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**ROCK MASS MECHANICAL PROPERTY ESTIMATIONS FOR THE
YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT**

by

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ABSTRACT

Rock mass mechanical properties are important in the design of drifts and ramps. These properties are used in evaluations of the impacts of thermomechanical loading of potential host rock within the Yucca Mountain Site Characterization Project. Representative intact rock and joint mechanical properties were selected for welded and nonwelded tuffs from the currently available data sources. Rock mass qualities were then estimated using both the Norwegian Geotechnical Institute (Q) and Geomechanics Rating (RMR) systems. Rock mass mechanical properties were developed based on estimates of rock mass quality, the current knowledge of intact properties, and fracture/joint characteristics. Empirical relationships developed to correlate the rock mass quality indices and the rock mass mechanical properties were then used to estimate the range of rock mass mechanical properties.

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The work in this report was performed under WBS 1.2.4.2.1.2.

The data in this report was developed subject to QA controls in QAGR S124212A, Revision 0, PCA 2.0, Task 2.1; the data is qualified and therefore can be used for licensing.

ACKNOWLEDGEMENTS

This report was prepared by the authors with significant input from peer and technical reviewers and support staff. Significant technical input was provided by C. E. Brechtel of J. F. T. Agapito & Associates, Inc., particularly with regard to development of the rock mass quality indices. Special technical input was provided by R. Price of Sandia National Laboratories during the data collection phase when existing reports and sources of laboratory data were sought and later during technical review of the draft document. S. P. Carlisle of J. F. T. Agapito & Associates, Inc. worked closely with M. Lin in developing the Scientific Notebook associated with this report and checking all data sources and calculations in accordance with the appropriate Quality Assurance procedures. The authors also wish to acknowledge the professional contribution of K. L. Greathouse for the word processing and editing of various drafts of this report.

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1. INTRODUCTION

Sandia National Laboratories (SNL), a participant in the Yucca Mountain Site Characterization Project (YMP) for the U.S. Department of Energy (DOE), is currently investigating the feasibility of locating a high-level nuclear waste repository at Yucca Mountain, Nevada. The investigations include development of a project-wide data base of the thermal and mechanical properties of the rock mass to support all phases of pre- and post-closure design and performance activities. This report estimates rock mass mechanical properties based on the existing data. Rock mass properties cannot be routinely measured, and must be estimated by using a combination of field observations, laboratory and field testing data, and empirical and/or analytical models.

In order to make estimates of rock mass mechanical properties, a review of the existing YMP data was initiated to develop the best available data set in the professional judgment of the authors.

The terms *fracture* and *joint* are used interchangeably in this report for all joints, bedding planes, or contact discontinuities. Characterization of joints and estimates of relative rock quality with Rock Quality Designation (RQD) for the thermomechanical units at the Yucca Mountain site were performed by Lin et al (1992) and served as the basis for this study. Intact rock mass mechanical properties from the Reference Information Base (RIB), Version 4.4 (DOE, 1991), and laboratory testing reports were collected and analyzed. Rock mass quality indices for both the Geomechanics (RMR) (Bieniawski, 1979) and Norwegian Geotechnical Institute (Q) (Barton et al, 1974) rock mass classification systems were estimated based on the intact properties, joint characteristics, and RQD. Appropriate rock mass strength criteria and mechanical models for representing the mechanical rock mass response of the tuff at Yucca Mountain have been recommended in the Drift Design Methodology by Hardy and Bauer (1991). Empirical relationships that associate the rock mass quality indices and the rock mass mechanical properties required for the Drift Design Methodology were used to estimate the rock mass properties.

The data used in this study are mainly from laboratory testing at ambient temperature under a standard loading rate. Loading rate, temperature, and saturation effects were not considered in this study.

Yucca Mountain stratigraphy, rock mass strength criteria, and rock mass mechanical models are reviewed in Chapter 2. A brief introduction to the rock mass classification systems and a strategy that uses five rock mass quality categories to represent the credible range of rock mass quality at Yucca Mountain are also included in that chapter. Intact rock and joint properties based on available sources are presented in Chapter 3. The procedure for developing rock mass quality indices from the RMR (Bieniawski, 1979) and Q (Barton et al, 1974) systems for six thermomechanical units is provided in Chapter 4. Derivations of rock mass strength criteria based on the intact strength, triaxial testing data, and the rock mass quality indices are presented in Chapter 5; and Chapter 6 presents the rock mass mechanical properties for the selected rock mass mechanical models. Chapter 7 discusses the results of this study.

2. BACKGROUND

This section presents background information for development of rock mass mechanical properties from various input data. Important features of the methodology for generating the rock mass properties, proposed by Hardy and Bauer (1991), are identified. These include the following:

- the Yucca Mountain geologic and thermomechanical stratigraphy,
- rock mass classification systems,
- ranges of projected rock mass quality for the different thermomechanical units,
- rock mass strength criteria,
- rock mass constitutive models, and
- correlations between rock mass quality and rock mechanical properties.

2.1 Methodology for Generating Rock Mass Properties

A methodology for defining rock mass properties from laboratory and field data was proposed by Hardy and Bauer (1991) to estimate the various parameters required to implement their Drift Design Methodology. Drift Design Methodology focuses on the potential repository horizon and utilizes various correlations between rock mass quality, as defined by two empirical classification systems, and the various rock mass properties required as input. Two empirical classification methods have been previously employed at Yucca Mountain (Langkopf and Gnirk, 1986)—the Q system (Barton et al, 1974) and the RMR system (Bieniawski, 1979)—and were also adopted for the rock mass properties estimation because their widespread application in underground excavation has allowed development of empirical correlations between rock mass properties and the rock mass quality numerical index.

In this approach, the rock mass quality indices, Q and RMR, are developed for each thermomechanical unit to be penetrated by Exploratory Studies Facility (ESF) excavations. The Q and RMR indices perform two main functions in estimating the rock mass properties:

- they facilitate characterizing the variability in rock conditions encountered both vertically and laterally throughout the potential repository site, and
- they provide the empirical basis for extrapolating laboratory measurements of rock and joint mechanical properties to the rock mass scale.

The range in rock mass quality for each thermomechanical unit is represented by five rock mass quality categories, with each category representing a particular level of probability of occurrence. The five levels of probability of occurrence were assigned using assumptions about distributions of the parameters used to calculate Q and RMR.

Rock mass constitutive models and rock mass strength criteria have been proposed to support the drift design and to define the rock mass mechanical properties required for input. These include both equivalent-continuum approaches that do not incorporate the behavior of joints and other models that require input of joint strength and deformation parameters.

Finally, the rock mass mechanical properties that correspond to the levels of probability of occurrence for the varying rock qualities are designated into five rock mass quality categories, calculated using both laboratory measurements and empirical correlations of rock mass quality and rock mass properties.

2.2 Yucca Mountain Stratigraphy

The stratigraphy of Yucca Mountain, as defined by Ortiz et al (1985), is illustrated in Figure 2-1. The stratigraphic members are defined based on classical geologic rules of nomenclature; the thermomechanical units are grouped and named based on the need and ability to group rock volumes based on similarities in rock mass thermal and mechanical properties. Each thermomechanical unit is described in Table 2-1.

This study focuses on the six thermomechanical units that the ESF will penetrate: the Tiva Canyon welded unit (TCw); the Upper Paintbrush nonwelded unit (PTn); the Topopah Spring welded unit, lithophysae-rich layer (TSw1); the Topopah Spring welded unit, lithophysae-poor layer (TSw2); the Topopah Spring welded unit, vitrophyre (TSw3); and the Calico Hills and Lower Paintbrush nonwelded unit (CHn1). The preliminary definition of these intervals and base elevations for the thermomechanical units were proposed by Ortiz et al (1985). The TSw1 was defined to be the lithophysae-rich portion of the welded, devitrified Topopah Spring Member and to contain more than 10% lithophysal cavities. The contact between TSw1 and the underlying TSw2 was placed at the base of the lowest ash flow in the Topopah Spring Member that contained 20% or more lithophysae (lithophysal cavities and vapor-phase-altered material) based on the assumption that lithophysal cavities account for half the lithophysae. The contact between TSw1 and TSw2 has recently been reevaluated by the Sample Overview Committee for the YMP. They pointed out in their report that contacts chosen by Ortiz et al (1985) for USW G-1 and UE-25a#1 were not consistent with application of the above criteria to contacts chosen in other drill holes or outcrops. Table 2-2 lists the base elevations for the six units from the four drill holes within or near the repository boundary. These values are from Ortiz et al (1985), with the exception that the contacts between TSw1 and TSw2 for drill holes USW G-1 and UE-25a#1 are the updated values based on the reevaluation report by the Sample Overview Committee (Appendix A).

2.3 Engineering Rock Mass Classifications

The RMR (Bieniawski, 1979) and Q (Barton et al, 1974) rock mass quality indices were used for engineering rock mass classification of the thermomechanical units at Yucca Mountain. Both systems have received wide acceptance in the rock mechanics community and have proven useful under a wide range of conditions. They include sufficient information to assess the stability of underground excavations under isothermal conditions. Approaches to extend the applications of the system to the thermal environment have been proposed by Hardy and Bauer (1991).

GEOLOGIC STRATIGRAPHY		THERMO-MECHANICAL UNIT	LITHOLOGIC EQUIVALENT
UNDIFFERENTIATED OVERBURDEN		UO	UNDIFFERENTIATED OVERBURDEN
PAINTBRUSH TUFF	TIVA CANYON MEMBER	TCw	WELDED, DEVITRIFIED
	YUCCA MOUNTAIN MEMBER	PTn	VITRIC, NONWELDED
	PAH CANYON MEMBER		
	TOPOPAH SPRING MEMBER	TSw1	LITHOPHYSAL, ALTERNATING LAYERS OF LITHOPHYSAE-RICH AND LITHOPHYSAE-POOR WELDED, DEVITRIFIED TUFF
		TSw2	"NONLITHOPHYSAL" (CONTAINS SPARSE LITHOPHYSAE), POTENTIAL SUBSURFACE REPOSITORY HORIZON
		TSw3	VITROPHYRE
	TUFFACEOUS BEDS OF CALICO HILLS	CHn1	ASH FLOWS AND BEDDED UNITS: UNITS CHn1, CHn2, AND CHn3 MAY BE VITRIC (v) OR ZEOLITIZED (z)
CHn2		BASAL BEDDED UNIT	
CHn3		UPPER UNIT	
CRATER FLAT TUFF	PROW PASS MEMBER	PPw	WELDED, DEVITRIFIED
		CFUn	ZEOLITIZED
	BULLFROG MEMBER	BFw	WELDED, DEVITRIFIED
		CFMn1	LOWER ZEOLITIZED
		CFMn2	ZEOLITIZED BASAL BEDDED
	TRAM MEMBER	CFMn3	UPPER ZEOLITIZED
		TRw	WELDED, DEVITRIFIED

Figure 2-1. Yucca Mountain Stratigraphy (Ortiz et al, 1985)

TABLE 2-1. DESCRIPTION OF THERMOMECHANICAL UNITS (after Ortiz et al, 1985)

Reference Stratigraphy Unit Name (Designator)	Description
Undifferentiated Overburden (UO)	Alluvium; colluvium; nonwelded vitric ash flow tuff of the Tiva Canyon Member of the Paintbrush tuff; any other tuff units that stratigraphically overlie the welded, devitrified Tiva Canyon Member.
Tiva Canyon welded unit (TCw)	Moderately to densely welded devitrified ash flow tuff of the Tiva Canyon Member of the Paintbrush tuff.
Upper Paintbrush nonwelded unit (PTn)	Partially welded to nonwelded vitric and occasionally devitrified tuffs of the lower Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Members of the Paintbrush tuff.
Topopah Spring welded unit, lithophysae-rich (TSw1)	Moderately to densely welded devitrified ash flows of the Topopah Spring Member of the Paintbrush tuff that locally contains more than approximately 10% by volume lithophysal cavities.
Topopah Spring welded unit, lithophysae-poor (TSw2)	Moderately to densely welded devitrified ash flows of the Topopah Spring Member of the Paintbrush tuff that contains less than approximately 10% by volume lithophysal cavities. This is the proposed repository host rock.
Topopah Spring welded unit, vitrophyre (TSw3)	Vitrophyre near the base of the Topopah Spring Member of the Paintbrush tuff.
Calico Hills and Lower Paintbrush nonwelded unit (CHn1)	Nonwelded ash flows, bedded and reworked tuffs of the lower Topopah Spring Member of the Paintbrush tuff and the tuffaceous beds of Calico Hills.
Calico Hills and Lower Paintbrush nonwelded unit (CHn2)	Basal bedded and reworked zones of the tuffaceous beds of the Calico Hills.
Calico Hills and Lower Paintbrush nonwelded unit (CHn3)	Upper partially welded ash flows of the Prow Pass Member of the Crater Flat tuff.
Prow Pass welded unit (PPw)	Moderately welded devitrified ash flows of the Prow Pass Member of the Crater Flat tuff.
Upper Crater Flat nonwelded unit (CFUn)	Nonwelded to partially welded zeolitic ash flows and bedded, reworked portions of the lower Prow Pass Member and the upper Bullfrog Member of the Crater Flat tuff.
Bullfrog welded unit (BFw)	Moderately to densely welded devitrified ash flows of the Bullfrog Member of the Crater Flat tuff.
Middle Crater Flat nonwelded unit (CFMn1)	Partially welded to nonwelded zeolitic ash flows of the lower Bullfrog Member of the Crater Flat tuff.
Middle Crater Flat nonwelded unit (CFMn2)	Zeolitic, basal bedded, reworked portion of the Bullfrog Member of the Crater Flat tuff.
Middle Crater Flat nonwelded unit (CFMn3)	Partially welded zeolitic ash flows of the upper portion of the Tram Member of the Crater Flat tuff.
Tram welded unit (TRw)	Moderately welded devitrified ash flows of the Tram Member of the Crater Flat tuff.

TABLE 2-2. BASE ELEVATIONS OF THERMOMECHANICAL UNITS FOR THE DRILL HOLES IN THE YUCCA MOUNTAIN SITE (from Ortiz et al, 1985)

Units	USW G-1 (4349 ft) [†]	USW G-4 (4165 ft) [†]	USW GU-3 (4857 ft) [†]	UE-25a#1 (3934 ft) [†]
TCw	Absent	4047	4514	3739
PTn	4069	3922	4427	3657
TSw1	3634 [‡]	3495	4160	3314 [‡]
TSw2	3062	2872	3670	2672
TSw3	3007	2820	3588	2617
CHn1	2613	2460	3350	2145

[†] Surface elevation

[‡] See Appendix A.

2.3.1 Geomechanics Classification System

Six parameters are used to calculate the RMR index: strength of the intact rock (C); Rock Quality Designation rating (R_{RQD}); joint spacing (JF); condition of joints (JC); groundwater condition (JW); and rating adjustment for joint orientation (AJO). Table 2-3, developed by Bieniawski (1979), lists the index values for each parameter for ranges in the basic data. The sum for the parameter indices is used to calculate the RMR as follows:

$$RMR = C + R_{RQD} + JF + JC + JW + AJO \quad (2-1)$$

The RMR index is linearly correlated with a corresponding qualitative description of five rock quality categories ranging from very poor to very good rock in Table 2-3. Joints are the major factor in this classification system. Four parameters (JF, JC, JW, and AJO) are joint related, and RQD is partially joint related.

2.3.2 Norwegian Geotechnical Institute System

Six parameters are also considered in the Q system: RQD; joint set number (Jn); joint roughness number (Jr); joint alteration number (Ja); joint water reduction factor (Jw); and stress reduction factor (SRF). Table 2-4, developed by Barton et al (1974), can be used to assign index values to each parameter. The Q index is then calculated from

$$Q = \left(\frac{RQD}{Jn} \right) \left(\frac{Jr}{Ja} \right) \left(\frac{Jw}{SRF} \right) \quad (2-2)$$

The first pair of parameters is found to be a crude measure for block size (RQD/Jn), the second for interblock shear strength (Jr/Ja), and the third for active stress (Jw/SRF). The Q index is logarithmically correlated with corresponding qualitative descriptions of nine rock quality categories ranging from exceptionally poor to exceptionally good. The nature of joints is also a major factor for this system.

2.4 Range of Projected Rock Mass Quality

Since core drilling data from the Yucca Mountain site indicate vertical and lateral variability (Spengler et al, 1981; Scott and Castellanos, 1984; Spengler and Chornack, 1984; Spengler, 1979), a single value for rock mass quality for any thermomechanical unit is not useful. Instead, a range of rock mass quality is estimated for each thermomechanical unit following the methodology

TABLE 2-3. RMR CLASSIFICATION SYSTEM (from Bieniawski, 1979)

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

Parameter		Range of Values					For this low range, uniaxial compressive test is preferred		
1	Strength of intact rock material	> 10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa		5-25 MPa	1-5 MPa	< 1 MPa
	Point-load strength index	> 250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa				
	Uniaxial compressive strength	15	12	7	4		2	1	0
2	Rating	90 - 100%	75 - 90%	50 - 75%	25 - 50%		< 25 %		
	Drill core quality RQD	20	17	13	8		3		
3	Rating	> 2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm		< 50 mm		
	Spacing of Discontinuities	20	15	10	8		5		
4	Condition of discontinuities	Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces OR Gouge < 5 mm thick OR Separation 1 - 5 mm Continuous		Soft gouge > 5 mm thick OR Separation > 5 mm Continuous		
	Rating	30	25	20	10		0		
5	Inflow per 10 m tunnel length	None	< 10 liters/min.	10 - 125 liters/min.	25 - 125 liters/min.		> 125		
	Groundwater Ratio	OR	OR	OR	OR		OR		
	Ratio	0	0.0 - 0.1	0.1 - 0.2	0.2 - 0.5		> 0.5		
	General conditions	OR	OR	OR	OR		OR		
	Rating	15	10	7	4		Flowing		

TABLE 2-3. RMR CLASSIFICATION SYSTEM (concluded)

B. RATING ADJUSTMENT FOR JOINT ORIENTATIONS

Strike and Dip Concentration of Joints		Very Favorable	Favorable	Fair	Unfavorable	Very Unfavorable
Ratings	Tunnels	0	-2	-6	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-60	-60

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 ◀ 81	80 ◀ 61	60 ◀ 41	40 ◀ 21	< 20
Class No.	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK MASS CLASSES

Class No.	I	II	III	IV	V
Average stand-up time	10 yrs from 15 m span	6 months for 8 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min. for 1 m span
Cohesion of the rock mass	> 400 KPa	300 - 400 KPa	200 - 300 KPa	100 - 200 KPa	< 100 KPa
Friction angle of the rock mass	> 45°	35° - 45°	25° - 35°	15° - 25°	< 15°

TABLE 2-4. Q CLASSIFICATION SYSTEM (from Barton et al, 1974)

1.	ROCK QUALITY DESIGNATION (RQD)		
A.	Very poor	0 - 25	<i>Note:</i> (i) Where RQD is report or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate Q (ii) RQD intervals of 5, i.e., 100, 95, 90 etc., are sufficiently accurate
B.	Poor	25 - 50	
C.	Fair	50 - 75	
D.	Good	75 - 90	
E.	Excellent	90 - 100	
2.	JOINT SET NUMBER (J_n)		
A.	Massive, one or few joints	0.5 - 1.0	<i>Note:</i> (i) For intersections use $(3.0 \times J_n)$ (ii) For portals use $(2.0 \times J_n)$
B.	One joint set	2	
C.	One joint set plus random	3	
D.	Two joint sets	4	
E.	Two joint sets plus random	6	
F.	Three joint sets	9	<i>Note:</i> (i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m (ii) $J_r = 0.5$ can be used for planar slickensided joints having lineations, provided the lineations are favorably oriented
G.	Three joint sets plus random	12	
H.	Four or more joint sets, random, heavily jointed, "sugar cube," etc.	15	
J.	Crushed rock, earth-like	20	
3.	JOINT ROUGHNESS NUMBER (J_r)		
	(a) Rock wall contact and		
	(b) Rock mass contact before 10 cms shear		
A.	Discontinuous joints	4	<i>Note:</i> (i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m (ii) $J_r = 0.5$ can be used for planar slickensided joints having lineations, provided the lineations are favorably oriented
B.	Rough or irregular, undulating	3	
C.	Smooth, undulating	2	
D.	Slickensided, undulating	1.5	
E.	Rough or irregular, planar	1.5	
F.	Smooth, planar	1.0	<i>Note:</i> (i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m (ii) $J_r = 0.5$ can be used for planar slickensided joints having lineations, provided the lineations are favorably oriented
G.	Slickensided, planar	0.5	
	(c) No rock wall contact when sheared		
H.	Zone containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)	
J.	Sandy, gravelly or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)	

Descriptions and Ratings for the Parameters J_a and J_w

4.	JOINT ALTERATION NUMBER (J_a)		ϕ_r (approx.)	
	(a) Rock wall contact			
A.	Tightly healed, hard, nonsoftening, impermeable filling, i.e., quartz or epidote	0.75	(-)	<i>Note:</i> (i) Values of ϕ_r are intended as an approximate guide to the mineralogical properties of the alteration products, if present
B.	Unaltered joint walls, surface staining only	1.0	(25° - 35°)	
C.	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0	(25° - 30°)	
D.	Silty- or sandy-clay coatings, small clay-fraction (nonsoftening)	3.0	(20° - 25°)	
E.	Softening or low friction clay mineral coatings, i.e., kaolinite, mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays. (Discontinuous coatings, 1-2 mm or less in thickness)	4.0	(8° - 16°)	
	(b) Rock wall contact before 10 cms shear			

TABLE 2-4. Q CLASSIFICATION SYSTEM (continued)

F.	Sandy particles, clay-free disintegrated rock, etc.	4.0	(25° - 30°)	
G.	Strongly overconsolidated, non-softening clay mineral fillings (continuous, < 5 mm in thickness)	6.0	(16° - 24°)	
H.	Medium or low overconsolidation, softening, clay mineral fillings. (continuous, <5 mm in thickness)	8.0	(12° - 16°)	
J.	Swelling clay fillings, i.e., montmorillonite (continuous, <5 mm in thickness). Value of Ja depends on percent of swelling clay-size particles, and access to water, etc.	8.0-12.0	(6° - 12°)	
<i>(c) No rock wall contact when sheared</i>				
K, L, M.	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition)	6.0, 8.0 or 8.0-12.0	(6° - 24°)	
N.	Zones or bands of silty or sandy clay, small clay fraction (nonsoftening)	5.0		
O, P, R.	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition)	10.0, 13.0 or 13.0-20.0	(6° - 24°)	
5.	JOINT WATER REDUCTION (Jw) FACTOR		Approx. water pressure (kg/cm ²)	
A.	Dry excavations or minor inflow, i.e., <5l/min. locally	1.0	< 1	<i>Note:</i> (i) Factors C to F are crude estimates. Increase Jw if drainage measures are installed (ii) Special problems caused by ice formation are not considered
B.	Medium inflow or pressure, occasional outwash of joint fillings	0.66	1.0 - 2.5	
C.	Large inflow or high pressure in competent rock with unfilled joints	0.5	2.5 - 10.0	
D.	Large inflow or high pressure, considerable outwash of joint fillings	0.33	2.5 - 10.0	
E.	Exceptionally high inflow or water pressure at blasting, decaying with time	0.2-0.1	>10.0	
F.	Exceptionally high inflow or water pressure continuing without noticeable decay	0.1-0.05	>10.0	
6.	STRESS REDUCTION FACTOR (SRF) <i>(a) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated</i>			<i>Note:</i> (i) Reduce these values of SRF by 25-50% if the relevant shear zones only influence but do not intersect the excavation
A.	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10.0		
B.	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation ≤ 50 m)	5.0		
C.	Single weakness zones containing clay, or chemically disintegrated rock (depth of excavation > 50 m)	2.5		
D.	Multiple shear zones in competent rock (clay free), loose surrounding rock (any depth)	7.5		

TABLE 2-4. Q CLASSIFICATION SYSTEM (concluded)

E.	Single shear zones in competent rock (clay free) (depth of excavation ≤ 50 m)			5.0	
F.	Single shear zones in competent rock (clay free) (depth of excavation > 50 m)			2.5	
G.	Loose open joints, heavily jointed or "sugar cube," etc. (any depth)			5.0	
(b) Competent rock, rock stress problems					
II.	Low stress, near surface	σ_c/σ_t >200	σ_1/σ_3 >13	2.5	(ii) For strongly anisotropic stress field (if measured): when $5 \leq \sigma_1/\sigma_3 \leq 10$, reduce σ_c and σ_t to $0.8 \sigma_c$ and $0.8 \sigma_t$; when $\sigma_1/\sigma_3 > 10$, reduce σ_c and σ_t to $0.6 \sigma_c$ and $0.6 \sigma_t$, where: σ_c = unconfined compression strength, σ_t = tensile strength (point load), σ_1 and σ_3 = major and minor principal stresses
J.	Medium stress	200-10	13-0.66	1.0	
K.	High stress, very tight structure (usually favorable to stability, may be unfavorable to wall stability)	10-5	0.66-0.33	0.5-2.0	
L.	Mild rock burst (massive rock)	5-2.5	0.33-0.16	5-10	
M.	Heavy rock burst (massive rock)	<2.5	<0.16	10-20	
(c) Squeezing rock; plastic flow of incompetent rock under the influence of high rock pressures					
N.	Mild squeezing rock pressure			5-10	(iii) Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for such cases (see H)
O.	Heavy squeezing rock pressure			10-20	
(d) Swelling rock; chemical swelling activity depending on presence of water					
P.	Mild swelling rock pressure			5-10	
R.	Heavy swelling rock pressure			10-15	

proposed by Hardy and Bauer (1991). The possible range of each individual parameter used to calculate the RMR and Q indices was established and a preliminary statistical approach used to select values that represent five rock mass categories representing that range from the poorest (category 1) to the best (category 5). The rock mass quality categories 1 through 5 are defined so that either 95%, 80%, 60%, 30%, or 10% of the rock is projected to exceed the parameter value for that category.

Variation of the RQD parameter was based upon the actual distribution of the drilling data, as determined by Lin et al (1992), in each thermomechanical unit in the four core holes USW G-1, USW GU-3, USW G-4, and UE-25a#1. For each rock mass quality category, the RQD value was selected using probability paper so that the probability of a higher value of RQD was 95%, 80%, 60%, etc. The RQD data were not directly determined during core logging and were estimated using other recorded data. Figure 2-2a shows a probability plot with RQD data from the TSw1 unit with the RQD value at the associated levels of probability.

Variation in the remaining five parameters for each of the Q and RMR calculations was based on the estimated range in the parameter indicated by the base data from the site. The parameter was then assumed to be distributed uniformly over the range, and parameter index values were selected by the probability levels, as shown in Figure 2-2b.

The RMR and Q indices for the extremely poor rock mass quality category (category 1) were then obtained by combining the category 1 index values for each individual parameter using Equations 2-1 and 2-2. The RMR and Q indices for the very poor (category 2), poor (category 3), fair (category 4), and good (category 5) rock mass quality categories were also obtained from the corresponding category index values using the same procedure.

(a)

(b)

Figure 2-2. Illustration of Probability Based Selection of Parameters for Rock Mass Quality Category

Note that with five categories defined for each of the six individual parameters within the RMR and Q systems, there are up to 30 combinations of parameter categories to calculate the RMR and Q indices. The approach adopted in this study was to combine the least and most favorable parameter categories into rock mass categories 1 and 5, respectively. The percentages of rock mass quality encountered underground will differ from the percentage of each individual parameter category indicated by this approach.

2.5 Rock Mass Strength Criteria

Rock and rock masses are observed to have some strength at zero confining pressure and are assumed to have increasingly greater strength as the confining pressure increases. The strength criteria characterizes the strength-confining pressure relationships. Hardy and Bauer (1991) recommended an averaging process based on the empirical strength criterion of Yudhbir et al (1983) and Hoek and Brown (1988) to represent the rock mass at the Yucca Mountain site.

Yudhbir et al (1983) used the generalized form of the equation first proposed by Bieniawski (1974) to represent the rock mass strength dependence on confining stress. The general equation proposed by Yudhbir et al (1983) was

$$\sigma_1 = A \sigma_c + B \sigma_c \left(\frac{\sigma_3}{\sigma_c} \right)^\alpha, \quad (2-3)$$

where σ_c = intact rock uniaxial compressive strength,

σ_1 = strength of the rock mass,

σ_3 = confining stress,

A = dimensionless parameter dependent on the RMR index, and

α, B = rock material constants dependent on rock type.

The value of A for the rock mass was correlated by Yudhbir et al (1983) with the RMR by Equation 2-4.

$$A = e^{0.0765(\text{RMR}) - 7.65} \quad (2-4)$$

Hoek and Brown (1980) also developed a relationship for relating RMR to rock mass strength. Experience gained from a wide range of projects indicated that the rock mass strengths estimated were reasonable when used for slope stability studies in which the rock mass was disturbed and loosened by relaxation from excavation of the slope. However, the estimated rock mass strengths were generally too low in applications involving underground excavations in which the confining stresses do not permit the same degree of loosening as would occur in a slope. A revised set of relationships between the rock mass classification and strength was proposed by Hoek and Brown (1988) to consider the undisturbed, interlocking rock masses. With σ_1 , σ_3 , and σ_c as defined for Equation 2-3, the Hoek and Brown (1988) strength equation is

$$\sigma_1 = \sigma_3 + \sqrt{m \sigma_c \sigma_3 + s \sigma_c^2}, \quad (2-5)$$

where m = a constant that depends on both the strength of the intact rock and RMR and

s = a constant that depends on RMR.

The dependence of m and s on the RMR is as follows:

$$m = m_i e^{(RMR - 100)/28} \quad \text{and} \quad s = e^{(RMR - 100)/9}, \quad (2-6)$$

where m_i = a constant determined from triaxial strength tests on intact rock, which is evaluated by a best fit of Equation 2-5 to laboratory test data with $s = 1.0$.

The Yudhbir et al (1983) and Hoek and Brown (1988) criteria were used to develop a relationship of strength versus confining pressure for each thermomechanical unit. The relationship was developed by evaluating the Yudhbir and Hoek and Brown methods separately for each unit and then averaging the two predicted strengths at discrete confining pressures. A power-law relationship of the form

$$\sigma_1 = A + B \sigma_3^c \quad (2-7)$$

was then developed by fitting the resulting average strength versus confining pressure data to describe the strength-confinement response for each unit.

2.6 Rock Mass Constitutive Models

The constitutive models used to predict the deformational response for the rock masses include linear elastic, elasto-plastic, jointed rock continuum, the compliant joint model (CJM) of Chen (1986); the joint empirical model (JEM) of Blanford and Key (1990), distinct block models (DBM) (Cundall, 1980), and discrete joint/fault representation models (Crouch, 1976). The linear elastic, elasto-plastic, jointed rock continuum, JEM, and CJM are all equivalent-continuum models, in which either rock mass scale mechanical properties are used or the effects of joints are considered by continuous averaging over the rock volume.

The characteristics of joint geometry and joint mechanical behavior can have a major impact on the ability to model the rock mass. A method to select an appropriate model based on rock jointing characteristics was proposed by Hardy and Bauer (1991). Based on the range of expected conditions evident in cores from, and surface exposures near, the proposed repository location, the elastic, elasto-plastic, CJM, and DBM were selected as potential models for predicting the deformational response for the rock mass at Yucca Mountain.

Mechanical properties required for the different rock mass constitutive models are illustrated in Table 2-5. The mechanical properties required for the elastic model are elastic modulus and Poisson's ratio, which are also used in the elasto-plastic model. In addition, input for the elasto-plastic model includes rock mass Mohr-Coulomb strength parameters and rock mass tensile strength.

The properties required for the CJM model include joint geometric parameters, joint mechanical properties, and elastic properties of intact material between the joints. The DBM requires a similar set of inputs but uses a different form of joint deformability modulus.

2.7 Correlation of Rock Mass Quality and Rock Mass Mechanical Properties

The mechanical properties required for input to the different constitutive models were estimated from the existing data base using laboratory data, field data, rock mass quality indices, and other empirical criteria. Figure 2-3 presents the general path followed for development of each parameter and shows the interrelation of the different types of data. Some input parameters are

TABLE 2-5. CONSTITUTIVE MODEL PARAMETERS

Model	Joints					
	Rock Matrix			Rock Mass		
	Strength	Deformation		Strength	Deformation	
Elastic	---	---		C_m, ϕ_m, T_m	E_m, ν_m	
Elasto-plastic	---	---		C_m, ϕ_m, T_m	E_m, ν_m, ψ_m	
CJM	σ_c, m_i, s_i	E_i, ν_i		---	---	
DBM	σ_c, m_i, s_i	E_i, ν_i		---	---	
ψ	dilation angle		T		tensile strength	
C	cohesion		m, s		Hoek and Brown strength parameters	
ϕ	friction angle		k_n		linear joint normal stiffness	
E	deformation modulus		A_n		half-closure stress	
ν	Poisson's ratio		u_{max}		maximum joint closure	
G_s'	shear stiffness before failure		θ_j		joint orientation	
G_s''	shear stiffness after failure		χ_j		joint continuity	
i	intact material property		λ_j		joint spacing	
m	rock mass material property		j		joint property	
σ_c	intact block compressive strength

Figure 2-3. Paths for Derivation of Rock Mass Mechanical Properties

based solely on laboratory testing or field data. Other inputs are developed from more complex paths in which rock mass quality is used in conjunction with laboratory data as input to an empirical criterion in which the input parameter is estimated.

Details of the development of the different parameters are presented in the following chapters. In Chapter 3, the existing data base of intact rock and joint properties is summarized. Chapter 4 develops the range of rock mass qualities for each thermomechanical unit. The empirical correlations used for rock mass strength and mechanical properties are developed in Chapters 5 and 6.

3. INTACT ROCK AND JOINT MECHANICAL PROPERTIES

This chapter compiles the intact rock and joint properties required for assessing rock quality indices and estimating rock mass mechanical properties. These data are obtained from the following sources: RIB, Version 4.4 (DOE, 1991); Site Characterization Plan, Conceptual Design Report (SCP-CDR) (SNL, 1987); a report on rock fracture analysis and RQD estimation (Lin et al, 1992); and reports on intact rock laboratory test data (Nimick et al, 1987; Price, 1983). The mechanical properties for the intact rock, such as uniaxial compressive strength, elastic modulus, Poisson's ratio, cohesion, and angle of internal friction, are listed in the intact rock properties subsection. Joint geometric properties, joint frictional properties, and joint stiffness are discussed in the joint properties subsection.

3.1 Intact Rock Properties

3.1.1 Uniaxial Compressive Strength

The values for the uniaxial compressive strength of the thermomechanical units in this study are listed in Table 3-1. The following describe the processes for selecting the representative values from the sources.

TABLE 3-1. INTACT ROCK UNIAXIAL COMPRESSIVE STRENGTH, ELASTIC MODULUS, AND POISSON'S RATIO (from DOE, 1991)

Thermomechanical Unit	Uniaxial Compressive Strength (MPa)	Elastic Modulus (MPa)	Poisson's Ratio
TCw	$161 \pm 63^{\dagger}$	19.9 ± 3.0	0.17 ± 0.04
PTn	26 ± 8	6.0 ± 1.8	0.23 ± 0.05
TSw1 (lithophysae-rich)	16 ± 5	15.5 ± 3.2	0.16 ± 0.03
TSw2	$161 \pm 63^{\dagger}$	32.7 ± 4.6	0.22 ± 0.03
TSw3	52 ± 22	$15.8 \pm \text{NA}$	$0.17 \pm \text{NA}$
CHn1	26 ± 8	6.0 ± 1.8	0.23 ± 0.05

NA - Not available

[†] Calculated in Appendix B

No data were indicated for the TCw unit in the RIB, Version 4.4. However, two uniaxial and three triaxial test results for the TCw unit were reported by Price (1983); a uniaxial compressive strength of 7 MPa and triaxial compressive strength of 895 MPa with 20 MPa confinement was reported. The range of the test results suggests the potential for large variation of the intact strength of the TCw unit. The RIB, Version 4.4 recommends using the uniaxial test results of the TSw1 unit as representative for the TCw unit. However, according to the description of thermomechanical units listed in Table 2-1, no lithophysae were reported in the TCw tuff. The mechanical properties of TCw should therefore resemble the lithophysae-poor TSw2 more than the lithophysae-rich TSw1. Thus, the uniaxial compressive strength of the TSw2 unit was selected as being representative of the TCw unit.

Data were not available for the PTn unit in the RIB, Version 4.4, and the uniaxial test results of the CHn1 unit were recommended. Three groups of uniaxial test results are listed in the RIB, Version 4.4 for the CHn1 unit: 90 MPa for the vitric portion, 26 ± 8 MPa for the zeolitized USW G-1 and USW G-2 group, and 14 ± 4 MPa for the zeolitized USW G-4 group. The first and third groups contain only one and two samples, respectively, whereas the second group includes thirteen samples. The second group values of 26 ± 8 MPa with higher statistical confidence were therefore selected as the uniaxial compressive strength for the PTn and CHn1 units.

As indicated in Figure 2-1, alternating layers of lithophysae-rich and lithophysae-poor tuff are contained in TSw1. Data suggest that the TSw1 lithophysae-poor tuff has similar mechanical and bulk properties as TSw2. Therefore, TSw2 properties were assumed representative of lithophysae-poor portions of TSw1. Properties listed for the TSw1 unit in this report specifically represent only the lithophysae-rich layers. The uniaxial compressive strengths of the TSw1 unit were therefore selected as 16 ± 5 MPa. These results were originally derived from samples taken from an outcrop at Busted Butte to represent the upper lithophysal zone (Price et al, 1985).

It is mentioned in Section 2.1 that the contact in two holes between the TSw1 and TSw2 units has been reevaluated recently in two holes by the Sample Overview Committee. The contact elevations between the TSw1 and TSw2 units for drill holes USW G-1 and UE25-a#1 were approximately 300 ft higher after the reevaluation. The uniaxial compressive strengths for the TSw2 unit were therefore reevaluated based on the original data source and the new thermomechanical boundary. Appendix B lists 56 test results for the TSw2 unit, for which a mean uniaxial strength of 161 MPa and standard deviation of 63 MPa were obtained.

In the TSw3 unit, two groups of uniaxial test results are listed in the RIB, Version 4.4: 52 ± 22 MPa for hole USW G-2 and 75 MPa for hole USW G-4. The uniaxial compressive strengths selected for the TSw3 unit were 52 ± 22 MPa, since this group contained two samples while the other group included only one sample.

3.1.2 Elastic Modulus and Poisson's Ratio

The values for elastic modulus and Poisson's ratio for the thermomechanical units used in this study are also listed in Table 3-1. Data were derived from the RIB, Version 4.4. The selection processes were similar to those for the uniaxial compressive strengths.

3.1.3 Mohr-Coulomb Strength Parameters

The values for Mohr-Coulomb strength parameters (cohesion and angle of internal friction) for the thermomechanical units used in this study are listed in Table 3-2. The strength parameters were developed from the least-square curve fit between measured parameters of axial stress (σ_1) and confining pressure (σ_3). The expression takes the form

$$\sigma_1 = \sigma_c + N\sigma_3 \quad , \quad (3-1)$$

where σ_c = uniaxial compressive strength and

N = confinement factor.

The parameters σ_c and N were then used to generate a Mohr-Coulomb failure criterion relating the shear (τ) and normal stresses (σ_n) on the plane of failure to the material constants of cohesion and angle of internal friction:

$$\tau = C_o + \sigma_n \tan \phi \quad , \quad (3-2)$$

where C_o = cohesion (see Equation 3-3) and

$$C_o = \sigma_c / 2\sqrt{N} \quad (3-3)$$

ϕ = angle of internal friction (see Equation 3-4).

$$\phi = 2(\tan^{-1} \sqrt{N} - 45^\circ) \quad . \quad (3-4)$$

TABLE 3-2. INTACT ROCK MOHR-COULOMB STRENGTH PROPERTIES (from DOE, 1991)

Thermomechanical Unit	Cohesion (MPa)	Angle of Internal Friction
TCw	36	41
PTn	12	11
TSw1 (lithophysae-rich)	6	13
TSw2	36	41
TSw3	12	41
CHn1	12	11

The existing triaxial test data for the thermomechanical units that the ESF will penetrate have been compiled and listed in Appendix C. No data are currently available for the PTn and TSw1 units, and there are insufficient data for the TCw and TSw3 units. The 31 sets of triaxial data for the TSw2 unit listed in Appendix C and the uniaxial compressive strength data listed in Appendix B were used to obtain the parameters σ_c and N of Equation 3-1 for the welded tuff units. The 19 sets of triaxial data in Appendix C and the uniaxial compressive strength data in Price (1983) for the CHn1 unit were used to obtain the parameters σ_c and N of Equation 3-1 for the nonwelded tuff units. Cohesion and angle of internal friction for both the welded and nonwelded tuff units were then calculated using Equations 3-3 and 3-4.

The cohesion and angle of internal friction derived from the data of TSw2 are not applicable to every welded tuff unit. The laboratory uniaxial compressive data for both the TSw3 and the lithophysae-rich portion of TSw1 were considerably lower than TSw2. Therefore, cohesion for the TSw3 unit was calculated assuming that the angle of internal friction was the same as for TSw2, and Equation 3-3 was then used with the existing laboratory uniaxial compressive strength data. For the lithophysae-rich TSw1 portion, the strength parameters were developed using empirical relationships with porosity proposed by Nimick and Schwartz (1987). The empirical relationships are expressed as

$$\phi = \sin^{-1} \left[\frac{0.079n^{-1.86}}{2 + 0.079n^{-1.86}} \right] \quad \text{and} \quad (3-5)$$

$$c = 51.14 \tan \phi \quad , \quad (3-6)$$

where ϕ = the angle of internal friction expressed in degrees,

C = cohesion expressed in MPa, and

n = the functional porosity.

Because the resulting cohesion calculated using Equation 3-6 was not consistent with the existing test data, the cohesion of the lithophysae-rich portion of TSw1 was calculated using Equation 3-4 and the existing uniaxial compressive strength data.

3.2 Joint Properties

3.2.1 Joint Geometric Properties

Joint geometric properties have been developed in Lin et al (1992), and the resulting corrected linear fracture frequency for each joint set inclined in 10° intervals for the thermomechanical units were used in this study to obtain the joint spacings required both in the rock mass classification RMR system and in the CJM rock mass model. The values for the corrected linear fracture frequency are listed in Table 3-3.

3.2.2 Joint Frictional Properties

The joint frictional properties were defined as cohesion and coefficient of friction at joint slip. An empirical relation for friction of rock joints, proposed by Barton (1973), that incorporates joint roughness, joint wall compressive strength, and residual friction angle was used to generate the shear strength envelope. This empirical relationship is written as

$$\tau = \sigma_n \tan \left[\text{JRC} \log_{10} \left(\frac{\text{JCS}}{\sigma_n} \right) + \phi_r \right] , \quad (3-7)$$

where τ = peak shear strength,

σ_n = effective normal stress,

JRC = joint roughness coefficient,

JCS = joint wall compressive strength, and

ϕ_r = residual friction angle.

The ranges of JRC for both welded and nonwelded tuff units were discussed in Lin et al (1992) based on core and outcrop data studies by others. The intact uniaxial compressive strengths were used as JCS assuming the joints to be unweathered. The ranges of residual friction angle were taken from the laboratory testing results of fractures on the tuffaceous rocks of the Topopah Spring and Bullfrog Members conducted by Morrow and Byerlee (1984). Table 3-4 lists JRC and ϕ_r for the five rock mass quality categories, assuming the parameters to be distributed uniformly. Shear strength envelopes with various normal stresses were then developed for each rock mass quality category in each thermomechanical unit from JRC, JCS, ϕ_r , and Equation 3-7.

TABLE 3-3. CORRECTED LINEAR FRACTURE FREQUENCY FOR EACH JOINT SET INCLINED IN 10° INTERVALS (from Lin et al, 1992)

Drill Holes	0-10 deg	10-20 deg	20-30 deg	30-40 deg	40-50 deg	50-60 deg	60-70 deg	70-80 deg	80-90 deg
TCw Unit									
Mean	0.42	0.76	0.57	0.59	0.42	0.60	1.40	2.17	9.21
Upper range	0.93	1.68	1.02	0.94	0.55	0.81	1.83	3.06	15.05
Lower range	0.11	0.28	0.25	0.18	0.32	0.48	0.84	1.38	2.20
PTn Unit									
Mean	0.17	0.19	0.12	0.05	0.14	0.12	0.26	0.19	1.94
Upper range	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lower range	NA	NA	NA	NA	NA	NA	NA	NA	NA
TSw1 Unit									
Mean	0.18	0.21	0.16	0.12	0.14	0.15	0.32	1.04	5.28
Upper range	0.52	0.62	0.48	0.32	0.37	0.45	0.92	2.00	12.35
Lower range	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.35	1.55
TSw2 Unit									
Mean	0.25	0.29	0.25	0.22	0.23	0.24	0.56	2.51	11.28
Upper range	0.50	0.60	0.46	0.35	0.35	0.44	0.89	5.92	24.07
Lower range	0.05	0.05	0.07	0.05	0.05	0.06	0.19	0.81	2.99
TSw3 Unit									
Mean	0.18	0.24	0.21	0.17	0.19	0.20	0.50	1.80	8.07
Upper range	0.40	0.49	0.37	0.25	0.28	0.35	0.71	2.29	9.61
Lower range	0.06	0.06	0.09	0.10	0.10	0.09	0.20	1.55	6.98
CHn1 Unit									
Mean	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.18	0.72
Upper range	0.06	0.06	0.06	0.06	0.06	0.08	0.08	0.39	1.44
Lower range	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.08	0.23

TABLE 3-4. JRC AND ϕ_r FOR THE FIVE ROCK MASS QUALITY CATEGORIES

Unit		Rock Mass Quality Category				
		1	2	3	4	5
TCw	JRC	3.23	4.22	5.44	7.52	8.84
	ϕ_r	35.40	36.40	37.80	39.90	41.30
PTn	JRC	2.30	3.20	4.40	6.20	7.40
	ϕ_r	35.40	36.40	37.80	39.90	41.30
TSw1 (lithophysae-rich)	JRC	3.23	4.22	5.44	7.52	8.84
	ϕ_r	35.40	36.40	37.80	39.90	41.30
TSw2	JRC	3.23	4.22	5.44	7.52	8.84
	ϕ_r	35.40	36.40	37.80	39.90	41.30
TSw3	JRC	3.23	4.22	5.44	7.52	8.84
	ϕ_r	35.40	36.40	37.80	39.90	41.30
CHn1	JRC	2.30	3.20	4.40	6.20	7.40
	ϕ_r	35.40	36.40	37.80	39.90	41.40

The frictional properties, cohesion, and coefficient of friction were derived by linear curve fit of the shear strength envelopes developed using Equation 3-7. The least-square best-fit method was used for curve fitting the range of normal stresses from 0 to 3 MPa, which is representative of the projected minimum principal stress range near the boundary of the ESF excavations. The derived cohesion and coefficient of friction for the range of rock mass qualities in each of the thermomechanical units are listed in Table 3-5.

TABLE 3-5. JOINT FRICTIONAL PROPERTIES

Unit		Rock Mass Quality Category				
		1	2	3	4	5
TCw	Cohesion (MPa)	0.03	0.05	0.08	0.14	0.21
	Coefficient of friction	0.86	0.95	1.08	1.30	1.48
PTn	Cohesion (MPa)	0.02	0.03	0.05	0.08	0.11
	Coefficient of friction	0.76	0.82	0.89	1.02	1.11
TSw1 (lithophysae-rich)	Cohesion (MPa)	0.03	0.04	0.06	0.10	0.13
	Coefficient of friction	0.77	0.82	0.89	1.00	1.08
TSw2	Cohesion (MPa)	0.03	0.05	0.08	0.14	0.21
	Coefficient of friction	0.86	0.95	1.08	1.30	1.48
TSw3	Cohesion (MPa)	0.03	0.05	0.07	0.12	0.17
	Coefficient of friction	0.82	0.88	0.98	1.14	1.27
CHn1	Cohesion (MPa)	0.02	0.03	0.05	0.08	0.11
	Coefficient of friction	0.76	0.82	0.89	1.02	1.11

3.2.3 Joint Stiffness

Joint deformations in the CJM are described by a hyperbolic normal stress closure relationship and a bilinear shear stiffness expression. Two parameters—the half-closure stress (A_n) and the

maximum closure of the joint (u_{max})—are used to characterize the normal stiffness relationship (Figure 3-1), which was adapted from Thomas (1982) and originated by Goodman (1976) as Equation 3-8:

$$\sigma_n = -A_n \left(\frac{u_n}{u_{max} - u_n} \right) \quad , \quad (3-8)$$

where σ_n and u_n = the normal stress component and the corresponding normal displacement across the joint, respectively.

Figure 3-1. Nonlinear Elastic Normal Joint Behavior

Shear stiffness is described using a bilinear model with an elastic stiffness (G_s) until the joint shear failure is reached, and with a linear, hardening stiffness (G_s'), after the critical shear stress.

The values of half-closure stress (A_n) and the maximum closure of joint (u_{max}) listed in Table 3-6 were obtained from the SCP-CDR. These values were derived from studies of joint mechanical behavior by Peters et al (1984) and Olsson (1987, 1988). Elastic shear stiffness values were developed based on the size and stress-dependent study on shear stiffness reported by Bandis et al (1983). The hardening shear stiffness was assumed to be zero or equivalent to perfectly plastic behavior for this study.

The values of parameters in both stiffness expressions are listed in Table 3-6 for each thermomechanical unit.

TABLE 3-6. JOINT STIFFNESS PARAMETERS

Thermomechanical Unit	Half-Closure Stress (MPa)		Maximum Closure of Joint (μm)		Elastic Shear Stiffness (MPa/m)	
	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound
TCw	2.0	0.5	36.0	3.0	10^6	10^3
PTn	2.8	1.2	26.0	5.4	10^6	10^3
TSw1 (lithophysae-rich)	2.0	0.5	36.0	3.0	10^6	10^3
TSw2	2.0	0.5	36.0	3.0	10^6	10^3
TSw3	2.0	0.5	36.0	3.0	10^6	10^3
CHn1	2.8	1.2	26.0	5.4	10^6	10^3

The joint deformation in the DBM has a different formulation than in the CJM. Both normal and shear stiffnesses in the DBM are defined as either constant values or the function of normal stress. Their values can be determined from interpolation or curve fit of the joint deformation curves defined for the CJM.

4. ROCK MASS QUALITY INDICES

This chapter describes the information available to rate the thermomechanical units and provide the rating indices for each parameter of the RMR and Q systems. The possible range of each individual parameter is represented by the five rock mass quality categories discussed in Section 2.5. The rock mass quality categories 1 to 5 are used to represent five rock mass categories ranging from the poorest to the best. The rock mass quality indices for both systems were then calculated using Equations 2-3 and 2-4. An empirical equation proposed by Bieniawski (1976) was used to translate the Q indices to the RMR ratings. The design RMR was then selected as the average of the RMR values that was derived from the translated and original RMR values.

4.1 Rock Mass Quality Indices for the Rock Mass Rating System

4.1.1 Strength (C)

The first parameter, the only strength-related parameter in the RMR system, is the strength of intact rock. The mean values of the uniaxial compressive strength listed in Table 3-1 are used as the representative intact rock strength for all five rock mass quality categories. Table 4-1 lists the mean compressive strength for the thermomechanical units and their corresponding RMR strength ratings, C.

TABLE 4-1. UNCONFINED COMPRESSIVE STRENGTH

Thermomechanical Unit	Mean Compressive Strength (MPa)	RMR Strength Rating (C)
TCw	161	12
PTn	26	4
TSw1 (lithophysae-rich)	16	2
TSw2	161	12
TSw3	52	7
CHn1	26	4

4.1.2 Rock Quality Designation Rating (R_{RQD})

RQDs for the five rock mass quality categories were developed in Lin et al (1992). Table 4-2 lists the RQD values for each rock mass category. The corresponding ratings of RQD in the RMR system (R_{RQD}) as determined from Table 2-3 are listed in Table 4-3.

TABLE 4-2. RQD VALUES FOR THE FIVE ROCK MASS QUALITY CATEGORIES

Thermomechanical Unit	Rock Mass Quality Category				
	1	2	3	4	5
TCw	34	50	63	81	92
PTn	29	48	61	69	72
TSw1	10	24	46	74	90
TSw2	16	26	41	62	84
TSw3	39	58	66	81	89
CHn1	22	58	77	91	94

TABLE 4-3. R_{ROD} VALUES FOR THE FIVE ROCK MASS QUALITY CATEGORIES

Thermomechanical Unit	Rock Mass Quality Category				
	1	2	3	4	5
TCw	8	13	13	17	20
PTn	8	8	13	13	13
TSw1	3	3	8	13	17
TSw2	3	8	8	13	17
TSw3	8	13	13	17	17
CHn1	3	13	17	20	20

4.1.3 Joint Frequency (JF)

Fractures that may intersect the underground excavation are the main concern in the RMR system. The high angle joint set was recognized as predominant at Yucca Mountain (Lin et al, 1992). Therefore, the linear fracture frequency along a scanline parallel to the horizontal plane is considered as the joint frequency for RMR rating. The joint frequency was calculated based on the corrected linear fracture frequency for each joint set inclined at 10° intervals (Table 3-3) and the following equation:

$$\begin{aligned}\lambda_L = & \lambda(5^\circ) \times \cos 85^\circ + \lambda(15^\circ) \times \cos 75^\circ + \lambda(25^\circ) \times \cos 65^\circ \\ & + \lambda(35^\circ) \times \cos 55^\circ + \lambda(45^\circ) \times \cos 45^\circ + \lambda(55^\circ) \times \cos 35^\circ \\ & + \lambda(65^\circ) \times \cos 25^\circ + \lambda(75^\circ) \times \cos 15^\circ + \lambda(85^\circ) \times \cos 5^\circ, \quad (4-1)\end{aligned}$$

where λ_L = the linear fracture frequency along a scanline parallel to the horizontal plane,

$\lambda(\phi)$ = fracture frequency for a given inclination interval, and

ϕ = mid-point angle of the inclination interval.

The calculated minimum and maximum joint frequencies among the four drill holes are used as the possible range for RMR rating. The range of joint frequency and joint spacing, derived using Equation 4-1, are listed in Table 4-4. JF ratings for the five rock mass quality categories were assumed to be uniformly distributed within the rating range and the resulting decimal points have been rounded off.

TABLE 4-4. JF FOR THE FIVE ROCK MASS QUALITY CATEGORIES

Thermo-mechanical Unit	Range of Fracture Frequency (m^{-1})	Range of Joint Spacing (m)	JF Rating Range	JF for Rock Mass Quality Category				
				1	2	3	4	5
TCw	5.58-21.2	0.047-0.179	5 - 8	5	6	6	7	8
PTn	2.7	0.371	10	10	10	10	10	10
TSw1	2.13-16.29	0.061-0.469	8 - 10	8	8	9	9	10
TSw2	4.10-31.25	0.032-0.244	5 - 10	5	6	7	9	10
TSw3	9.36-12.67	0.079-0.107	8	8	8	8	8	8
CHn1	0.49-1.78	0.560-2.045	10 - 20	11	12	14	17	19

4.1.4 Condition of Joints (JC)

According to Bieniawski (1979), the roughness for the joint surfaces, separation of the joints, and joint wall degree of weathering are the elements of consideration for the condition of joints. Joint roughness and infilling thickness for the joints at Yucca Mountain have been studied in Lin et al (1992). "Discontinuous" to "smooth, undulating" and "smooth, undulating" to "smooth, planar" were the descriptions for the joint roughness of the welded and nonwelded tuff respectively. The precise measurement of the thickness of infillings is not available now. Thin fracture infillings were recorded within the Topopah Spring Member and Calico Hills in Langkopf and Gnirk (1986). No information was found for the degree of weathering on joint walls.

Based on the above information and the engineering judgment of the authors, the RMR descriptions assigned to the fractures in the welded tuff units are "slightly rough surfaces, separation of less than 1 mm, slightly weathered walls" as a lower bound and "very rough surfaces, not continuous, no separation, unweathered wall rock" as an upper bound. The RMR description assigned to the fractures in the nonwelded tuff units is "slightly rough surface, separation of less than 1 mm, soft joint wall rock."

Table 4-5 summarizes the RMR rating for joint conditions assigned to each unit. Uniform distribution within the rating range was assumed for estimating the values of the five rock mass quality categories.

TABLE 4-5. JC FOR THE FIVE ROCK MASS QUALITY CATEGORIES

Thermomechanical Unit	RMR Rating Range	JC for Rock Mass Quality Category				
		1	2	3	4	5
TCw	25 - 30	25	26	27	29	30
PTn	20	20	20	20	20	20
TSw1	25 - 30	25	26	27	29	30
TSw2	25 - 30	25	26	27	29	30
CHn1	20	20	20	20	20	20

4.1.5 Groundwater

A RMR rating of 15 was assigned to all six thermomechanical units, based on the calculation of the inflow of groundwater per 10-m excavation length. Montazer and Wilson (1984) estimated the vertical flux in the matrix of the unsaturated Topopah Spring formation ranges from 10^{-7} to 0.2 mm/yr. Assuming the dimension of the opening as 6.1 m (20 ft) and the vertical influx as 0.2 mm/yr (3.8×10^{-7} L/m²/min.), the maximum water-inflow rate per 10 m of excavation would be 2.32×10^{-5} L/min. The groundwater condition was therefore described as "dry" with such a small amount of groundwater inflow.

4.1.6 Adjustment for Joint Orientation (AJO)

One unique feature in the RMR system is that it includes the rating adjustment for joint orientation with respect to underground opening. The effect of joint strike and dip orientation in tunneling, shown in Table 4-6, is provided by Bieniawski (1979). The information regarding the joint strike orientation to the excavation axis is not available at this time. Because nearly vertical joints prevail at the Yucca Mountain site, the effect ranges from "very unfavorable" (RMR rating

TABLE 4-6. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATIONS IN TUNNELING (from Bieniawski, 1979)

Strike Perpendicular to Tunnel Axis				Strike Parallel	Dip 0°-20°	
Drive With Dip		Drive Against Dip		to Tunnel Axis	Irrespective	
Dip 45°-90°	Dip 20°-45°	Dip 45°-90°	Dip 20°-45°	Dip 45°-90°	Dip 20°-45°	of Strike
Very favorable	Favorable	Fair	Unfavorable	Very unfavorable	Fair	Unfavorable

of -12) to "very favorable" (RMR rating of 0) and was assigned as the adjustment for joint orientation. The values of -11, -10, -7, -4, and -1 were assigned as the RMR rating for the five rock mass quality categories assuming a uniform distribution within the range.

4.1.7 Results of Rock Mass Rating Values

RMR values were calculated using the six parameters discussed in the preceding subsections and Equation 2-1. The individual parameters and the calculated RMR values are summarized in Tables 4-7 to 4-12 for each thermomechanical unit.

TABLE 4-7. RMR PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TC_w UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
Strength (C)	12	12	12	12	12
RQD rating	8	13	13	17	20
Joint frequency (JF)	5	6	6	7	8
Joint condition (JC)	25	26	27	29	30
Groundwater	15	15	15	15	15
Joint orientation (AJO)	-11	-10	-7	-4	-1
RMR	54	62	66	76	83

TABLE 4-8. RMR PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, PT_n UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
Strength (C)	4	4	4	4	4
RQD rating	8	8	13	13	13
Joint frequency (JF)	10	10	10	10	10
Joint condition (JC)	20	20	20	20	20
Groundwater	15	15	15	15	15
Joint orientation (AJO)	-11	-10	-7	-4	-1
RMR	46	47	55	58	61

TABLE 4-9. RMR PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TS_w1 LITHOPHYSAL-RICH UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
Strength (C)	2	2	2	2	2
RQD rating	3	3	8	13	17
Joint frequency (JF)	8	8	9	9	10
Joint condition (JC)	25	26	27	29	30
Groundwater	15	15	15	15	15
Joint orientation (AJO)	-11	-10	-7	-4	-1
RMR	42	45	54	64	72

TABLE 4-10. RMR PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TS_w2 UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
Strength (C)	12	12	12	12	12
RQD rating	3	8	8	13	17
Joint frequency (JF)	5	6	7	9	10
Joint condition (JC)	25	26	27	29	30
Groundwater	15	15	15	15	15
Joint orientation (AJO)	-11	-10	-7	-4	-1
RMR	49	57	62	73	82

TABLE 4-11. RMR PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TS_w3 UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
Strength (C)	7	7	7	7	7
RQD rating	8	13	13	17	17
Joint frequency (JF)	8	8	8	8	8
Joint condition (JC)	25	26	27	29	30
Groundwater	15	15	15	15	15
Joint orientation (AJO)	-11	-10	-7	-4	-1
RMR	52	59	63	72	75

TABLE 4-12. RMR PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, CHn1 UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
Strength (C)	4	4	4	4	4
RQD rating	3	13	17	20	20
Joint frequency (JF)	11	12	14	17	19
Joint condition (JC)	20	20	20	20	20
Groundwater	15	15	15	15	15
Joint orientation (AJO)	-11	-10	-7	-4	-1
RMR	41	54	63	72	77

4.2 Rock Mass Quality Indices for the Norwegian Geotechnical Institute System

4.2.1 Rock Quality Designation (RQD)

RQDs for the five rock mass quality categories were developed in Lin et al (1992) and listed in Table 4-2.

4.2.2 Joint Set Number (Jn)

Fracture orientations have been studied in Lin et al (1992) and are based on oriented core data and borehole television observations. One to three joint sets were identified in the welded tuff units; the Q system descriptions of "one joint set" (Jn=2), "three joint sets" (Jn=9) were therefore assigned as the upper and lower bounds for the welded tuff units. No subsurface data were available to determine the joint set number for the nonwelded tuff units. However, relatively few joints were observed for the nonwelded tuff, the Q system description of "massive, no or few joints" (Jn=0.5-1.0) was therefore assigned to the nonwelded tuff units. Table 4-13 summarizes the values for the Jn parameter for each unit. Uniform distribution within the upper and lower bounds was assumed for estimating the values of the five rock mass quality categories.

TABLE 4-13. Jn FOR FIVE ROCK MASS QUALITY CATEGORIES

Units	Jn Rating Range	Jn for Rock Mass Quality Category				
		1	2	3	4	5
TCw	9 - 2	8.7	7.6	6.2	4.1	2.7
PTn	1.0 - 0.5	1.0	0.9	0.8	0.7	0.6
TSw1	9 - 2	8.7	7.6	6.2	4.1	2.7
TSw2	9 - 2	8.7	7.6	6.2	4.1	2.7
TSw3	9 - 2	8.7	7.6	6.2	4.1	2.7
CHn1	1.0 - 0.5	1.0	0.9	0.8	0.7	0.6

4.2.3 Joint Roughness Number (Jr)

Joint roughnesses at Yucca Mountain have been studied in Lin et al (1992). "Discontinuous" (Jr=4.0) to "smooth, undulating" (Jr=2.0) and "smooth, undulating" (Jr=2.0) to "smooth, planar" (Jr=1.0) were the descriptions for the joint roughness of the welded and nonwelded tuff, respectively.

Table 4-14 summarizes the values for the Jr parameter for each unit. Uniform distribution within the upper and lower bounds was assumed for estimating the values of the five rock mass quality categories.

TABLE 4-14. Jr FOR FIVE ROCK MASS QUALITY CATEGORIES

Units	Jr Rating Range	Jr for Rock Mass Quality Category				
		1	2	3	4	5
TCw	2.0 - 4.0	2.1	2.4	2.8	3.4	3.8
PTn	1.0 - 2.0	1.1	1.2	1.4	1.7	1.9
TSw1	2.0 - 4.0	2.1	2.4	2.8	3.4	3.8
TSw2	2.0 - 4.0	2.1	2.4	2.8	3.4	3.8
TSw3	2.0 - 4.0	2.1	2.4	2.8	3.4	3.8
CHn1	1.0 - 2.0	1.1	1.2	1.4	1.7	1.9

4.2.4 Joint Alteration (Ja)

According to Langkopf and Gnirk (1986), the fracture infillings were generally thin within the Topopah Spring Member and Calico Hills. A high percentage of the fractures observed were described by them as discolored. Soft or low-friction clay mineral coatings were also found along the fracture surface from the core log (Lin et al, 1992).

Based on the above information, "unaltered joint walls, surface staining only" (Ja=1.0) to "softening or low friction clay mineral coatings" (Ja=4.0) were the descriptions for the Ja parameter of all the thermomechanical units. The Ja values of 3.9, 3.4, 2.8, 1.9, and 1.3 were assigned for the five rock mass quality categories and a uniform distribution within the range was assumed.

4.2.5 Joint Water Reduction Factor (Jw)

The discussion in Section 4.1.5, groundwater for RMR system, also applies in this section. The Q system description of the joint water reduction factor (Jw) as "dry excavations" was assigned for all five units. A value of 1.0 is given as the Jw for all thermomechanical units.

4.2.6 Stress Reduction Factor (SRF)

The SRF is introduced in the Q system with four categories: weak zone(s) intersecting excavation, competent rock, squeezing rock, and swelling rock. The rock descriptions for the Yucca Mountain site are applicable only to the first two categories based on available field data. For the "competent rock," the ratios of uniaxial compressive strengths to the estimated overburden stresses are required to assess SRF. Table 4-15 presents the uniaxial compressive strength, overburden stress, their ratios, and the corresponding SRF values for each thermomechanical unit. The SRF values listed in Table 4-15 were assigned as the upper bound for each unit because of the competent rock nature. As for "weakness zones intersecting excavation," a "heavily jointed" (SRF=5) description was assigned for the highly jointed welded tuff units as the lower bound.

Table 4-16 presents the ranges of SRF and individual values for the five rock mass quality categories assuming uniform distribution within the range.

TABLE 4-15. RATIOS OF UNIAXIAL COMPRESSIVE STRENGTH TO THE ESTIMATED OVERBURDEN STRESSES AND THEIR CORRESPONDING SRF

Thermomechanical Units	TCw	PTn	TSw1 (lithophysae-rich)	TSw2	TSw3	CHn1
$\sigma_c^\dagger$	161	26	16	161	52	26
$\sigma_v^\dagger$	1.0	1.95	4.10	8.30	8.70	10.7
σ_c/σ_v	161	13.3	3.9	19.4	6.0	2.4
SRF	1.0	1.0	7.8	1.0	1.7	10.0

[†] σ_c = uniaxial compressive strength, σ_v = overburden stress

TABLE 4-16. SRF FOR FIVE ROCK MASS QUALITY CATEGORIES

Thermomechanical Unit	Q SRF Rating Range	SRF for Rock Mass Quality Category				
		1	2	3	4	5
TCw	5.0 - 1.0	4.8	4.2	3.4	2.2	1.4
PTn	1.0	1.0	1.0	1.0	1.0	1.0
TSw1 (lithophysae-rich)	7.8	7.8	7.8	7.8	7.8	7.8
TSw2	5.0 - 1.0	4.8	4.2	3.4	2.2	1.4
TSw3	5.0 - 1.7	4.8	4.3	3.7	2.7	2.0
CHn1	10.0	10.0	10.0	10.0	10.0	10.0

4.2.7 Results of Norwegian Geotechnical Institute Indices

Q indices were calculated using the six parameters discussed in the preceding subsections and Equation 2-2. The individual parameters and the calculated Q indices are summarized in Tables 4-17 to 4-22 for each thermomechanical unit, respectively.

4.3 Rock Mass Quality Indices Used for Mechanical Properties Correlation

A review of the RMR (Tables 4-7 to 4-12) and Q (Tables 4-17 to 4-22) values indicates the relative rock qualities predicted by the two systems are different. This is primarily because of a constant strength index used in the RMR system, while the Q system considers the effect of in situ stress and strength index in the SRF. The Q indices were translated into direct RMR values using a correlation equation proposed by Bieniawski (1976):

$$\text{RMR} = 9 \ln Q + 44 \quad (4-2)$$

The average RMR values derived from the translated and original RMR values were selected as the rock mass quality indices for mechanical properties correlation. The translated, original, and average RMR values for the thermomechanical units are listed in Table 4-23.

TABLE 4-17. Q PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TC_w UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
RQD	34.0	50.0	63.0	81.0	92.0
J _n	8.7	7.6	6.2	4.1	2.7
J _r	2.1	2.4	2.8	3.4	3.8
J _a	3.9	3.4	2.8	1.9	1.3
J _w	1.0	1.0	1.0	1.0	1.0
SRF	4.8	4.2	3.4	2.2	1.4
Q	0.45	1.11	2.99	16.07	71.14

TABLE 4-18. Q PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, PT_n UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
RQD	29.0	48.0	61.0	69.0	72.0
J _n	1.0	0.9	0.8	0.7	0.6
J _r	1.1	1.2	1.4	1.7	1.9
J _a	3.9	3.4	2.8	1.9	1.3
J _w	1.0	1.0	1.0	1.0	1.0
SRF	1.0	1.0	1.0	1.0	1.0
Q	8.07	18.82	38.13	94.98	191.33

TABLE 4-19. Q PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TS_{w1} LITHOPHYSAE-RICH UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
RQD	10.0	24.0	46.0	74.0	90.0
J _n	8.7	7.6	6.2	4.1	2.7
J _r	2.1	2.4	2.8	3.4	3.8
J _a	3.9	3.4	2.8	1.9	1.3
J _w	1.0	1.0	1.0	1.0	1.0
SRF	7.8	7.8	7.8	7.8	7.8
Q	0.08	0.29	0.95	4.14	12.49

TABLE 4-20. Q PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TS_w2 UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
RQD	16.0	26.0	41.0	62.0	84.0
J _n	8.7	7.6	6.2	4.1	2.7
J _r	2.1	2.4	2.8	3.4	3.8
J _a	3.9	3.4	2.8	1.9	1.3
J _w	1.0	1.0	1.0	1.0	1.0
SRF	4.8	4.2	3.4	2.2	1.4
Q	0.21	0.57	1.94	12.30	64.96

TABLE 4-21. Q PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, TS_w3 UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
RQD	39.0	58.0	66.0	81.0	89.0
J _n	8.7	7.6	6.2	4.1	2.7
J _r	2.1	2.4	2.8	3.4	3.8
J _a	3.9	3.4	2.8	1.9	1.3
J _w	1.0	1.0	1.0	1.0	1.0
SRF	4.8	4.3	3.7	2.7	2.0
Q	0.51	1.25	2.88	13.09	48.18

TABLE 4-22. Q PARAMETER ESTIMATED VALUES FOR EACH ROCK MASS QUALITY CATEGORY, CH_n1 UNIT

Parameter	Rock Mass Quality Category				
	1	2	3	4	5
RQD	22.0	58.0	77.0	91.0	94.0
J _n	1.0	0.9	0.8	0.7	0.6
J _r	1.1	1.2	1.4	1.7	1.9
J _a	3.9	3.4	2.8	1.9	1.3
J _w	1.0	1.0	1.0	1.0	1.0
SRF	10.0	10.0	10.0	10.0	10.0
Q	0.61	2.27	4.81	12.53	24.98

TABLE 4-23. SUMMARY TABLE FOR THE ROCK MASS QUALITY INDICES

Thermomechanical Unit		Rock Mass Quality Category				
		1	2	3	4	5
TCw	Q	0.45	1.11	2.99	16.07	71.14
	Translated RMR [†]	37	45	54	69	82
	RMR	54	62	66	76	83
	Average RMR	45	53	60	73	83
PTn	Q	8.07	18.82	38.13	94.98	191.33
	Translated RMR	63	70	77	85	91
	RMR	46	47	55	58	61
	Average RMR	54	59	66	72	76
TSw1 (lithophysae-rich)	Q	0.08	0.29	0.95	4.14	12.49
	Translated RMR	21	33	44	57	67
	RMR	42	45	54	64	72
	Average RMR	32	39	49	61	69
TSw2	Q	0.21	0.57	1.94	12.30	64.96
	Translated RMR	30	39	50	67	82
	RMR	49	57	62	73	82
	Average RMR	40	48	56	70	82
TSw3	Q	0.51	1.25	2.88	13.09	48.18
	Translated RMR	38	46	54	67	79
	RMR	52	59	63	72	75
	Average RMR	45	53	58	70	77
CHn1	Q	0.61	2.27	4.81	12.53	24.98
	Translated RMR	40	51	58	67	73
	RMR	41	54	63	72	77
	Average RMR	40	53	60	70	75

[†] Calculated using correlation between RMR and Q (Equation 4-2)

5. ROCK MASS STRENGTHS

Rock mass strengths based on the empirical strength criteria of Yudhbir et al (1983) and Hoek and Brown (1988) for the thermomechanical units are developed in this chapter. As introduced in Section 2.4, rock mass quality indices, intact rock uniaxial compressive strengths, and triaxial compressive testing data are required to develop rock mass strengths. Both average RMR (Table 4-23) and intact rock compressive strengths (Table 3-1) have been derived or compiled in the previous sections. The existing intact rock triaxial test data are listed in the tables of Appendix C.

5.1 Yudhbir Criterion

The Yudhbir et al (1983) general equation has been introduced in Section 2.5 (Equations 2-3 and 2-4):

$$\sigma_1 = A \sigma_c + B \sigma_c \left(\frac{\sigma_3}{\sigma_c} \right)^\alpha ,$$

where σ_c = intact rock uniaxial compressive strength,
 σ_1 = the strength of the rock mass,
 σ_3 = the confining stress,
 A = a dimensionless parameter dependent on the RMR, and
 α, B = rock material constants dependent on rock type.

The values of A for the rock mass are obtainable from the RMR. The equation relating the RMR to A is given below:

$$A = e^{0.0765(\text{RMR}) - 7.65} .$$

The material constants B and α are the constants related to the rock type and have to be determined by curve fitting of the triaxial compressive testing results. No data were available for the PTn and TSw1 units, and data for the TCw and TSw3 units were insufficient. TSw2 and CHn1 were the only two units with sufficient triaxial data to determine the material constants B and α . The derived material constants for TSw2 and CHn1 were used for the welded and nonwelded tuff units, respectively.

The triaxial data listed in Appendix C and the uniaxial compressive strength data listed in Price (1983) for the CHn1 unit were used to curve fit Equation 2-3 to obtain the material constants B and α for the nonwelded tuff units. Using a least-square technique, a good fit of the data was obtained. However, an uncharacteristic concave shape was given by the least-square best-fit of the TSw2 data. Because of the uncharacteristic result derived from the curve fit, values for tuff rock suggested by Yudhbir et al (1983) were adopted for the welded tuff units. Table 5-1 lists the values of B and α used for each thermomechanical unit.

Predicted values of compressive strength for various levels of confining stress were then calculated using the parameters A , B , and α and Equation 2-3.

TABLE 5-1. INTACT ROCK CONSTANTS FOR THE ROCK MASS STRENGTH CRITERIA

Thermomechanical Units	Yudhbir Criterion		Hoek and Brown Criterion
	B	α	m_i
TCw	2.0	0.65	8.0
PTn	1.6	0.89	1.7
TSw1	2.0	0.65	8.0
TSw2	2.0	0.65	8.0
TSw3	2.0	0.65	8.0
CHn1	1.6	0.89	1.7

5.2 Hoek and Brown Criterion

The Hoek and Brown (1988) rock mass strength equation has been given in Section 2.5 (Equations 2-5 and 2-6).

$$\sigma_1 = \sigma_3 + \sqrt{m \sigma_c \sigma_3 + s \sigma_c^2} ,$$

where m = a constant that depends on the properties of the rock and

$$m = m_i e^{(RMR - 100)/28}$$

s = a constant that depends on the extent to which the rock is fractured.

$$s = e^{(RMR - 100)/9}$$

Similar to B and α in the Yudhbir criterion, the parameter m_i represents the intact rock constant and has to be determined by curve fitting of the triaxial compressive testing results. The triaxial test data from both the TSw2 and CHn1 units were successfully used for least-square best-fits of m_i in the Hoek and Brown criterion. The values of m_i determined for the TSw2 and CHn1 units were assigned as the values for the welded and nonwelded tuff units, respectively. These values are also listed in Table 5-1.

The values of parameters m and s for the five rock mass quality categories can be calculated based on the determined m_i values, average RMR (Table 4-23), and the above empirical relationships. Predicted values of compressive strength for various levels of confining stress were then calculated using the parameters m and s and Equation 2-5.

5.3 Design Rock Mass Strengths and Power Law Relationship

The strength versus confinement relationship was developed for both the Yudhbir et al (1983) and Hoek and Brown (1988) criteria. Following the procedure of Hardy and Bauer (1991), the compressive strengths from the Yudhbir and Hoek and Brown methods were averaged to obtain the design rock mass strengths. Figures 5-1 to 5-6 present the design rock mass strengths with confining stress of 0 to 3 MPa for each thermomechanical unit, respectively. Rock mass strengths for all five rock quality categories are included in each figure.

Figure 5-1. Rock Mass Strength Curves for the TCw Unit

Figure 5-2. Rock Mass Strength Curves for the PTn Unit

Figure 5-3. Rock Mass Strength Curves for the TSsw1 Unit

Figure 5-4. Rock Mass Strength Curves for the TSsw2 Unit

Figure 5-5. Rock Mass Strength Curves for the TSw3 Unit

Figure 5-6. Rock Mass Strength Curves for the CHn1 Unit

A power law relationship of the form (Equation 2-7)

$$\sigma_1 = A + B\sigma_3^C$$

was employed to describe the nonlinear design rock mass strength developed by averaging the two failure criteria. The parameters A, B, and C were determined by curve fitting the strength envelopes using a least-square best-fit. Table 5-2 presents the results of the best fit.

TABLE 5-2. POWER LAW CONSTANTS FOR ROCK MASS STRENGTH

Thermomechanical Unit	Rock Mass Quality Category	A	B	C
TCw	1	4.94	10.36	0.692
	2	8.07	10.28	0.712
	3	12.46	10.10	0.730
	4	26.43	9.62	0.753
	5	53.25	9.11	0.763
PTn	1	1.38	2.41	0.869
	2	1.89	2.39	0.881
	3	2.92	2.35	0.895
	4	4.26	2.30	0.907
	5	5.49	2.27	0.914
TSw1	1	0.24	4.64	0.662
	2	0.35	4.79	0.662
	3	0.63	4.99	0.668
	4	1.30	5.19	0.681
	5	2.16	5.26	0.697
TSw2	1	3.64	10.34	0.682
	2	5.94	10.33	0.700
	3	9.71	10.21	0.720
	4	23.31	9.70	0.751
	5	49.95	9.15	0.763
TSw3	1	1.59	7.27	0.671
	2	2.59	7.39	0.685
	3	3.53	7.41	0.696
	4	7.50	7.32	0.727
	5	11.70	7.17	0.744
CHn1	1	0.59	2.39	0.850
	2	1.30	2.41	0.869
	3	2.01	2.38	0.884
	4	3.76	2.31	0.905
	5	5.15	2.27	0.912

6. ROCK MASS MECHANICAL PROPERTIES

In this chapter, rock mass mechanical properties are estimated for the range of rock mass quality predicted for each thermomechanical unit at the Yucca Mountain site. RMR values, derived in Chapter 4, were used with empirical relationships that correlate RMR and the relevant rock mass mechanical properties. The rock mass mechanical properties are discussed within the context of the constitutive models currently chosen for application at Yucca Mountain.

6.1 Rock Mass Mechanical Properties for the Elastic and Elasto-Plastic Models

The elastic and elasto-plastic models both require elastic modulus and Poisson's ratio for the rock mass. Strength criteria are also required and include tensile strength and Mohr-Coulomb strength parameters. These data are used to post-process the analytical results in the elastic case, since no yield is assumed. For the elasto-plastic model, which directly estimates rock mass yield, the dilation angle is also required as input data.

6.1.1 Rock Mass Elastic Modulus

Serafim and Periera (1983) developed a correlation between the RMR and rock mass elastic modulus (E) that was recommended for use by Hardy and Bauer (1991):

$$E = 10^{\frac{(RMR-10)}{40}}, \quad (6-1)$$

where E is in GPa.

Table 6-1 lists the rock mass elastic modulus based upon RMR values derived in Chapter 4 (Table 4-23) and Equation 6-1 for each category of rock quality and each thermomechanical unit. The equation predicts elastic modulus values that exceed the values for intact samples (Table 3-1) for the higher rock qualities. For example, when an RMR value is greater than 71 for the TSw2 unit, the rock mass elastic modulus exceeds the intact rock elastic modulus (32.7 MPa). The calculated moduli were therefore adjusted so that the upper bound limit of the rock mass modulus was equal to the intact rock elastic modulus. These results are presented in Table 6-1.

TABLE 6-1. ROCK MASS ELASTIC MODULUS (GPa) FOR THE RANGE OF ROCK MASS QUALITY

Thermomechanical Unit	Rock Mass Quality Category				
	1	2	3	4	5
TCw	7.66	12.20	17.71	19.90	19.90
PTn	6.00	6.00	6.00	6.00	6.00
TSw1 (lithophysae-rich)	3.48	5.24	9.21	15.50	15.50
TSw2	5.47	9.02	14.04	31.61	32.70
TSw3	7.46	11.69	15.80	15.80	15.80
CHn1	5.74	6.00	6.00	6.00	6.00

6.1.2 Rock Mass Poisson's Ratios

Empirical relationships to estimate Poisson's ratio from rock mass quality were not available. The intact rock Poisson's ratios listed in Table 3-1 were therefore adopted as the rock mass Poisson's ratios for all five rock mass quality categories.

6.1.3 Rock Mass Tensile Strengths

Empirical relationships to estimate rock mass tensile strength based upon rock mass quality were not available. Since joint strength and persistence are expected to be factors for limiting rock mass tensile strength, Hardy and Bauer (1991) recommended that the rock mass tensile strength be set at the value of one-half the rock mass joint cohesion, predicted using the joint persistence criteria derived in the CJM section. Table 6-2 lists rock mass tensile strengths calculated based on the estimated cohesion of the vertical joint set discussed in Section 6.2.2.

TABLE 6-2. ROCK MASS TENSILE STRENGTH (MPa)

Thermomechanical Unit	Rock Mass Quality Category				
	1	2	3	4	5
TCw	0.21	1.14	3.06	7.38	11.23
PTn	0.04	0.18	0.46	1.09	1.63
TSw1 (lithophysae-rich)	0.16	0.77	1.89	4.23	6.24
TSw2	0.35	1.59	3.62	7.52	10.67
TSw3	0.10	0.45	1.09	2.38	3.46
CHn1	0.11	0.47	1.01	1.92	2.61

6.1.4 Rock Mass Mohr-Coulomb Strength Parameters and Dilation Angles

Rock mass strength criteria were developed in Chapter 5 using a power law. The Mohr-Coulomb parameters required for the elasto-plastic model were then obtained by curve fitting the rock mass strength envelopes (σ_1 , σ_3) using the least-square best-fit method and calculating the cohesion and angle of internal friction using the procedure described in Section 3.1.3. The best-fit was performed over the range of confining pressures from 0 to 3 MPa, which is representative of the projected range in minimum principal stresses near the boundary of the repository excavations. Table 6-3 presents the strength parameters from the best-fit results. The nonassociated flow rule, suggested by Michelis and Brown (1986), which uses a dilation angle equal to half the internal friction angle, was considered suitable for the tuff (Hardy and Bauer, 1991), and the resulting values for dilation angle are also listed in Table 6-3.

6.2 Rock Mass Mechanical Properties for the Compliant Joint and Distinct Block Models

Both the CJM and DBM require definition of the geometric parameters of joint sets, the mechanical properties of the joints, and the mechanical properties of the intact blocks of rock between joints. This section discusses the methods used to develop these input parameters based upon the range in projected rock mass quality for each thermomechanical unit.

Limited oriented core data from the Tiva Canyon and Topopah Spring Members in holes USW GU-3 and USW G-4 and fracture dip data for all core in the holes USW G-1, USW G-4, USW GU-3, and UE-25a#1 were reviewed by Lin et al (1992) to define the joint geometric parameters when fracture dip occurrence was corrected for sampling bias caused by the relationship of the borehole orientation and the fracture dip (Terzaghi correction). The near vertical fractures (60° - 90° dip) were strongly dominant and averaged between 75% and 90% of all fractures measured in the Tiva Canyon, Pah Canyon, Topopah Spring, and Calico Hills Members. The existence of a consistent set of low-angle dips (0° - 30°) has been proposed and would average 5% to 15% of all fractures measured for the four geologic members. Further characterization of the Yucca Mountain site may show the fracture at low dips to be random, but the estimated properties of the low dip joints were developed for completeness of the data.

TABLE 6-3. STRENGTH PARAMETERS AND DILATION ANGLES FOR THE MOHR-COULOMB CRITERION

Thermomechanical Unit	Rock Mass Quality Category	Mohr-Coulomb		
		Cohesion (MPa)	Angle of Internal Friction (ϕ)	Dilation Angle ($\phi/2$)
TCw	1	1.4	49	24
	2	1.9	49	24
	3	2.7	49	25
	4	5.3	49	24
	5	10.5	48	24
PTn	1	0.6	20	10
	2	0.7	20	10
	3	1.1	20	10
	4	1.5	20	10
	5	2.0	20	10
TSw1 (lithophysae-rich)	1	0.4	30	15
	2	0.4	31	15
	3	0.5	32	16
	4	0.7	33	17
	5	0.9	34	17
TSw2	1	1.1	48	24
	2	1.5	49	24
	3	2.2	49	25
	4	4.7	49	24
	5	9.9	48	24
TSw3	1	0.8	41	20
	2	1.0	42	21
	3	1.2	42	21
	4	2.0	43	21
	5	2.9	43	21
CHn1	1	0.3	19	10
	2	0.5	20	10
	3	0.8	20	10
	4	1.4	20	10
	5	1.9	20	10

Each of the thermomechanical units is addressed in the following sections except CHn1 where the total number of fractures measured was small and was estimated to be near one occurrence per 5 m of core log by Lin et al (1992). On the basis of this, application of the jointed models would not be required for CHn1.

6.2.1 Joint Spacings

Joint spacings for each rock mass quality category were required as part of the CJM and DBM. This was achieved using the equation proposed by Hudson and Priest (1979) to relate total joint frequency to RQD:

$$RQD = 100e^{-0.1\lambda}(0.1\lambda + 1) \quad , \quad (6-2)$$

where λ = total joint frequency.

The total joint frequencies for each of the five rock mass quality categories were obtained using the RQDs developed in Lin et al (1992) and Equation 6-2. The percentages of occurrence for high-angle (60° - 90°) and low-angle (0° - 30°) dips were developed in Lin et al (1992) (Table 3-3), and were then used to derive the vertical and horizontal joint set frequencies by taking the calculated total joint frequencies and multiplying them by the percentages of occurrence for each set.

Estimation of joint frequency using RQD assumes that joints are the primary factor in determining RQD. This assumption appears valid for the welded tuff units. However, for the PTn, application of Equation 6-2 produced total joint frequencies ranging between 10.4 and 24.9 m⁻¹, which was considerably higher than the total fracture frequency (3.18 m⁻¹) in the core logging data. In this case, RQD was more a function of general rock competence and was influenced by lost core and rubble zones. The range of total fracture frequency for the PTn was therefore set at 1.94 to 3.18 m⁻¹, which corresponds to the vertical fracture and total fracture frequencies in Table 3-3, respectively. Fracture frequency for PTn was assumed to vary uniformly for this range for assignment to each rock mass quality category. The total joint frequencies, high-angle and low-angle joint set percentages, and the horizontal and vertical joint spacings (reverse of frequencies) for each thermomechanical unit are presented in Table 6-4.

6.2.2 Joint Frictional Strength

The Mohr-Coulomb strength parameters (cohesion and angle of friction) are developed in this subsection to describe the joint strength. In practice, many joints are discontinuous, requiring both failure of intact material at the termination of joints and slip along existing joints for large-scale displacements to occur. A simple method to approximate the strength of a discontinuous joint, proposed by Hardy and Bauer (1991) is to develop effective strength parameters for the joint that are equal to the length-weighted averages of the joint and intact material. The effective strength parameters are described by the following equations:

$$c_j^e = \chi c_j + (1 - \chi)c_r \quad , \text{ and} \quad (6-3)$$

$$\phi_j^e = \chi \phi_j + (1 - \chi)\phi_r \quad , \quad (6-4)$$

where χ = continuity of the joint,

c = cohesion,

ϕ = friction angle,

j = subscript refers to joint properties,

r = subscript refers to intact rock properties, and

e = superscript denoting effective cohesion or friction angle.

The continuities of joints (χ) for the Yucca Mountain site have been estimated based on traces of joints in photographs of excavations in the TSw2 (Hardy and Bauer, 1991). The continuity of vertical fractures (χ_v) ranging from 0.50 to 1.00 and the continuity of horizontal fractures (χ_h) ranging from 0 to 0.50 were derived in the preliminary application of the Drift Design Methodology. Table 6-5 lists the joint continuity values for the five rock mass quality categories.

TABLE 6-4. SUMMARY OF CALCULATION OF ORTHOGONAL JOINT SET SPACINGS

Thermomechanical Unit	Rock Mass Quality Category	Total Joint Frequency (m ⁻¹)	Horizontal Joint Set Percentage	Vertical Joint Set Percentage	Horizontal Joint Set Frequency (m ⁻¹)	Vertical Joint Set Frequency (m ⁻¹)	Horizontal Joint Set Spacing (m)	Vertical Joint Set Spacing (m)
TCw	1	22.60	10.82	79.20	2.45	17.90	0.41	0.06
	2	16.80	10.82	79.20	1.82	13.31	0.55	0.08
	3	12.90	10.82	79.20	1.40	10.22	0.72	0.10
	4	8.00	10.82	79.20	0.87	6.34	1.16	0.16
	5	4.70	10.82	79.20	0.51	3.72	1.97	0.27
PTn	1	3.12	14.99	75.23	0.47	2.35	2.14	0.43
	2	2.93	14.99	75.23	0.44	2.21	2.28	0.45
	3	2.68	14.99	75.23	0.40	2.02	2.49	0.50
	4	2.31	14.99	75.23	0.35	1.74	2.89	0.57
	5	2.06	14.99	75.23	0.31	1.55	3.23	0.64
TSw1 (lithophysae-rich)	1	38.90	7.20	87.37	2.80	33.99	0.36	0.03
	2	27.50	7.20	87.37	1.98	24.03	0.51	0.04
	3	18.10	7.20	87.37	1.30	15.81	0.77	0.06
	4	9.90	7.20	87.37	0.71	8.65	1.40	0.12
	5	5.30	7.20	87.37	0.38	4.63	2.62	0.22
TSw2	1	32.90	5.01	90.63	1.65	29.82	0.61	0.03
	2	26.40	5.01	90.63	1.32	23.93	0.76	0.04
	3	19.90	5.01	90.63	1.00	18.04	1.00	0.06
	4	13.20	5.01	90.63	0.66	11.96	1.51	0.08
	5	7.10	5.01	90.63	0.36	6.43	2.81	0.16
TSw3	1	20.60	5.48	89.71	1.13	18.48	0.89	0.05
	2	14.30	5.48	89.71	0.78	12.83	1.28	0.08
	3	12.10	5.48	89.71	0.66	10.85	1.51	0.09
	4	8.00	5.48	89.71	0.44	7.18	2.28	0.14
	5	5.60	5.48	89.71	0.31	5.02	3.26	0.20

TABLE 6-5. ESTIMATED JOINT CONTINUITY FOR PROBABILITY LEVEL

Rock Mass Quality Category	Joint Continuity (χ)	
	Horizontal	Vertical
1	0.475	0.975
2	0.400	0.900
3	0.300	0.800
4	0.150	0.650
5	0.050	0.550

Calculation of weighted average joint strength combined continuity estimates with estimated ranges in the parameters of joint and intact rock strengths presented in Chapter 3, where the strength parameters were assumed to be uniformly distributed over the ranges listed in Tables 3-2 and 3-5. The selected values of strength parameters (c , ϕ) and continuity (χ) were then used to calculate the weighted overall strength parameters according to Equations 6-3 and 6-4. The resulting joint effective strength parameters are listed in Table 6-6.

TABLE 6-6. WEIGHTED AVERAGE JOINT STRENGTH USED FOR THE CJM

Thermomechanical			Rock Mass Quality Category				
Unit			1	2	3	4	5
Horizontal Joint Set	TCw	c (MPa)	18.9	21.6	25.2	30.6	34.2
		ϕ (°)	41	42	43	43	42
	PTn	c (MPa)	6.3	7.2	8.4	10.2	11.4
		ϕ (°)	24	22	20	16	13
	TSw1 (lithophysae-rich)	c (MPa)	3.2	3.6	4.2	5.1	5.7
		ϕ (°)	25	24	22	18	15
	TSw2	c (MPa)	18.9	21.6	25.2	30.6	34.2
		ϕ (°)	41	42	43	43	42
	TSw3	c (MPa)	6.3	7.2	8.4	10.2	11.4
		ϕ (°)	40	41	42	42	42
	CHn1 [†]	c (MPa)	6.3	7.2	8.4	10.2	11.4
		ϕ (°)	24	22	20	16	13
Vertical Joint Set	TCw	c (MPa)	0.9	3.6	7.3	12.7	16.3
		ϕ (°)	41	43	46	48	49
	PTn	c (MPa)	0.3	1.2	2.4	4.3	5.5
		ϕ (°)	37	36	36	33	31
	TSw1 (lithophysae-rich)	c (MPa)	0.2	0.6	1.3	2.2	2.8
		ϕ (°)	37	37	36	34	32
	TSw2	c (MPa)	0.9	3.6	7.3	12.7	16.3
		ϕ (°)	41	43	46	48	49
	TSw3	c (MPa)	0.3	1.2	2.5	4.3	5.5
		ϕ (°)	39	41	44	46	47
	CHn1 [†]	c (MPa)	0.3	1.2	2.4	4.3	5.5
		ϕ (°)	37	36	36	33	31

[†] Derived for calculation of rock mass tensile strength for elasto-plastic model

6.2.3 Joint Stiffness

The half-closure stress (A_n) and maximum joint closure (u_{max}) are parameters used to describe normal joint stiffness; elastic shear stiffness (G_s) and hardening stiffness (G_s') are the parameters used to characterize the joint shear deformation. The ranges of values for these parameters listed in Table 3-6 were used to generate the joint stiffness for five rock mass quality categories. Values for the five rock mass qualities are selected assuming uniform distribution within the ranges. Parameters which produced more joint deformations were associated with lower rock mass quality. The parameters developed for the joint stiffness are listed in Table 6-7.

TABLE 6-7. CJM JOINT STIFFNESS PROPERTIES

Thermomechanical		Rock Mass Quality Category				
Unit		1	2	3	4	5
TCw	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
PTn	u_{max} (m)	2.50E-05	2.19E-05	1.78E-05	1.16E-05	7.46E-06
	A_n (MPa)	1.28	1.52	1.84	2.32	2.64
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
TSw1 (lithophysae-rich)	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
TSw2	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
TSw3	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05

6.2.4 Intact Block Elastic Properties

Elastic modulus and Poisson's ratio for the intact blocks between joints were assumed to be equivalent to properties developed in laboratory tests. The intact rock elastic properties listed in Table 3-1 are therefore used as the intact block elastic properties. No variation was assumed for the different rock mass qualities.

6.2.5 Compressive Strength of Intact Blocks

The size effect of intact block strength for the welded tuff in the Topopah Spring Member was determined by Price (1986). A power law best-fit result was reported as

$$\sigma_c = 1944 D^{-0.846} + 69.5 \quad , \quad (6-5)$$

where σ_c = uniaxial compressive strength (MPa) and

D = sample diameter (mm).

This size effect was assumed to be a valid expression for estimating the compressive strength of intact blocks for all the densely welded thermomechanical units. The strengths of the block were calculated by the size-strength relationship in Equation 6-5 using the spacing of vertical joints (Section 6.2.1) as the intact block size. For nonwelded units, the laboratory strength values were used without any size effect because no correlation has been developed. Table 6-8 lists the block strength for each rock mass quality category.

TABLE 6-8. ESTIMATED STRENGTH OF INTACT BLOCKS USED FOR THE CJM (MPa)

Unit	Rock Mass Quality Category				
	1	2	3	4	5
TCw	134	120	110	96	87
PTn	26	26	26	26	26
TSw1 (lithophysae-rich)	16	16	16	16	16
TSw2	161	152	135	115	97
TSw3	52	52	52	52	52

7. DISCUSSION

Site-specific geotechnical data for the thermomechanical units to be penetrated by ESF excavations at the Yucca Mountain site are limited at this stage of site characterization. The data used in this report were obtained or derived from the best available field and laboratory data. Both field and laboratory characterization have been concentrated in the candidate repository horizon (TSw2) and the underlying Calico Hills tuffs (CHn1). Information for other thermomechanical units was incomplete, and the parameter values for the TSw2 and CHn1 units were adopted as the values for the other welded and nonwelded units assuming that similar mechanical properties occur in all welded and nonwelded units, respectively. As new data are developed, estimates of these material properties should be updated.

These results assume no temperature, saturation, or loading effects. The effects of varying testing conditions on the mechanical properties for the intact rock and joints have been investigated, but the results are inconclusive. The data used in this study are mainly from the laboratory testing with ambient temperature and under a standard loading rate.

The low intact rock strength of the lithophysae-rich tuff samples taken from the outcrop of Busted Butte (Price et al, 1985) was not representative of the intact strength for the entire TSw1 unit. TSw1 contains alternating layers of lithophysae-rich and lithophysae-poor tuff, and the lithophysae-poor portions of the TSw1 tuff were assumed to have mechanical and bulk properties equal to TSw2. Existing test data for the Busted Butte samples were assumed representative of the lithophysae-rich portions of TSw1.

Rock mass quality indices for the candidate repository units have been evaluated in an earlier work by Langkopf and Gnirk (1986). Good agreement is found between the range established by them and the results presented in this study. For example, the RMR ratings estimated by Langkopf and Gnirk (1986) for the TSw2 unit range from 48 to 84, whereas the average RMR values for the five rock mass quality categories in the same unit predicted in this study are 40, 48, 56, 70 and 82.

The derivation of rock mass quality indices, RMR and Q, did not include considerations of thermal and seismic stresses. The effect of thermal and seismic stresses can be assessed with the Q system by modifying the SRF parameter to account for the increased stresses. Details for incorporating thermal and seismic effects into the Q system can be found in Hardy and Bauer (1991).

The rock mass strength and modulus for various rock mass quality categories have been calculated and presented in Chapters 5 and 6. A rock mass modulus ranging from 5.47 to 32.7 GPa was predicted for the TSw2 unit, whereas the rock mass cohesion for the same unit varied from 1.1 to 9.9 MPa. The large variance for these predicted results is caused by the wide variation of joint abundance and the expected variability of joint mechanical properties observed from the core hole samples.

Although rock mass mechanical properties were derived for the analytical models currently chosen for application at Yucca Mountain, these properties have other general uses. The derived rock mass quality indices and strengths are useful in empirical techniques for both geotechnical design and performance assessment.

The derived rock mass properties in this study are summarized in Appendix D and recommended for inclusion in the RIB. The procedure presented for deriving these properties is of equal importance as the final results. Should more site-specific data be collected as the project proceeds, this procedure can be applied as a guide for deriving the updated rock mass properties.

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APPENDIX A

Core Evaluation to Determine Contacts Between Thermomechanical Units TSw1 and TSw2—By the Sample Overview Committee

May 15, 1991

David C. Dobson, YMP, NV
J. Russell Dyer, YMP, NV

CORE EVALUATION TO DETERMINE CONTACTS BETWEEN THERMAL-MECHANICAL UNITS TSw1 AND TSw2

Reference: (1) Letter, Gertz to TPOs, dtd. 4/23/91
(2) Letter, Clanton to SOC Members, dtd. 4/29/91

The evaluation of core was undertaken as part of the regularly scheduled Sample Overview Committee Meeting held at the Sample Management Facility on May 7, 1991. The criteria under which the evaluation was performed are shown in Enclosure 1.

The following people served as core evaluators: Chris Rautman, Sandia National Laboratories (SNL); David Vaniman, Los Alamos National Laboratory (LANL); Rick Spengler, U.S. Geological Survey (USGS); Uel S. Clanton, Department of Energy, Yucca Mountain Site Characterization Project (DOE/YMP); and John Peck, Technical and Management Support Services/Science Applications International Corporation (T&MSS/SAIC). The following people served as observers during the evaluation:

Stephen Bolivar, LANL
Albert C. Williams, DOE-Quality Assurance
W. Arch Girdley, DOE/YMP
Donna Sinks, T&MSS/SAIC
Jim McCormick, Raytheon Services Nevada
John Davis, T&MSS/SAIC
Robert Saunders, T&MSS/Westinghouse
Chris Lewis, T&MSS/Harza
Wunan Lin, Lawrence Livermore National Laboratory
John A. Hartley, T&MSS/Harza
Chris Weiss, T&MSS/SAIC

Core from the following boreholes was examined during the evaluation: UE25-a#1, UE25-a#7, USW G-4, USW GU-3, and USW G-1. Core which spanned the contact intervals previously designated by SNL (Ortiz et al., 1985) for units TSw1 and TSw2 was examined as well as contacts defined by the USGS (numerous reports) between the upper lithophysal and middle non-lithophysal units of the Topopah Spring Member of the Paintbrush Tuff. The evaluation showed

clearly that contacts chosen by Ortiz et al. (1985) from interpretation of borehole logs in two boreholes (USW G-1 and UE25-a#1) were not stratigraphically consistent with contacts chosen in other boreholes or in outcrop. The evaluation further determined that the contact between the upper lithophysal and middle non-lithophysal units of the Topopah Spring Member is readily recognizable in all the boreholes examined and is coincident with the contact between the TSw1 and TSw2 units chosen by Ortiz et al. except for those two holes mentioned previously.

The evaluators were asked to independently choose the contact depth in all five boreholes for the contact between the upper lithophysal and middle non-lithophysal units. This contact is recommended by the evaluation team to be recognized as the contact between thermal-mechanical units TSw1 and TSw2. The tabulation below gives the depth and elevation of the contact in each borehole established by consensus of the evaluators.

BOREHOLE	DEPTH	ELEVATION
UE25-a#1	650 ft	3314 ft
UE25-a#7	775 ft*	3308 ft**
USW G-4	680 ft	3487 ft
USW GU3	720 ft***	4137 ft
	690 ft***	4167 ft
USW G-1	715 ft	3634 ft

*depth in borehole not corrected for true vertical depth (borehole drilled at 26 degree angle from vertical)

**true elevation corrected for 26 degree angle

***two contacts chosen to envelope a 30-ft transition zone (both values to be used to check model sensitivity)

Elevations were derived by subtracting the depth from ground elevations recorded in Fenix and Scisson, Inc. report DOE/NV/10322-24, 1987 for the five boreholes from which core was examined.

The evaluation team concluded that the contact of the TSw1/TSw2 units is a consistent lithologic contact. It is easily recognized in the core samples, is correlatable across the repository block from north to south and from west to east, and corresponds to the lithologic contact recognized by the USGS as the base of the upper lithophysal unit of the Topopah Spring Member. It meets the criteria used for the evaluation.

We recommend that the elevations of the contact determined by the evaluation team be used by SNL as revised input to its three-dimensional model of reference thermal-mechanical stratigraphy at Yucca Mountain.

May 15, 1991

This evaluation was carried out under BTP-RSE-001. The disclaimer in Enclosure 1 needs to be made a part of the record wherever the data resulting from this evaluation are used.

John H. Peck, Responsible Staff Member

Uel S. Clanton, Evaluator

Chris Rautman, Evaluator

Rick Spengler, Evaluator

David Vaniman, Evaluator

JHP-BP-L91-9642

CORE EVALUATION MEETING
MAY 7, 1989

CRITERIA FOR EVALUATION

1. PURPOSE

THE PURPOSE OF THIS EVALUATION IS TO REACH CONSENSUS ON THE PLACEMENT OF THE CONTACT BETWEEN THERMAL-MECHANICAL UNITS Tsw1 and Tsw2 IN FOUR BOREHOLES WHICH HAVE CORE AVAILABLE TO OBSERVE IN THE STRATIGRAPHIC INTERVAL IN QUESTION

2. APPROACH

A SHORT PRESENTATION WILL BE GIVEN BY THE SANDIA REPRESENTATIVE REGARDING THE DEFINITION OF THERMAL-MECHANICAL UNITS OF THE TOPOPAH SPRINGS STRATIGRAPHIC UNIT AS BACKGROUND INFORMATION.

A SHORT PRESENTATION WILL BE GIVEN BY A USGS REPRESENTATIVE REGARDING THE STRATIGRAPHIC SUBDIVISIONS OF THE TOPOPAH SPRINGS BASED ON USGS STUDIES AND THE RECOGNITION OF CONTACTS AMONG THOSE UNITS

A ROUNDTABLE DISCUSSION WILL SERVE TO CLARIFY THE DIFFERENCES, IF ANY, BETWEEN DEFINITION OF CONTACTS CHOSEN BY THE USGS FOR STRATIGRAPHIC PURPOSES AND CONTACTS CHOSEN BY SANDIA FOR MODELING AND ENGINEERING PURPOSES

CORE FROM THE FOUR BOREHOLES WILL BE EXAMINED BY THE EVALUATORS TO VERIFY CONTACTS CHOSEN PREVIOUSLY AND REACH CONSENSUS ON THE PLACEMENT OF THE CONTACT BETWEEN UNITS Tsw1 AND Tsw2 USING THE BACKGROUND INFORMATION AS BASIS FOR THE CHOICE OF CONTACT.

3. CRITERIA

THE CONTACT CHOSEN MUST BE CONSISTENT WITH CRITERIA USED PREVIOUSLY BY SANDIA FOR CHOSING CONTACTS

THE CONTACT CHOSEN MUST HAVE A CONSISTENT AND RECOGNIZABLE STRATIGRAPHIC RELATIONSHIP TO UNIT CONTACTS DEFINED BY THE USGS

THE CONTACT CHOSEN MUST BE ABLE TO BE DEFINED CONSISTENTLY AMONG THE FOUR BOREHOLES ON VISUALLY IDENTIFIABLE FEATURES READILY APPARENT TO ALL EVALUATORS

MINERALOGICAL FEATURES, MICROSTRUCTURE, OR OTHER CHARACTERISTICS IDENTIFIABLE ONLY THROUGH LABORATORY ANALYSIS SHALL NOT BE USED IN THE ESTABLISHMENT OF THE CONTACT CHOSEN

QUALITATIVE ESTIMATES OF ROCK PROPERTIES SUCH AS COMPETENCE, DEGREE OF FRACTURING, DENSITY, HARDNESS, RELATIVE ABUNDANCE OF VOID SPACE, ETC. MAY BE USED AS SUPPORTIVE EVIDENCE TO LOCATE THE CONTACT, BUT THE CONTACT PLACEMENT SHALL BE MADE USING SPECIFIC VISUAL FEATURES WHICH CAN BE CORRELATED FROM CORE TO CORE

4. RESULTS OF EVALUATION

THE CONTACT EVALUATION SHOULD RESULT IN A CONSENSUS CONCERNING THE LOCATION OF THE CONTACT BETWEEN Tsw1 AND Tsw2. THE POSITION OF THE POTENTIAL REPOSITORY HORIZON WITHIN THE Tws2 UNIT WILL BE REEVALUATED BY SANDIA BASED ON THE RESULTS OF THE EVALUATION. THE RESULTS WILL BE DOCUMENTED AND SENT TO SANDIA AS INPUT FOR RECOMMENDING A POTENTIAL REPOSITORY HORIZON.

NOTE: IT IS RECOGNIZED THAT THE CORE BEING EXAMINED IS NOT QUALIFIED FOR USE IN A LICENSING PROCESS. HOWEVER, THE RESULTS OF CORE EXAMINATION SHALL BE DEEMED AS CORROBRATIVE EVIDENCE WHICH MAY BE USED IN DEFINING PRELIMINARY RECOMMENDATIONS SUBJECT TO LATER VERIFICATION. ALL ELEVATIONS OF CONTACTS DETERMINED BY THIS EVALUATION SHOULD BE CONSIDERED APPROXIMATE ONLY, PROBABLY WITHIN A RANGE OF PLUS OR MINUS 10 FEET.

APPENDIX B

Summary of Uniaxial Compressive Test Data for TSw2 Unit

TABLE B-1. UNIAIXAL COMPRESSIVE STRENGTH LABORATORY TEST DATA FOR TS_{w2} UNIT (Ambient Temperature Experiment at $\epsilon = 10^{-5} \text{ s}^{-1}$)

Sample ID	UCS	Source
A1-723	138.0	Olsson and Jones (1980)
A1-1250	166.0	
G1-939	108.0	Nimick and Schwartz (1987)
G1-1021.8	75.2	
G1-1060.8	142.8	Price et al (1982)
G1-1096.0	59.8	
G1-1154.9	106.2	
G2-1561.3A	85.0	
G2-1561.3C	73.0	Nimick et al (1987)
G2-1561.3D	86.0	
G2-1561.3E	61.0	
G2-1579.1A	170.0	
G2-1579.1C	97.0	
G2-1579.1D	175.0	
G2-1579.1E	96.0	
G2-1587.8B	165.0	
G2-1587.8D	155.0	
GU3-760.91A	210.3	Price et al (1984)
GU3-760.91B	234.4	
GU3-760.92A	215.5	
GU3-760.92B	221.4	
GU3-760.93A	245.2	
GU3-760.93B	222.2	
GU3-760.94A	205.2	
GU3-760.94B	183.5	
GU3-760.95A	229.7	
GU3-760.95B	226.4	
GU3-1050.41	131.3	
GU3-1050.42	147.7	
GU3-1050.43	152.1	
GU3-1067.83	115.3	
GU3-1067.84	120.1	
G4-686.6A	270.0	Nimick et al (1985)
G4-686.6D	326.0	
G4-686.6G	180.0	
G4-742.75E	235.0	
G4-742.75F	256.0	
G4-742.75G	279.0	
G4-748.6A	196.0	
G4-748.6B	190.0	
G4-7490A	268.0	
G4-7490B	188.0	
G4-910.7A	131.0	
G4-911.3A	160.0	
G4-911.3B	88.0	
G4-911.3C	118.0	
G4-965.2A	187.0	
G4-965.2D	131.0	
G4-965.2H	148.0	
G4-1001.9A	99.0	
G4-1001.9B	170.0	
G4-1001.9C	147.0	
G4-1002.4B	179.0	
G4-1002.4C	137.0	
G4-1065.8A	12.0	
G4-1065.8C	124.0	
MEAN	161.4	
STANDARD DEVIATION	63.3	

APPENDIX C

Summary of Triaxial Test Data of Currently Available Sources

TABLE C-1. SUMMARY OF TRIAXIAL TEST DATA

Unit	Sample ID	Confining Pressure (MPa)	Compressive Strength (MPa)	Strain Rate (s ⁻¹)	Source
TCw	A1-87.6a	10	406	0.0001	Olsson and Jones (1980)
TCw	A1-87.6b	20	895	0.0001	
TCw	A1-185.0	20.7	125.7	0.0001	
TSw2	A1-739.3	20.7	153.7	0.0001	
TSw2	A1-1250a	10	422	0.0001	
TSw2	A1-1250b	20	638	0.0001	
TSw2	G1-352.0	5	77.5	0.00001	Price et al (1982)
TSw2	G1-354.6	5	224.3	0.00001	
TSw2	G1-359.5	5	114.7	0.00001	
TSw2	G1-362.4	10	129.3	0.00001	
TSw2	G4-686.6B	5	161	0.00001	Nimick et al (1985)
TSw2	G4-686.6E	5	92	0.00001	
TSw2	G4-686.6C	10	354	0.00001	
TSw2	G4-686.6F	10	370	0.00001	
TSw2	G4-965.2B	10	107	0.00001	
TSw2	G4-965.2E	10	257	0.00001	
TSw2	10AE20Z	10	203.3	0.00001	Price et al (1987)
TSw2	10AE12Z	10	196.5	0.00001	
TSw2	10AE3Z	10	163.6	0.00001	
TSw2	10AE42X	10	161.7	0.00001	
TSw2	10AE15Y	10	127.3	0.00001	
TSw2	10AE14Y	10	230	0.00001	Nimick and Schwartz (1987)
TSw2	10AE12Y	10	192	0.00001	
TSw2	10AE8Y	10	50	0.00001	
TSw2	10AE10Y	10	191	0.00001	
TSw2	10AE18Z	10	171	0.00001	
TSw2	10AE26W	10	115	0.00001	
TSw2	10AE15W	20	272	0.00001	
TSw2	10AE47Z	20	176	0.00001	
TSw2	10AE9W	20	232	0.00001	
TSw2	10AE15X	20	212	0.00001	
TSw2	10AE42W	20	180	0.00001	
TSw3	G2-1646.8-B	10	42	0.00001	Nimick et al (1987)
TSw3	G2-1646.8-C	10	37	0.00001	
TSw3	G2-1659.2-A	10	78	0.00001	
TSw3	G2-1659.2-B	10	63	0.00001	
CHn1	G1-1487.2SL3	10	35.4	0.00001	Price and Jones (1982)
CHn1	G1-1487.2SL3A	10	36	0.00001	
CHn1	G1-1487.2SL5	10	39.9	0.00001	
CHn1	G1-1487.2SL5A	10	41.4	0.00001	
CHn1	G1-1487.2SL4	20	46.7	0.00001	
CHn1	G1-1487.2SL4A	20	56.1	0.00001	
CHn1	G1-1487.2SL6	20	37.1	0.00001	
CHn1	G1-1487.2SL6A	20	54.4	0.00001	
CHn1	G1-1604.6	20	46.1	0.0001	Olsson and Jones (1980)
CHn1	G1-1633.4	20.7	88.2	0.0001	
CHn1	G1-1661.6	20	90.3	0.0001	
CHn1	G1-1664.9SL9	10	45.7	0.00001	Price and Jones (1982)
CHn1	G1-1664.9SL9A	10	37.6	0.00001	
CHn1	G1-1664.912	10	71.3	0.00001	
CHn1	G1-1664.912A	10	67.6	0.00001	
CHn1	G1-1664.910	20	54.8	0.00001	
CHn1	G1-1664.910A	20	56.2	0.00001	
CHn1	G1-1666.224C	10	28.9	0.00001	
CHn1	G1-1666.224D	10	36.8	0.00001	

APPENDIX D

Information Recommended for Reference Information Base

D.1 INTRODUCTION

The results of this study are summarized in this appendix and are recommended for inclusion in the RIB. These results are described within the following five subsections:

- Definition for the Five Rock Mass Quality Categories
- Rock Mass Quality Indices
- Rock Mass Strength
- Rock Mass Mechanical Properties for the Elastic and Elasto-Plastic Models
- Rock Mass Mechanical Properties for the Compliant Joint and Distinct Block Models

The rock mass mechanical properties are discussed within the context of the constitutive models currently chosen for application at the Yucca Mountain site.

No data from this study is considered for entry into the Site and Engineering Properties Data Base (SEPDB).

D.1.1 Definition for the Five Rock Mass Quality Categories

Since core drilling data from the Yucca Mountain site indicate vertical and lateral variability (Spengler et al, 1981; Scott and Castellanos, 1984; Spengler and Chornack, 1984; Spengler, 1979), a single value for rock mass quality for any thermomechanical unit is not useful. Instead, a range of rock mass quality is estimated for each thermomechanical unit following the methodology proposed by Hardy and Bauer (1991). The possible range of each individual parameter used to calculate the RMR and Q indices was established and a preliminary statistical approach used to select values that represent five rock mass categories representing that range from the poorest (category 1) to the best (category 5). The rock mass quality categories 1 through 5 are defined so that either 95%, 80%, 60%, 30%, or 10% of the rock is projected to exceed the parameter value for that category.

The RMR and Q indices for the extremely poor rock mass quality category (category 1) were then obtained by combining the category 1 index values for each individual parameter using Equations D-1 and D-2 in Section D.1.2. The RMR and Q indices for the very poor (category 2), poor (category 3), fair (category 4), and good (category 5) rock mass quality categories were also obtained from the corresponding category index values using the same procedure.

D.1.2 Rock Mass Quality Indices

Six parameters are considered in the Q system: RQD; joint set number (Jn); joint roughness number (Jr); joint alteration number (Ja); joint water reduction factor (Jw); and stress reduction factor (SRF). Each parameter is assigned index values using the table established by Barton et al (1974). The Q index is then calculated from

$$Q = \left(\frac{RQD}{Jn} \right) \left(\frac{Jr}{Ja} \right) \left(\frac{Jw}{SRF} \right) \quad (D-1)$$

Six parameters are also used to calculate the RMR index: strength of the intact rock (C); Rock Quality Designation rating (R_{RQD}); joint spacing (JF); condition of joints (JC); groundwater condition (JW); and rating adjustment for joint orientation (AJO). The index values for each parameter can be found in the table developed by Bieniawski (1979). The sum for the parameter indices is used to calculate the RMR as follows:

$$\text{RMR} = C + R_{\text{RQD}} + \text{JF} + \text{JC} + \text{JW} + \text{AJO} \quad . \quad (\text{D-2})$$

Translated RMR values from Q indices were obtained using a correlation equation proposed by Bieniawski (1976):

$$\text{RMR} = 9 \ln Q + 44 \quad . \quad (\text{D-3})$$

The average RMR values were then derived from the translated and original RMR values. Table D-1 summarizes the derived rock mass quality indices for each thermomechanical unit.

TABLE D-1. SUMMARY TABLE FOR THE ROCK MASS QUALITY INDICES

Thermomechanical		Rock Mass Quality Category				
Unit		1	2	3	4	5
TCw	Q	0.45	1.11	2.99	16.07	71.14
	Translated RMR	37	45	54	69	82
	RMR	54	62	66	76	83
	Average RMR	45	53	60	73	83
PTn	Q	8.07	18.82	38.13	94.98	191.33
	Translated RMR	63	70	77	85	91
	RMR	46	47	55	58	61
	Average RMR	54	59	66	72	76
TSw1 (lithophysae-rich)	Q	0.08	0.29	0.95	4.14	12.49
	Translated RMR	21	33	44	57	67
	RMR	42	45	54	64	72
	Average RMR	32	39	49	61	69
TSw2	Q	0.21	0.57	1.94	12.30	64.96
	Translated RMR	30	39	50	67	82
	RMR	49	57	62	73	82
	Average RMR	40	48	56	70	82
TSw3	Q	0.51	1.25	2.88	13.09	48.18
	Translated RMR	38	46	54	67	79
	RMR	52	59	63	72	75
	Average RMR	45	53	58	70	77
CHn1	Q	0.61	2.27	4.81	12.53	24.98
	Translated RMR	40	51	58	67	73
	RMR	41	54	63	72	77
	Average RMR	40	53	60	70	75

D.1.3 Rock Mass Strength

Rock and rock masses are observed to have some strength at zero confining pressure and are assumed to have increasingly greater strength as the confining pressure increases. The strength criteria characterizes the strength-confining pressure relationships. Hardy and Bauer (1991) recommended an averaging process based on the empirical strength criterion of Yudhbir et al (1983) and Hoek and Brown (1988) to represent the rock mass at the Yucca Mountain site. Both criteria depend upon various rock characteristics, confined and unconfined compression tests and are a function of the RMR. The Yudhbir et al (1983) and Hoek and Brown (1988) criteria were used to develop a relationship of strength versus confining pressure for each thermomechanical unit. The

relationship was developed by evaluating the Yudhbir and Hoek and Brown criteria separately and then averaging the two predicted strengths at discrete confining pressure. A power-law relationship of the form

$$\sigma_1 = A + B \sigma_3^C \quad (D-4)$$

where σ_1 = strength of the rock mass,

A , B , and C = parameters determined by curve fitting, and

σ_3 = confining stress

was then developed by fitting the resulting average strength versus confining pressure data to describe the strength-confinement response. Table D-2 presents the best-fit results.

TABLE D-2. POWER LAW CONSTANTS FOR ROCK MASS STRENGTH

Thermomechanical Unit	Rock Mass Quality Category	A	B	C
TCw	1	4.94	10.36	0.692
	2	8.07	10.28	0.712
	3	12.46	10.10	0.730
	4	26.43	9.62	0.753
	5	53.25	9.11	0.763
PTn	1	1.38	2.41	0.869
	2	1.89	2.39	0.831
	3	2.92	2.35	0.895
	4	4.26	2.30	0.907
	5	5.49	2.27	0.914
TSw1	1	0.24	4.64	0.662
	2	0.35	4.79	0.662
	3	0.63	4.99	0.668
	4	1.30	5.19	0.681
	5	2.16	5.26	0.697
TSw2	1	3.64	10.34	0.682
	2	5.94	10.33	0.700
	3	9.71	10.21	0.720
	4	23.31	9.70	0.751
	5	49.95	9.15	0.763
TSw3	1	1.59	7.27	0.671
	2	2.59	7.39	0.685
	3	3.53	7.41	0.696
	4	7.50	7.32	0.727
	5	11.70	7.17	0.744
CHn1	1	0.59	2.39	0.850
	2	1.30	2.41	0.869
	3	2.01	2.38	0.884
	4	3.76	2.31	0.905
	5	5.15	2.27	0.912

D.1.4 Rock Mass Mechanical Properties for the Elastic and Elasto-Plastic Models

The elastic and elasto-plastic models both require elastic modulus and Poisson's ratio for the rock mass. Strength criteria are also required and include tensile strength and Mohr-Coulomb strength parameters.

A correlation between RMR and rock mass elastic modulus (E) developed by Serafim and Periera (1983) was used:

$$E = 10^{\frac{(RMR-10)}{40}}, \quad (D-5)$$

where E is in GPa.

Equation D-5 predicts elastic modulus values that exceed the intact sample elastic modulus for the higher rock qualities. The calculated moduli were adjusted so that the upper bound limit of the rock mass modulus was equal to the intact rock elastic modulus.

Empirical relationships to estimate Poisson's ratio from rock mass quality are not available. The intact rock Poisson's ratios were adopted as the rock mass Poisson's ratios. The rock mass elastic modulus and Poisson's ratio derived are both included in Table D-3.

TABLE D-3. ROCK MASS ELASTIC MODULUS (GPa) AND POISSON'S RATIO FOR THE RANGE OF ROCK MASS QUALITY

Thermomechanical Unit	Poisson's Ratio	Elastic Modulus for Rock Mass Quality Category				
		1	2	3	4	5
TCw	0.17	7.66	12.20	17.71	19.90	19.90
PTn	0.23	6.00	6.00	6.00	6.00	6.00
TSw1 (lithophysae-rich)	0.16	3.48	5.24	9.21	15.50	15.50
TSw2	0.22	5.47	9.02	14.04	31.61	32.70
TSw3	0.17	7.46	11.69	15.80	15.80	15.80
CHn1	0.23	5.74	6.00	6.00	6.00	6.00

Empirical relationships to estimate rock mass tensile strength based upon rock mass quality are not available. Since joint strength and persistence are expected to be factors for limiting rock mass tensile strength, Hardy and Bauer (1991) recommended that the rock mass tensile strength be set at the value of one-half the rock mass joint cohesion, predicted using the joint persistence criteria derived for the CJM and DBM. Table D-4 lists rock mass tensile strengths calculated based on the estimated cohesion of the vertical joint set for the CJM and DBM.

TABLE D-4. ROCK MASS TENSILE STRENGTH (MPa)

Thermomechanical Unit	Rock Mass Quality Category				
	1	2	3	4	5
TCw	0.21	1.14	3.06	7.38	11.23
PTn	0.04	0.18	0.46	1.09	1.63
TSw1 (lithophysae-rich)	0.16	0.77	1.89	4.23	6.24
TSw2	0.35	1.59	3.62	7.52	10.67
TSw3	0.10	0.45	1.09	2.38	3.46
CHn1	0.11	0.47	1.01	1.92	2.61

The power law rock mass strength criteria, presented in Table D-2, were used to derive the Mohr-Coulomb strength parameters (cohesion and angle of internal friction). The strength parameters were developed from best fit between axial stress (σ_1) and confining pressure (σ_3). The expression takes the form

$$\sigma_1 = \sigma_c + N \sigma_3 \quad , \quad (D-6)$$

where σ_c = uniaxial compressive strength, and

N = confinement factor.

The parameters σ_c and N were then used to generate a Mohr-Coulomb criterion relating shear (τ) and normal stress (σ_n) on the plane of failure to the material constants of cohesion and angle of internal friction:

$$\tau = C_o + \sigma_n \tan \phi \quad , \quad (D-7)$$

where C_o = cohesion (see Equation D-8) and

$$C_o = \sigma_c / 2\sqrt{N} \quad (D-8)$$

ϕ = angle of internal friction (see Equation D-9).

$$\phi = 2(\tan^{-1} \sqrt{N} - 45^\circ) \quad (D-9)$$

The best fit was performed over the range of confining pressure from 0 to 3 MPa, which is representative of the projected range in minimum principal stresses near the boundary of the repository excavation. The nonassociated flow rule, suggested by Michelis and Brown (1986), which uses a dilation angle equal to half the internal friction angle, was considered suitable for the tuff (Hardy and Bauer, 1991). Table D-5 presents the strength parameters and dilation angle from the best-fit results.

D.1.5 Rock Mass Mechanical Properties for the Compliant Joint and Distinct Block Models

Both the CJM and DBM require definition of the geometric parameters of joint sets, the mechanical properties of the joints, and the mechanical properties of the intact blocks of rock between joints. This section discusses the methods used to develop these input parameters based upon the range in projected rock mass quality for each thermomechanical unit.

Limited oriented core data from the Tiva Canyon and Topopah Spring Members in holes USW GU-3 and USW G-4 and fracture dip data for all core in the holes USW G-1, USW G-4, USW GU-3, and UE-25a#1 were reviewed by Lin et al (1992) to define the joint geometric parameters when fracture dip occurrence was corrected for sampling bias caused by the relationship of the borehole orientation and the fracture dip (Terzaghi correction). The near vertical fractures (60° - 90° dip) were strongly dominant and averaged between 75% and 90% of all fractures measured in the Tiva Canyon, Pah Canyon, Topopah Spring, and Calico Hills Members. The existence of a consistent set of low-angle dips (0° - 30°) has been proposed and would average 5% to 15% of all fractures measured for the four geologic members. Further characterization of the Yucca Mountain site may show the fracture at low dips to be random, but the estimated properties of the low dip joints were developed for completeness of the data.

TABLE D-5. STRENGTH PARAMETERS AND DILATION ANGLES FOR THE MOHR-COULOMB CRITERION

Thermomechanical Unit	Rock Mass Quality Category	Mohr-Coulomb		
		Cohesion (MPa)	Angle of Internal Friction (ϕ)	Dilation Angle ($\phi/2$)
TCw	1	1.4	49	24
	2	1.9	49	24
	3	2.7	49	25
	4	5.3	49	24
	5	10.5	48	24
PTn	1	0.6	20	10
	2	0.7	20	10
	3	1.1	20	10
	4	1.5	20	10
	5	2.0	20	10
TSw1 (lithophysae-rich)	1	0.4	30	15
	2	0.4	31	15
	3	0.5	32	16
	4	0.7	33	17
	5	0.9	34	17
TSw2	1	1.1	48	24
	2	1.5	49	24
	3	2.2	49	25
	4	4.7	49	24
	5	9.9	48	24
TSw3	1	0.8	41	20
	2	1.0	42	21
	3	1.2	42	21
	4	2.0	43	21
	5	2.9	43	21
CHn1	1	0.3	19	10
	2	0.5	20	10
	3	0.8	20	10
	4	1.4	20	10
	5	1.9	20	10

Each of the thermomechanical units is addressed in the following sections except CHn1 where the total number of fractures measured was small and was estimated to be near one occurrence per 5 m of core log by Lin et al (1992). On the basis of this, application of the jointed models would not be required for CHn1.

Joint spacings for each rock mass quality category were required as part of the CJM and DBM. This was achieved using the equation proposed by Hudson and Priest (1979) to relate total joint frequency to RQD:

$$RQD = 100e^{-0.1\lambda}(0.1\lambda + 1) \quad , \quad (D-10)$$

where λ = total joint frequency.

The total joint frequencies for each of the five rock mass quality categories were obtained using the RQDs developed in Lin et al (1992) and the Equation D-10. The percentages of occurrence for high-angle (60° - 90°) and low-angle (0° - 30°) dips were developed in Lin et al (1992) (Table 3-3), and were then used to derive the vertical and horizontal joint set frequencies by taking the calculated total joint frequencies and multiplying them by the percentages of occurrence for each set.

Estimation of joint frequency using RQD assumes that joints are the primary factor in determining RQD. This assumption appears valid for the welded tuff units. However, for the PTn, application of Equation D-10 produced total joint frequencies ranging between 10.4 and 24.9 m⁻¹, which was considerably higher than the total fracture frequency (3.18 m⁻¹) in the core logging data. In this case, RQD was more a function of general rock competence and was influenced by lost core and rubble zones. The range of total fracture frequency for the PTn was therefore set at 1.94 to 3.18 m⁻¹, which corresponds to the vertical fracture and total fracture frequencies, respectively. Fracture frequency for PTn was assumed to vary uniformly for this range for assignment to each rock mass quality category.

The total joint frequencies, high-angle and low-angle joint set percentages, and the horizontal and vertical joint spacings for each thermomechanical unit are presented in Table D-6.

The Mohr-Coulomb strength parameters (cohesion and angle of friction) are developed to describe the joint strength. In practice, many joints are discontinuous, requiring both failure of intact material at the termination of joints and slip along existing joints for large-scale displacements to occur. A simple method to approximate the strength of a discontinuous joint, proposed by Hardy and Bauer (1991) is to develop effective strength parameters for the joint that are equal to the length-weighted averages of the joint and intact material. The effective strength parameters are described by the following equations:

$$c_j^e = \chi c_j + (1 - \chi)c_r, \text{ and} \quad (D-11)$$

$$\phi_j^e = \chi \phi_j + (1 - \chi)\phi_r, \quad (D-12)$$

where χ = continuity of the joint,

c = cohesion,

ϕ = friction angle,

j = subscript refers to joint properties,

r = subscript refers to intact rock properties, and

e = superscript denoting effective cohesion or friction angle.

The continuities of joints (χ) for the Yucca Mountain site have been estimated based on traces of joints in photographs of excavations in the TSw2 (Hardy and Bauer, 1991). The continuity of vertical fractures (χ_v) ranging from 0.50 to 1.00 and the continuity of horizontal fractures (χ_h) ranging from 0 to 0.50 were derived in the preliminary application of the Drift Design Methodology. The resulting joint effective strength parameters are listed in Table D-7.

The half-closure stress (A_n) and maximum joint closure (u_{max}) are parameters used to describe normal joint stiffness; elastic shear stiffness (G_s) and hardening stiffness (G_s') are the parameters used to characterize the joint shear deformation. The ranges of values for these parameters estimated from laboratory tests were used to generate the joint stiffness for five rock mass quality categories. Values for the five rock mass qualities are selected assuming uniform distribution within the ranges. Parameters which produced more joint deformations were associated with lower rock mass quality. The parameters developed for the joint stiffness are listed in Table D-8.

TABLE D-6. SUMMARY OF CALCULATION OF ORTHOGONAL JOINT SET SPACINGS

Thermomechanical Unit	Rock Mass Quality Category	Total Joint Frequency (m ⁻¹)	Horizontal Joint Set Percentage	Vertical Joint Set Percentage	Horizontal Joint Set Frequency (m ⁻¹)	Vertical Joint Set Frequency (m ⁻¹)	Horizontal Joint Set Spacing (m)	Vertical Joint Set Spacing (m)
TCw	1	22.60	10.82	79.20	2.45	17.90	0.41	0.06
	2	16.80	10.82	79.20	1.82	13.31	0.55	0.08
	3	12.90	10.82	79.20	1.40	10.22	0.72	0.10
	4	8.00	10.82	79.20	0.87	6.34	1.16	0.16
	5	4.70	10.82	79.20	0.51	3.72	1.97	0.27
PTn	1	3.12	14.99	75.23	0.47	2.35	2.14	0.43
	2	2.93	14.99	75.23	0.44	2.21	2.28	0.45
	3	2.68	14.99	75.23	0.40	2.02	2.49	0.50
	4	2.31	14.99	75.23	0.35	1.74	2.89	0.57
	5	2.06	14.99	75.23	0.31	1.55	3.23	0.64
TSw1 (lithophysae-rich)	1	38.90	7.20	87.37	2.80	33.99	0.36	0.03
	2	27.50	7.20	87.37	1.98	24.03	0.51	0.04
	3	18.10	7.20	87.37	1.30	15.81	0.77	0.06
	4	9.90	7.20	87.37	0.71	8.65	1.40	0.12
	5	5.30	7.20	87.37	0.38	4.63	2.62	0.22
TSw2	1	32.90	5.01	90.63	1.65	29.82	0.61	0.03
	2	26.40	5.01	90.63	1.32	23.93	0.76	0.04
	3	19.90	5.01	90.63	1.00	18.04	1.00	0.06
	4	13.20	5.01	90.63	0.66	11.96	1.51	0.08
	5	7.10	5.01	90.63	0.36	6.43	2.81	0.16
TSw3	1	20.60	5.48	89.71	1.13	18.48	0.89	0.05
	2	14.30	5.48	89.71	0.78	12.83	1.28	0.08
	3	12.10	5.48	89.71	0.66	10.85	1.51	0.09
	4	8.00	5.48	89.71	0.44	7.18	2.28	0.14
	5	5.60	5.48	89.71	0.31	5.02	3.26	0.20

TABLE D-7. WEIGHTED AVERAGE JOINT STRENGTH USED FOR THE CJM

Thermomechanical			Rock Mass Quality Category				
Unit			1	2	3	4	5
Horizontal Joint Set	TCw	c (MPa)	18.9	21.6	25.2	30.6	34.2
		ϕ (°)	41	42	43	43	42
	PTn	c (MPa)	6.3	7.2	8.4	10.2	11.4
		ϕ (°)	24	22	20	16	13
	TSw1 (lithophysae-rich)	c (MPa)	3.2	3.6	4.2	5.1	5.7
		ϕ (°)	25	24	22	18	15
	TSw2	c (MPa)	18.9	21.6	25.2	30.6	34.2
		ϕ (°)	41	42	43	43	42
	TSw3	c (MPa)	6.3	7.2	8.4	10.2	11.4
		ϕ (°)	40	41	42	42	42
Vertical Joint Set	CHn1 [†]	c (MPa)	6.3	7.2	8.4	10.2	11.4
		ϕ (°)	24	22	20	16	13
	TCw	c (MPa)	0.9	3.6	7.3	12.7	16.3
		ϕ (°)	41	43	46	48	49
	PTn	c (MPa)	0.3	1.2	2.4	4.3	5.5
		ϕ (°)	37	36	36	33	31
	TSw1 (lithophysae-rich)	c (MPa)	0.2	0.6	1.3	2.2	2.8
		ϕ (°)	37	37	36	34	32
	TSw2	c (MPa)	0.9	3.6	7.3	12.7	16.3
		ϕ (°)	41	43	46	48	49
Vertical Joint Set	TSw3	c (MPa)	0.3	1.2	2.5	4.3	5.5
		ϕ (°)	39	41	44	46	47
	CHn1 [†]	c (MPa)	0.3	1.2	2.4	4.3	5.5
		ϕ (°)	37	36	36	33	31

[†] Derived for calculation of rock mass tensile strength for elasto-plastic model

TABLE D-8. CJM JOINT STIFFNESS PROPERTIES

Thermomechanical		Rock Mass Quality Category				
Unit		1	2	3	4	5
TCw	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
PTn	u_{max} (m)	2.50E-05	2.10E-05	1.78E-05	1.16E-05	7.46E-06
	A_n (MPa)	1.28	1.52	1.84	2.32	2.64
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
TSw1 (lithophysae-rich)	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
TSw2	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05
TSw3	u_{max} (m)	3.44E-05	2.94E-05	2.28E-05	1.29E-05	6.30E-06
	A_n (MPa)	0.58	0.80	1.10	1.55	1.85
	G_s (MPa/m)	5.10E+04	2.01E+05	4.01E+05	7.00E+05	9.00E+05

The size effect of intact block strength for the welded tuff in the Topopah Spring Member was determined by Price (1986). A power law best-fit result was reported as

$$\sigma_c = 1944 D^{-0.846} + 69.5 \quad , \quad (D-13)$$

where σ_c = uniaxial compressive strength (MPa) and

D = sample diameter (mm).

This size effect was assumed to be a valid expression for estimating the compressive strength of intact blocks for all the densely welded thermomechanical units. The strengths of the block were calculated by the size-strength relationship in Equation D-13 using the spacing of vertical joints as the intact block size. For nonwelded units, the laboratory strength values were used without any size effect because no correlation has been developed. Table D-9 lists the block strength for each rock mass quality category.

TABLE D-9. ESTIMATED STRENGTH OF INTACT BLOCKS USED FOR THE CJM (MPa)

Unit	Rock Mass Quality Category				
	1	2	3	4	5
TCw	134	120	110	96	87
PTn	11	26	26	26	26
TSw1 (lithophysae-rich)	16	16	16	16	16
TSw2	161	152	135	115	97
TSw3	52	52	52	52	52

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