) and (b) are corresponding to the drift excavated in the nonlithophysal rock subjected to in situ and thermal loads with the K_o of 0.3 and 1.0, respectively. During the first year of ventilation, the maximum major principal stresses are expected to vary from about 8 to 27 MPa for category 1 rock and from 17 to about 35 MPa for category 5 rock. After the ventilation is shut down, the maximum major principal stresses are expected to vary from about 24 to 40 MPa for category 1 rock and from about 60 to 73 MPa for category 5 rock.

The depth of potential yield zones around the exhaust main in both the lithophysal and nonlithophysal rock units are predicted to be about 1 m or less, as illustrated by the "x" marks in Figure 8-4. The next section will demonstrate that the potential overstressing or loosening zones can be controlled by the ground support system.

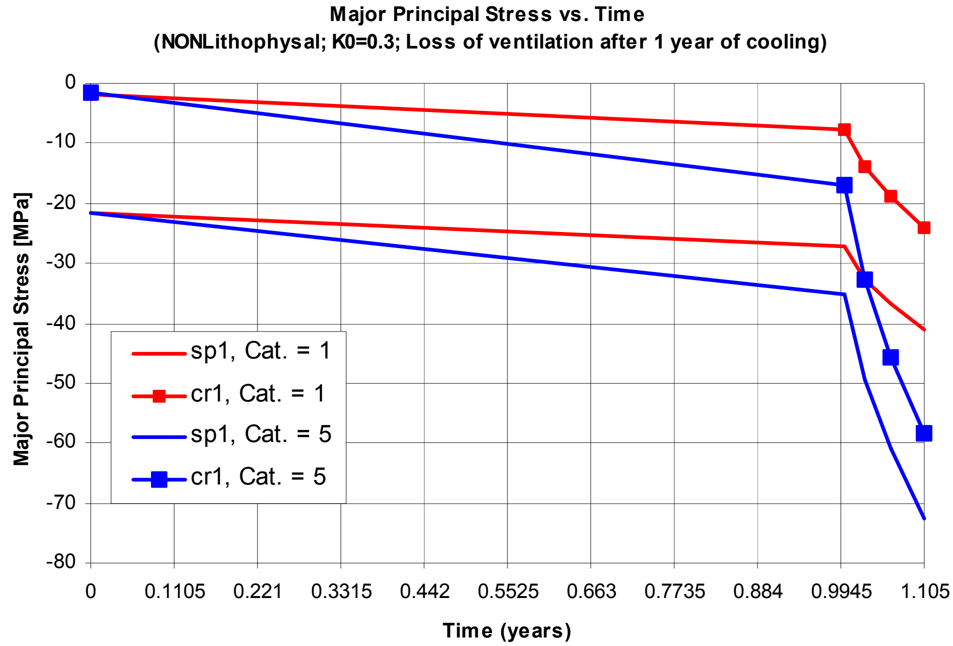


(a)

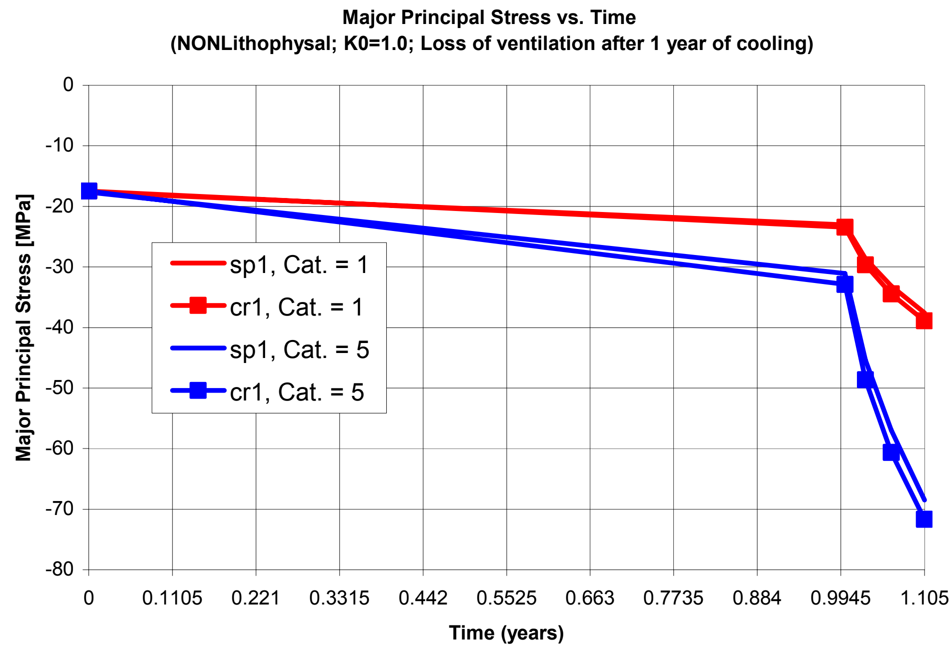


(b)

Figure 8-2. Time Histories of Major Principal Stresses near Crown and Springline of Unsupported Exhaust Mains in Lithophysal Rock with Categories 1 and 5 under In Situ, and Thermal Loads: (a) Ko=0.3; (b) Ko=1.0

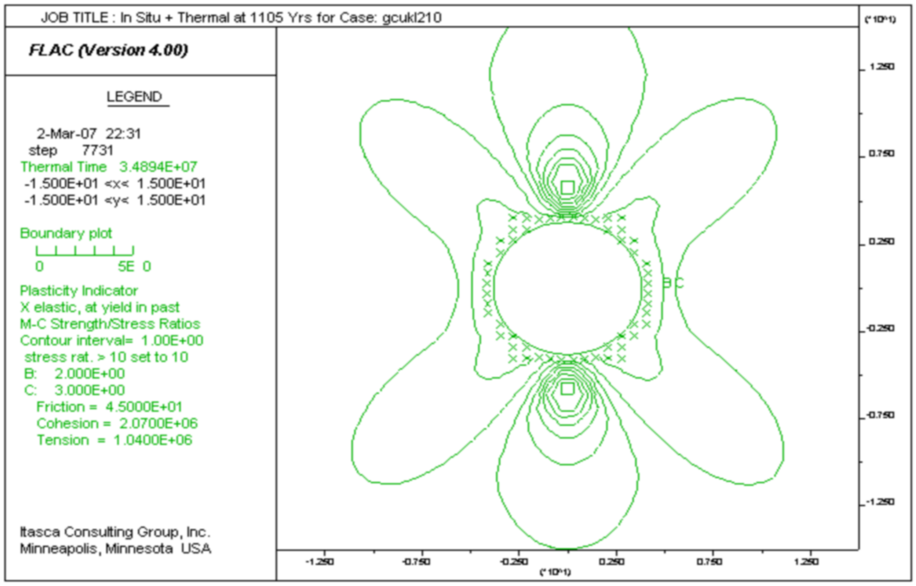


(a)

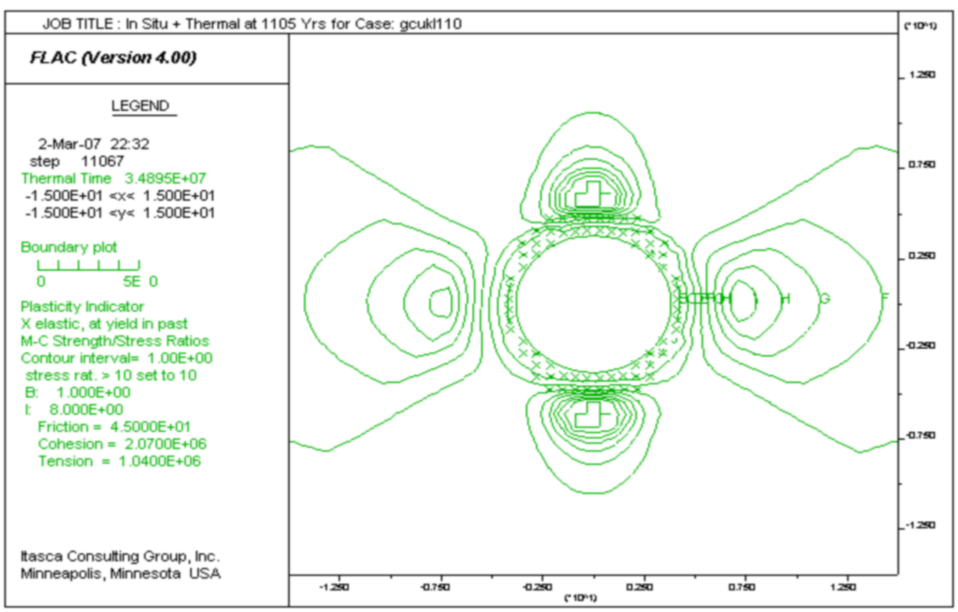


(b)

Figure 8-3. Time Histories of Major Principal Stresses near Crown and Springline of Unsupported Exhaust Mains in Nonlithophysal Rock with Categories 1 and 5 under In Situ, and Thermal Loads: (a) Ko=0.3; (b) Ko=1.0



(a)



(b)

Figure 8-4. Potential Yield Zone and Contours of Strength-to-Stress Ratios under In situ Stress and Thermal Load With Category 1 Rock Mass: (a) Lithophysal Rock (b) Nonlithophysal Rock

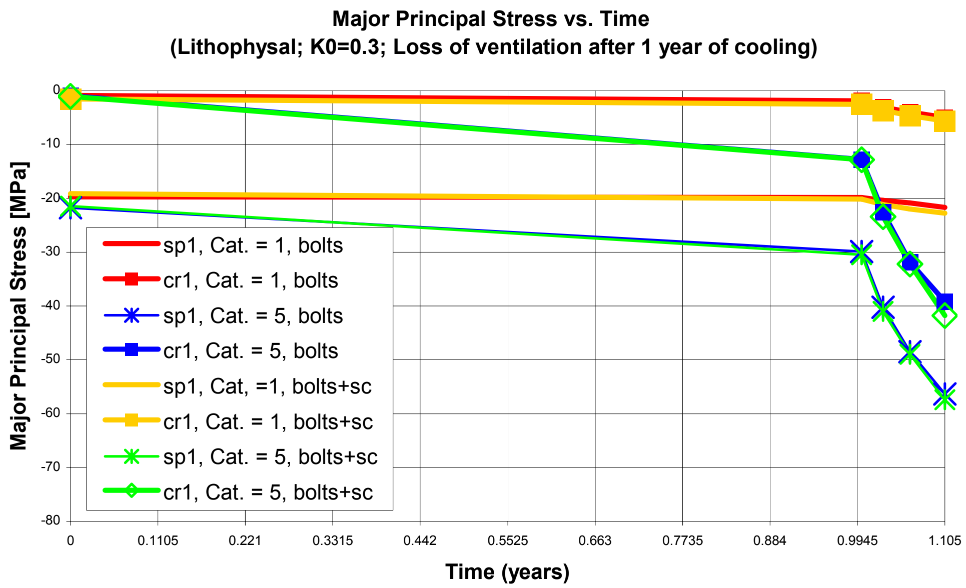
8.2 SUPPORTED OPENINGS

Numerical simulations of the behavior of a supported opening are conducted similar to the unsupported opening. The only difference is that bolts and shotcrete liner are incorporated in the model. Bolts are numerically induced to the FLAC model during the phase of excavation simulation. It must be pointed out that the structural stiffness from the installed ground support system is so insignificant compared to the surrounding rock mass that the ground support system does little in altering the stress distribution and displacement behavior in the rock. A comparison of Figure 8-5 to Figures 8-2(a) and 8-3(a) clearly confirms this point. The ground support system controls the detachment or dislodge of rock blocks from the surrounding rock mass and confines or retains the loosened rocks from falling.

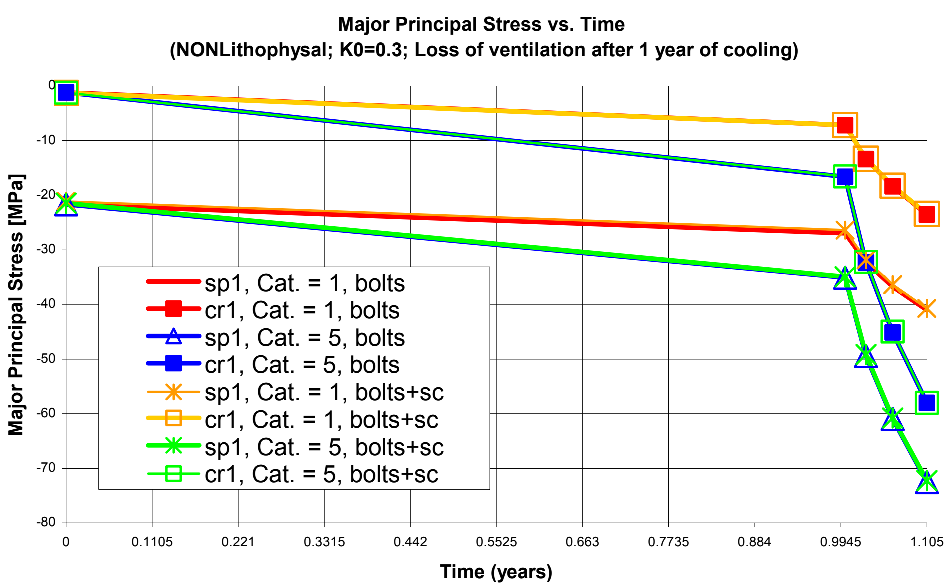
Upon installation of a ground support system, bolts and shotcrete will start picking up the loads in their attempt to confine, retain, or reinforce the loosening rock. This reinforcing mechanism is demonstrated in the plots shown in Figures 8-6 through 8-9. These plots show the axial force development and distribution along each bolt and for the shotcrete arch.

The axial force for rockbolts ranges approximately from 20 to 80 kN or 2 to 8 metric tons, well below the allowable axial force of 264 kN presented in Table 5-5. The maximum axial thrust in the shotcrete liner is shown to be close to 900 kN in the lithophysal rock, resulting in a compressive stress of about 9 MPa. Such a stress level will not crack the shotcrete. Considering that the thin shotcrete layer will be steel-fiber reinforced, cracks in the shotcrete liner do not significantly reduce the functionality of the shotcrete liner for retaining the rock together with bolts.

It should be pointed out that the current ground support design for exhaust mains does not include the shotcrete usage except for the intersections between emplacement drifts and exhaust mains. Nevertheless, a 100 mm shotcrete layer is numerically represented in FLAC models of the exhaust main only for the purpose of being able to extrapolate the numerical results for the intersections and exhaust shafts where shotcrete does get used as lining.

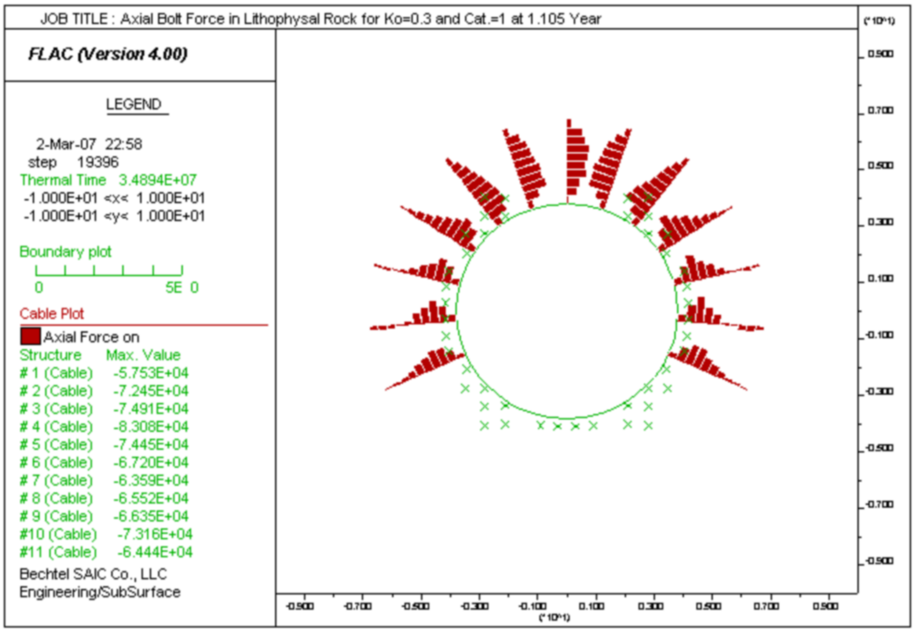


(a)

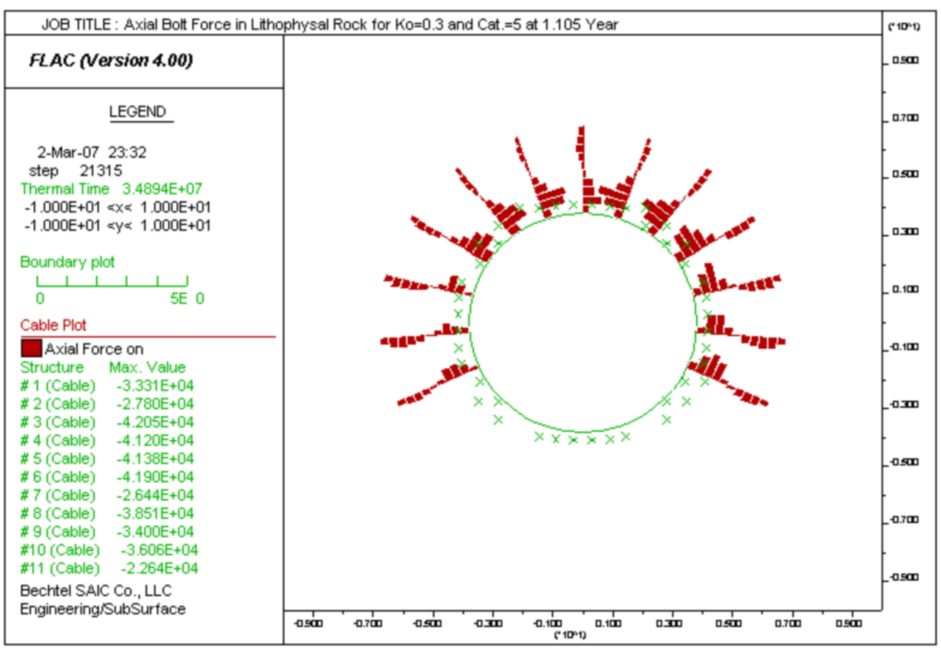


(b)

Figure 8-5. Time Histories of Major Principal Stresses near Crown and Springline of Supported Exhaust Mains with Category 1 under In Situ Ko=0.3 and Thermal Loads: (a) Lithophysal Rock (b) Nonlithophysal Rock

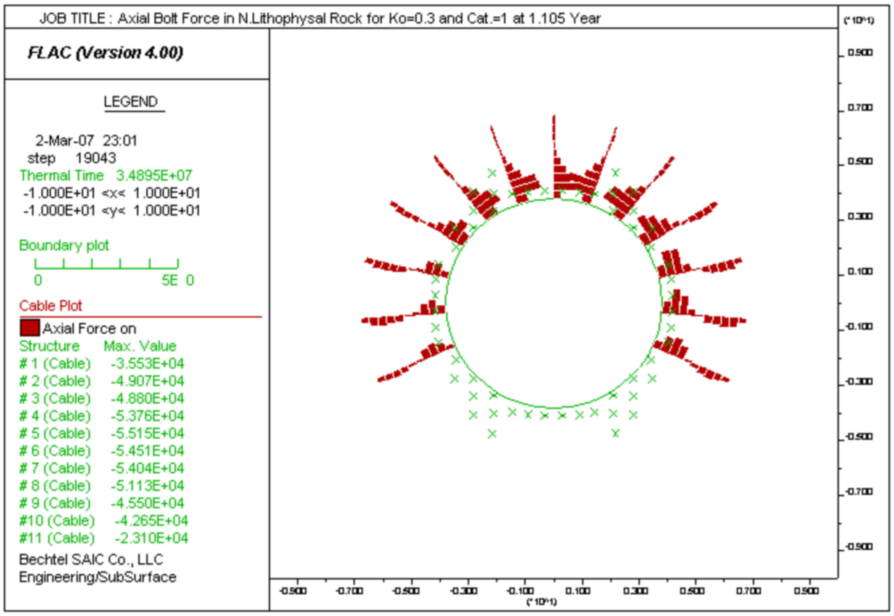


(a)

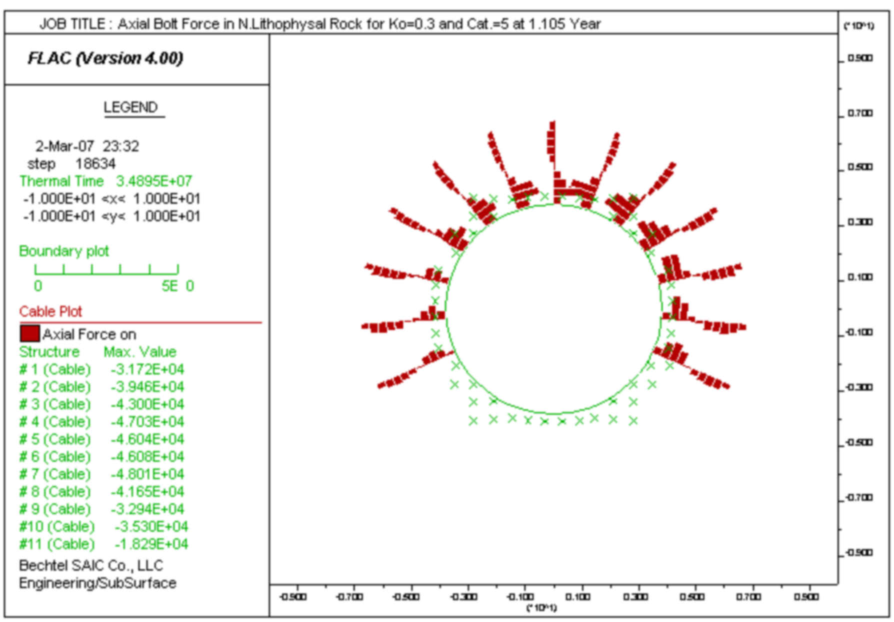


(b)

Figure 8-6. Axial Load Development in Rockbolts and Potential Overstressing Zones in the Lithophysal Rock with In Situ Ko = 0.3 and Thermal Loads: (a) Category 1 Rock; (b) Category 5 Rock

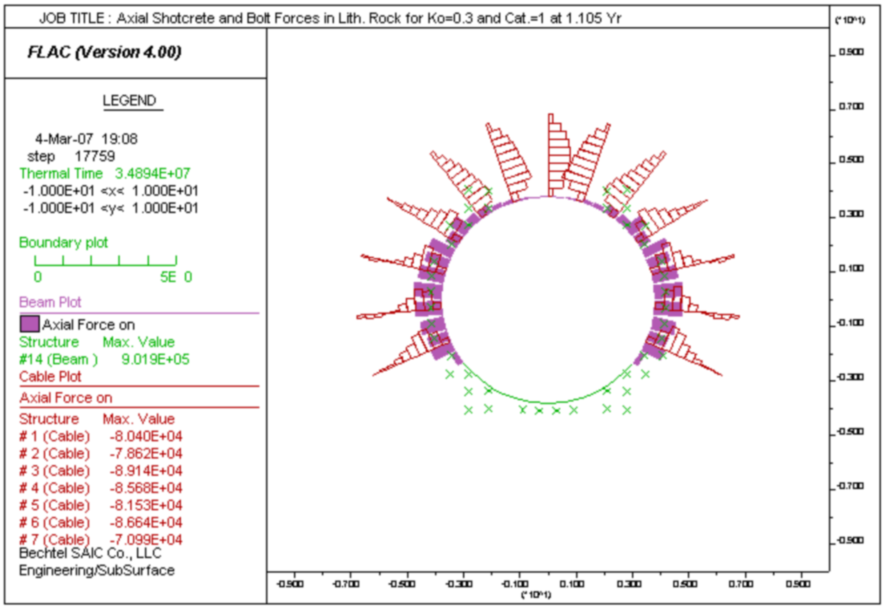


(a)

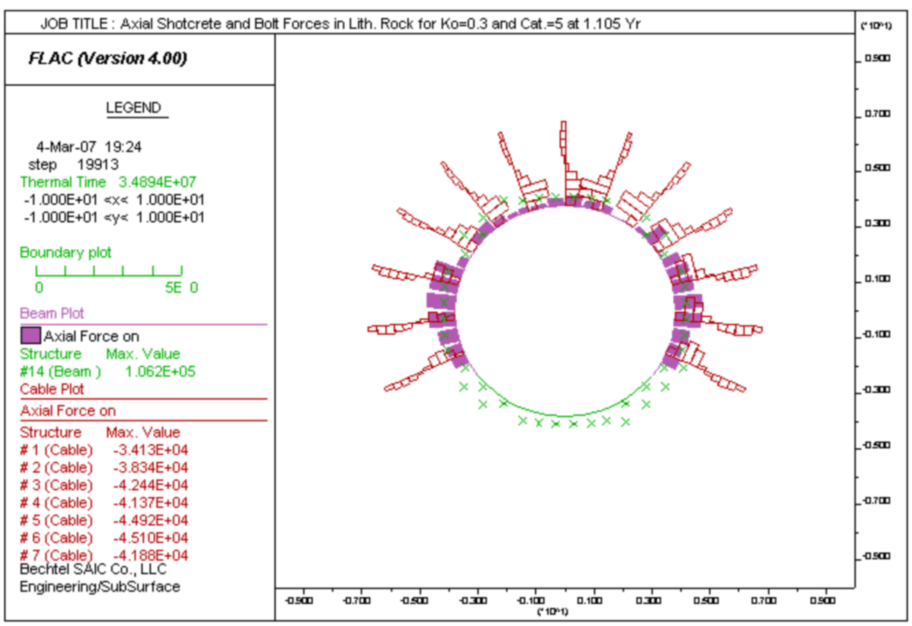


(b)

Figure 8-7. Axial Load Development in Rockbolts and Potential Overstressing Zones in the Nonlithophysal Rock with In Situ Ko = 0.3 and Thermal Loads: (a) Category 1 Rock; (b) Category 5 Rock

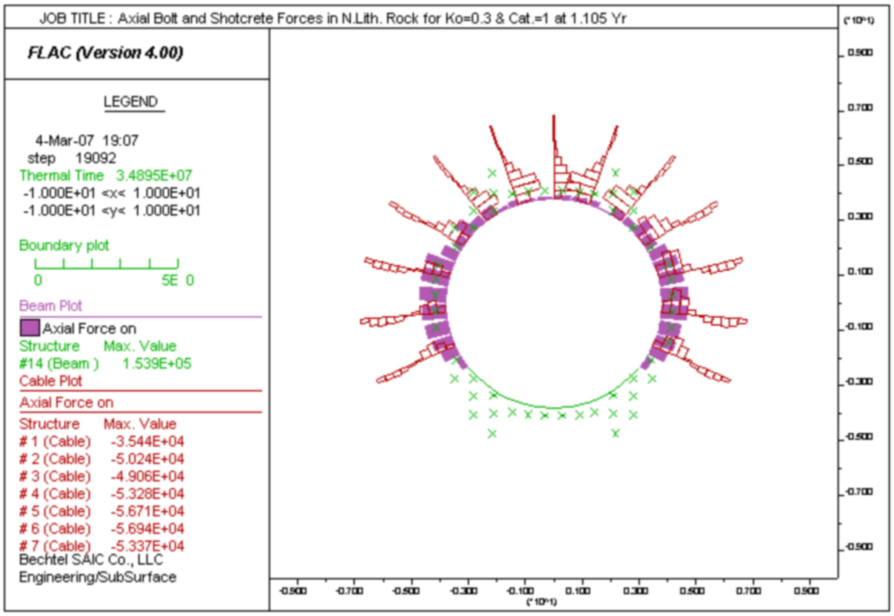


(a)

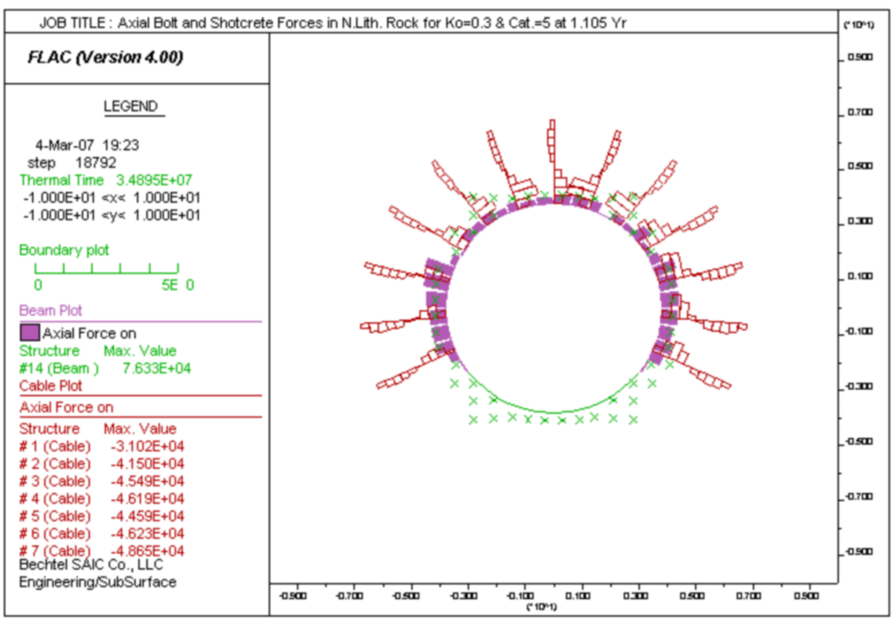


(b)

Figure 8-8. Axial Load Development in Rockbolts and Shotcrete and Potential Overstressing Zones in the Lithophysal Rock with In Situ Ko = 0.3 and Thermal Loads: (a) Category 1 Rock; (b) Category 5 Rock



(a)



(b)

Figure 8-9. Axial Load Development in Rockbolts and Shotcrete and Potential Overstressing Zones in the Nonlithophysal Rock with In Situ Ko = 0.3 and Thermal Loads: (a) Category 1 Rock; (b) Category 5 Rock

8.3 DISCUSSIONS

The numerical results obtained from simulating the thermomechanical responses of unsupported openings help gain insight into potential overstressing or loosening zones within the drift wall rock mass. Of primary concern is the general stability of the portion of the drift wall above the springline because of rockfall hazards. Table 8-1 lists the maximum stress concentrations developed by the combination of in situ stress load and subsequent thermal loading. Knowledge of these stress concentration magnitudes allows for a reasonable and practical assessment of opening stability. The following observations are derived from Table 8-1:

- As mentioned in Section 8.2, the presence of ground support systems does not alter the stress redistributions in the rock.

- While stress concentrations caused by excavation are about the same whether its is in Category 1 or Category 5 rock mass, Category 5 rock mass draws much higher thermally-induced stresses than Category 1 rock mass.

- The resultant stress levels seemingly either exceed or approach the unconfined compressive strength values listed in Tables 5-1 and 5-2. Theoretically speaking, only the skin of the drift wall sees no confinement in the radial direction. The compressive strength value increases rapidly as the confinement or confining stress in the radial direction increases. This explains why the potential overstressing zones are predicted to be shallow in both lithophysal or nonlithophysal rock.

The numerical results obtained from simulating the supported openings show that it is not likely to have the current ground support systems overstressed when subjected to the off-normal temperature up to 200 ^{o}C. The current ground support systems for exhaust mains should be able to withstand the thermal loading surge caused by the off-normal thermal scenario.

The numerical results obtained from simulating the typical exhaust main can be applied to the exhaust shafts and the intersections formed by exhaust mains and emplacement drifts. Upon excavation, an exhaust shaft will experience a more stable condition than an exhaust main because the shaft is subject to a nearly hydrostatic stress field in its cross section. The concrete or shotcrete liner for the shaft, when subjected to an off-normal thermal scenario, will behave in a similar manner as the exhaust main. A typical intersection formed by exhaust mains and emplacement drifts will be supported by rockbolts and shotcrete. Therefore, all the discussions about exhaust mains are considered valid for intersections.

As documented in ground support calculations (BSC 2004a and BSC 2004b), the primary potential failure mode of underground openings in the lithophysal rock is through raveling of small blocks of rock. In the nonlithophysal rock, the potential exists for isolated, small wedges of loosened rock formed by natural fractures to dislodge under the gravity. The general concept regarding ground support is that a combination of grouted rockbolts, with some means of surface protection (preferably shotcrete) be used. The rockbolts provide overall stability to the tunnel opening while the surface protection prevents progressive raveling of small rock fragments or blocks from the surface of the opening. These ground support systems are widely used in underground mines for ground control.

Table 8-1. Summary of Major Principal Stresses at Crown and Springline of Openings in Nonlithophysal and Lithophysal Rocks

Rock Type	Rock Mass Category	Horizontal-to-Vertical Stress Ratio	Ground Support Type	Major Principal Stress at Crown (MPa)			Major Principal Stress at Springline (MPa)		
				Ambient	177 °C	200 °C	Ambient	177 °C	200 °C
Nonlithophysal Rock	1	Ko = 0.3	U	22	37	41	2	19	24
			B	22	37	41	1	18	24
			B+S	21	36	41	1	18	23
		Ko = 1.0	U	18	33	38	17	34	39
			B	18	33	38	17	34	39
			B+S	17	33	37	17	34	39
	5	Ko = 0.3	U	22	61	73	2	46	58
			B	22	61	73	1	45	58
			B+S	21	61	72	1	45	58
		Ko = 1.0	U	18	57	69	17	61	72
			B	18	57	69	17	61	73
			B+S	18	57	68	17	61	73
Lithophysal Rock	1	Ko = 0.3	U	20	21	21	1	5	6
			B	20	21	22	1	4	5
			B+S	19	22	23	2	5	6
		Ko = 1.0	U	16	19	20	16	18	18
			B	17	20	20	17	18	19
			B+S	16	19	20	17	20	21
	5	Ko = 0.3	U	22	46	53	1	31	38
			B	22	48	56	1	32	39
			B+S	21	49	57	1	32	42
		Ko = 1.0	U	18	45	54	17	41	47
			B	18	44	53	17	41	50
			B+S	17	46	55	17	44	53

U Unsupported (no ground support modeled)
B Reinforced with rockbolts
B+S Reinforced with both rockbolts and shotcrete

8.4 EXPERIENCE WITH THE DRIFT SCALE TEST

General

The Drift Scale Test (DST) is an integral part of the Yucca Mountain Site Characterization program. The DST is a full-scale in situ thermal test with the purpose of developing a better understanding of thermal, mechanical, hydrological, and chemical processes, as well as the interaction between those processes taking place in the rock mass adjoining the subsurface facility of the nuclear waste repository at Yucca Mountain. Another purpose for the test is to obtain information about the performance of the metal components of the container cylinder shells and the ground support elements. An important aspect covers the comparison of performance of the two tunnel sections, one equipped with the concrete liner and the other supported with the very basic ground support system, including wire mesh and friction-type rockbolts.

The heated drift of the DST is 5 m in diameter, 47.5 m in length, and nominally isolated from the access drift by an insulated bulkhead. Heaters within the heated drift supplied about 184 kW of power at the beginning of the test and about 155 kW of power at later test stages. Data were collected from approximately 3,800 sensors every hour and additional measurements were taken at less frequent intervals using a variety of sensors and techniques.

On December 31, 1997, heaters in the heated drift were turned on; they were turned off on January 14, 2002. It took four years before the rock surrounding the drift cooled down to below 40 degrees from the test temperature level on the order of 200ºC, such that reentry into the drift on April 3, 2006 was possible.

Observations of DST Tunnel Performance Upon Reentry

As shown in Figures 8-10 and 8-11, the overall tunnel stability is excellent. Observation of the two tunnel sections equipped with (1) wire mesh and Swellex rockbolts and (2) cast-in-place concrete liner ground support revealed no major structural instabilities.

The effect of thermal stresses is more evident in the wire mesh/rockbolt supported section, where the rock surface is directly exposed to the elevated temperature. The thermally-induced stresses resulted in delaminating a thin layer of rock fragments forming small rock chips or flakes. Figure 8-11 shows the wire mesh effectively preventing the fallout of larger pieces. The DTS tunnel floor and box enclosure shown in Figure 8-12 illustrate the size and the number of small rock fragments that have fallen through the 3 in. x 3 in. wire mesh grid.

The tunnel section equipped with the cast-in-place concrete liner shown in Figures 8-13 and 8-14 displays no evidence of the liner deteriorating due to the elevated temperature. The tunnel invert shown in Figure 8-14 remains in excellent shape, free of concrete fragments that would indicate concrete damage. The concrete shrinkage cracks commonly observed in concrete during curing stage were identified before the start of the heating cycle. These cracks have shown no signs of deterioration or relative movement.

Figure 8-10. Overall View of the Drift Scale Test Tunnel with Wire Mesh and Rockbolt Ground Support System Installed

Figure 8-11. Loose Rock Fragments (Flakes) Retained in Place by Wire Mesh and Rockbolts

Figure 8-12. DST Tunnel Floor and Box Enclosure with Small Rock Fragments That Have Fallen through the 3 In. X 3 In. Wire Mesh Grid

Figure 8-13. DST Tunnel Section Equipped with the Cast-In-Place Concrete Liner Showing No Evidence of the Liner Deterioration

Figure 8-14.Invert Surface in Concrete-Lined Tunnel Section

DST Heated Drift Performance - Summary

Inspection of the drift in the spring of 2006 revealed the following:

- The two ground support systems, including the friction-type expandable rockbolts and cast-in-place concrete liner installed in the heated drift, performed very well.
- The concrete liner displayed no signs of stress-related effects and the shrinkage fractures commonly observed during the concrete curing stage displayed no indication of movement or temperature-related deterioration.
- In the heated drift section supported by rockbolts and wire mesh, some small rock failures localized in the tunnel crown rock were observed. These caused some sagging of the mesh stretched between the adjacent rockbolts. However, the sagging was very localized and the mesh stretching was not excessive.
- Thin rock flakes, ranging in thickness from very thin to less than approximately two inches, were formed in the roof parallel to the tunnel wall surface.
- The rock flaking resulted in the formation of small and thin rock chips that were able to pass through the 3 × 3 in. wire mesh grid and precipitated to the floor of the drift.

In general, the heated drift excavated in the Tptpmn unit performed as expected. Preparation of reports containing results of inspections, analyses of measurements, and post test evaluations are currently underway.

9. CONCLUSIONS

As presented in Section 2, the scope of this informal study focuses on addressing the following two specific concerns:

- How likely is it for the maximum off-normal temperatures to reach 177 ^{o}C in these openings?
- What would happen to the ground support and surrounding rock should the temperatures reach 177 ^{o}C?

First, there are no calculations or analyses done that address both off-normal thermal scenarios and exhaust side openings. An earlier calculation of *Thermal Calculation for Off-Normal Scenarios* (BSC 2004c [DIRS 172176]) predicted temperature profiles for emplacement drifts by assuming a series of ventilation shutdown scenarios. The calculation indicates that the emplacement drift wall temperature will never exceed 200 ^{o}C as long as ventilation at 15 m^3 per second is not interrupted for the first 25 years. Considering that the exhaust main has no direct heat radiation from waste packages, the exhaust main wall temperature would rise much slower than the emplacement drift. The latest calculation of *Drift Wall Thermal Response to Loss of Ventilation* (BSC 2007a, [DIRS 179893]) also addresses off-normal temperatures in emplacement drifts and indicates that heat transfer through conduction in rock is quite slow.

Therefore, the off-normal temperature scenario at the exhaust-side openings will not be the same as in the emplacement drifts and is expected to be much lower compared to the emplacement drifts. During the preclosure, ventilation, when interrupted unexpectedly, will be restored in a relatively short time period, within a 30-day window.

Based on the discussions above, it is an unlikely scenario for the exhaust-side openings to see a temperature approaching 177 ^{o}C when the maximum wall temperature for emplacement drifts is controlled below 200 ^{o}C. As seen in Figure 7-2, the temperature at a location one meter into the rock from the drift wall is about 80 ^{o}C cooler than the drift wall temperature. Based on Figure 7-2, it is estimated that it will take at least 1.4 years for the rock temperature to reach 177 ^{o}C at the location of one meter into the rock from the drift wall. Since exhaust mains are typically tens of meters away from the last emplaced waste package in the emplacement drift, the temperatures at exhaust mains will remain relatively low. In other words, the emplacement drift temperature would have to be much higher than 200 ^{o}C for a much longer time to facilitate enough heat transfer through conduction to elevate the temperature at the exhaust main locations to be close to 177 ^{o}C. Therefore, the off-normal temperature approaching 177 ^{o}C for the exhaust-side openings is a very unlikely scenario.

With what has been said about the first concern, the second one becomes hypothetical or a "what if" scenario. The study focuses on this scenario and all numerical modeling discussions and results are to answer what would happen to the ground support and surrounding rock should the temperatures reach 177 ^{o}C. As a matter of fact, the study even considers up to 200 ^{o}C as a peak off-normal temperature for the exhaust mains. Based on the results presented in Section 8 and discussions made in Section 9, the inaccessible nonemplacement openings (exhaust mains, intersections formed by exhaust mains and emplacement drifts, and exhaust shafts) will not be detrimentally affected or impacted when subjected to an off-normal temperature pulse up to 177 ^{o}C. Potential overstressing or loosening zones surrounding these openings are predicted to be one meter or less into the rock and can be controlled by the proposed ground support systems. With 3-m long fully grouted rockbolts, there is enough embedment length left to hold or retain the loosening rock blocks in place. It may be possible for thin shotcrete layers proposed for intersections to become overstressed and cracked due to high thermal loads from off-normal scenarios. However, cracking releases only high strain energy and will not be detrimental to its functioning because steel fiber reinforced shotcrete will be under compression and will continue to provide surface confinement. Similarly, the concrete or shotcrete lining in exhaust shafts is not expected to have its function impacted detrimentally when the off-normal temperatures occur. Based on the observation of the Heated Drift of the DST, the concrete liner shows no evidence of deterioration under a temperature of up to 200 ^{o}C and the fully grouted rockbolts together with wire mesh appears to have satisfactorily supported the Heated Drift.

This study is based on a rather simplified off-normal thermal scenario for emplacement drifts. The calculation of *Drift Wall Thermal Response to Loss of Ventilation* (BSC 2007a, [DIRS 179893]) assumes that the worst off-normal thermal scenario occurs in the early stage of the preclosure period, i.e., one year after emplacement. Ongoing revisions of ground support calculations for emplacement drifts, nonemplacement drifts, and shafts for LA will further evaluate the potential impacts of off-normal temperatures, in conjunction with seismic loads. The ground support maintenance plan will be revised to also account for off-normal thermal scenarios. This study will support those activities.

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