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Repository Design Long-Term Monitoring Programs

KRMC Training Program

Module 7: Classification, Conceptual Design, and Management of Nuclear Waste Disposal Facilities

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Outline

- Long-Term Performance Monitoring
- Site Investigation
  - Understanding ground behavior
    - During construction
    - During repository operations
    - Long-term (until repository closure and beyond)
  - In-situ Testing
  - Rock mass classifications
  - Estimating rock mass properties

Outline (continued)

- Drift design methodology
- Ground control at Yucca Mountain
- Drift degradation analyses at Yucca Mountain
- Performance confirmation

Long-Term Performance Monitoring

- Establish baseline characteristics of the repository site
  - Initial site characterization activities
  - Performance monitoring during tunnel construction
  - Tunnel design confirmation
- Long-term performance confirmation requires knowledge of the baseline characteristics to evaluate monitoring data.

Site Investigation

- Rock mechanics
  - Borehole investigations
  - Rock movements in tunnels
    - Tunnel response with convergence measurements
    - Rock displacements using extensometers
  - Geologic and geotechnical mapping
  - Stress changes
  - Rock damage
  - Loads in support structures
- Hydrology and hydrogeology
- Geochemistry

Site Investigation

- **Repository site characterization is the initial phase of performance confirmation.**
- **The data collected from site characterization studies provide the performance confirmation baseline to evaluate long-term monitoring data.**

Basis for In Situ Testing

- **The problem of safe disposal of high-level radioactive waste is complex and requires an explicitly stated methodology to link the various aspects of design and identify specific data requirements needed to specify an in situ testing program.**
- **The methodology for repository development includes clearly defining the objectives, constraints, and issues.**

Basis for In Situ Testing

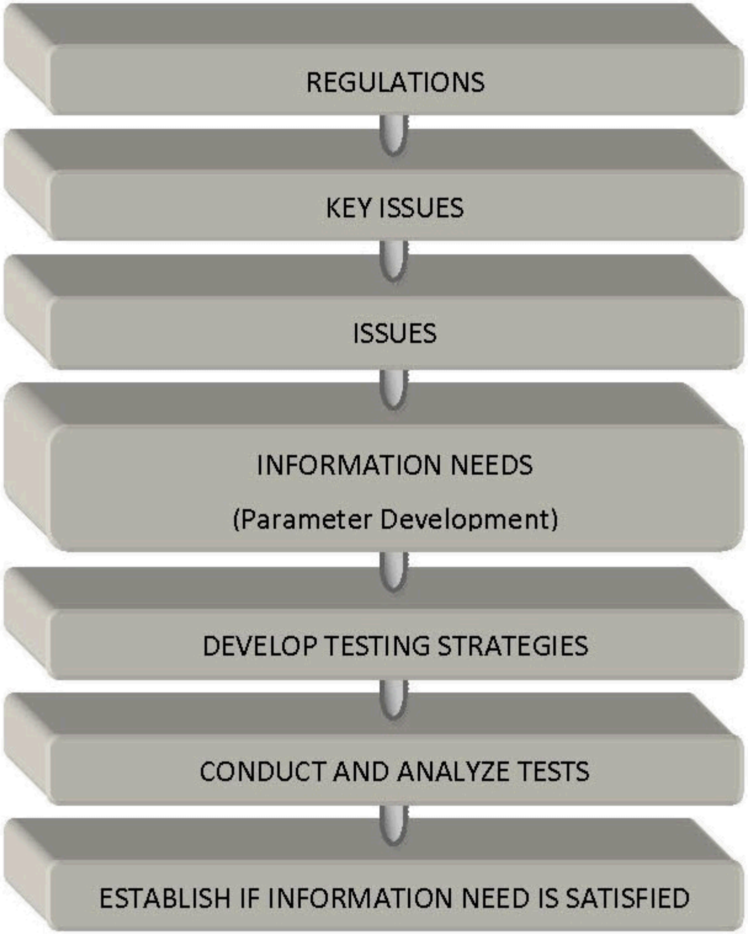
- **An analysis of features, events, and processes (FEPs) is part of the repository methodology and contributes to identifying in situ testing requirements.**
- **In order to effectively use performance assessment to evaluate a disposal system, three inputs are necessary:**
  1. **What can happen to the disposal system?**
  2. **What are the chances of it happening?**
  3. **What are the consequences if it happens?**
- **The answers to these questions are derived from many sources, including field studies and experiments.**
- **The information used in performance assessment is described in terms of *features* of the disposal system that can be used to describe its isolation capability, *events* that can affect the disposal system, and *processes* that are reasonably expected to act on the disposal system.**

Basis for In Situ Testing

- **Federal regulations impose key constraints, or criteria, that must be addressed.**
- **The issues are those problems areas that must be resolved to fulfill the objectives.**
- **The quantity and quality of information needed must be justified according to its contribution toward issue resolution.**

Basis for In Situ Testing

- Board (1989) suggests an "issues hierarchy" approach and identifies four key issues:
  - postclosure performance
  - preclosure radiologic safety
  - environmental quality
  - preclosure performance.
- Sufficient information to resolve each issue is all that is required.



Information Needs

- **The information needs are derived from what is required to resolve issues and analyze FEPs.**
- **Examples:**
  - **The need for a detailed geotechnical description of the candidate site including the overlying stratigraphy**
  - **The need to verify codes predicting the thermal and mechanical response of the rock mass**
  - **The need to assess the impact to the disturbed rock zone around the disposal room as a result of heating the rock mass**
  - **The need to assess the effectiveness of a shaft seal system.**

Information Needs

Broad Issue	Information Need	In Situ Test
A detailed geotechnical description of the candidate site including the overlying stratigraphy	1. Examine lateral and vertical variability of the rock 2. Determine in situ stress state 3. Determine fault locations and geologic/ geotechnical/hydrologic characteristics of host rock and overlying strata 4. Define a thermomechanical constitutive model for the host rock 5. Determine a range of in situ rock properties, including: a. thermal conductivity, rock specific heat, thermal expansion coefficient b. deformation modulus, Poisson's ratio c. strength properties of intact rock d. strength properties of rock mass e. creep properties	a, b, c, d, e
Verification of codes predicting the thermal and mechanical response of the rock mass	1. Determine suitable numerical models to be used in design and performance assessment 2. Determine the confidence level which the code can be used for prediction of preclosure thermomechanical response	a, e, f, g, h, i

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Information Needs

Broad Issue	Information Need	In Situ Test
Assessment of the impact to the disturbed rock zone around the disposal room as a result of heating the rock mass	1. Determine extent and properties of the disturbed zone under heated conditions 2. Determine fracture healing characteristics under heated conditions	a, c, d, f, h
Assessment of the effectiveness of a shaft seal system	1. Determine the permeability of seal materials 2. Determine the thermomechanical response of seal materials and bulkheads in the laboratory and in situ under repository conditions	j

In Situ Tests:

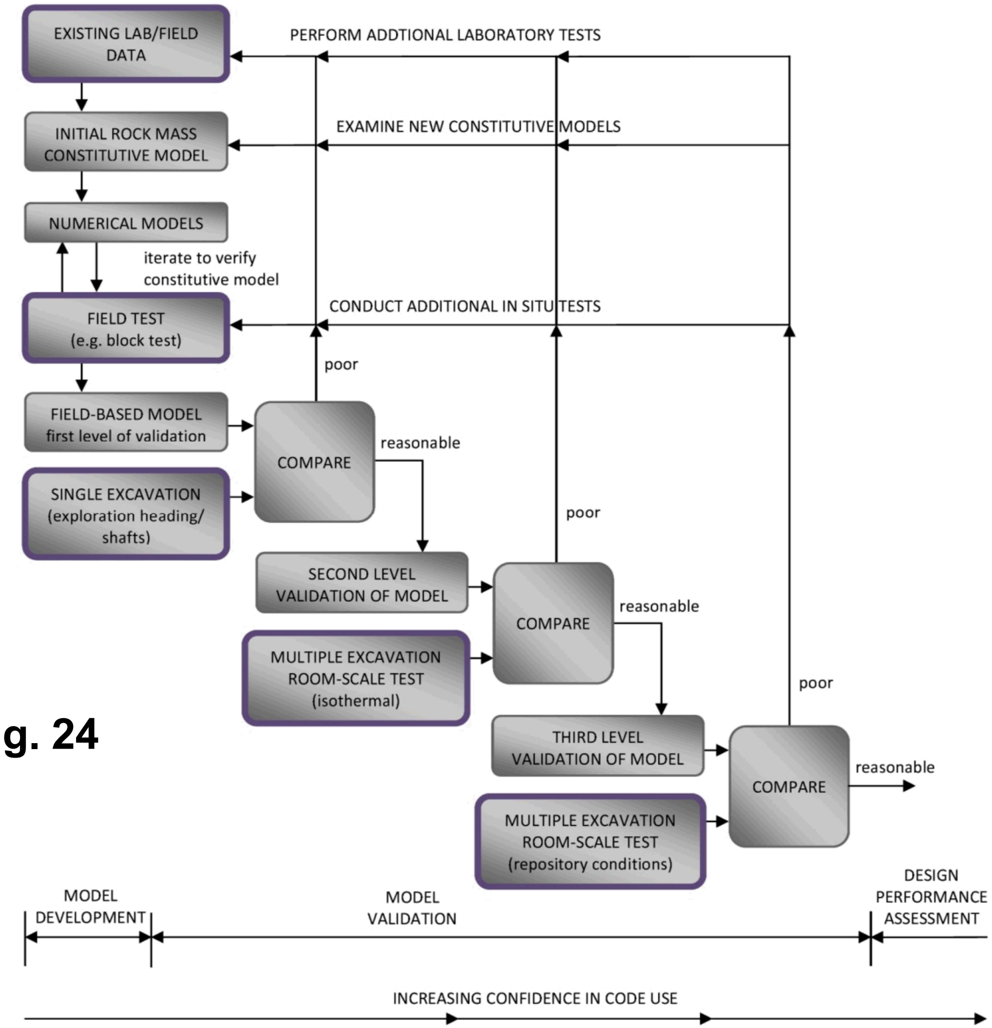
(a) *geotechnical mapping, geophysical surveys*
(b) *in situ stress measurement*
(c) *microseismic monitoring*
(d) *permeability measurement*
(e) *controlled in situ compression test (e.g. heated block)*
(f) *single heading excavation test/measurement of displacement response*
(g) *multiple excavation test – non-thermal*
(h) *multiple excavation test – thermal*
(i) *full-scale heater test*
(j) *seal testing.*

Source: Board 1989, Table 5

Testing Methodology

- An iterative-type approach for in situ testing as recommended by Board (1989, Section 5) is suggested for developing a high-level nuclear waste repository.
- This approach relies on numerical models because empirical data from actual repository thermal loading does not exist.
- The iterative approach addresses information needs through the in situ determination of thermal, mechanical, and hydrologic properties of rock.
- The methodology provides for the development of full-scale repository openings to evaluate the thermomechanical response of the rock mass under anticipated repository conditions.
- Using this approach, the in situ testing confirms the predictive ability of repository models and provides a range of expected parameters and rock mass response.

Testing Methodology



Source: Board 1989, Fig. 24

Rock Mass Classification

- Rock mass classifications form the backbone of the empirical design approach and are widely used in rock engineering.
- Rock mass classifications provide
  - A quantitative assessment of rock mass conditions
  - Support requirements
  - Basis for assessment of rock mass properties

Rock Mass Classification

- The most widely used systems are
  - Rock Mass Rating (RMR) System (also known as the Geomechanics Classification) developed by Prof. Z.T. Bieniawski
  - Q-System developed by Dr. Nick Barton and others at the Norwegian Geotechnical Institute

RMR System

- **The RMR system uses 6 parameters to classify a rock mass**
  - **Uniaxial compressive strength of the rock mass (*C*)**
  - **Rock quality designation (RQD_i)**
  - **Spacing of discontinuities (*JS*)**
  - **Condition of discontinuities (*JC*)**
  - **Groundwater conditions (*JW’*)**
  - **Orientation of discontinuities (*JO*)**

$$\mathrm{RMR} = C + RQD_i + JS + JC + JW' + JO$$

- **The value of RMR increases with rock quality from 0 to 100**

RMR System

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Ranges of Values						
1	Strength of intact rock material	Point-load strength index (MPa)	>10	4–10	2–4	1–2	For this low range, uniaxial compressive test is preferred		
		Uniaxial compressive strength (MPa)	>250	100–250	50–100	25–50	5–25	1–5	<1
	Rating		15	12	7	4	2	1	0
2	Drill core quality RQD (%)		90–100	75–90	50–75	25–50	<25		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		>2 m	0.6–2 m	200–600 mm	60–200 mm	<60 mm		
	Rating		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 wall	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	Groundwater	Inflow per 10 m tunnel length (L/min)	None	<10	10–25	25–125	>125		
			or	or	or	or	or		
		Ratio $\frac{\text{Joint water pressure}}{\text{Major principal stress}}$	0	<0.1	0.1–0.2	0.2–0.5	>0.5		
			or	or	or	or	or		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

RMR System

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS

Strike and Dip Orientations of Discontinuities		Very Favorable	Favorable	Fair	Unfavorable	Very Unfavorable
Ratings	Tunnels and mines	0	−2	−5	−10	−12
	Foundations	0	−2	−7	−15	−25
	Slopes	0	−5	−25	−50	−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	20 yr for 15-m span	1 yr for 10-m span	1 wk for 5-m span	10 h for 2.5-m span	30 min for 1-m span
Cohesion of the rock mass (kPa)	>400	300−400	200−300	100−200	<100
Friction angle of the rock mass (deg)	>45	35−45	25−35	15−25	<15

Source: Bieniawski 1989, Table 4-1

RMR System

CHART E Guidelines for Classification of Discontinuity Conditions[a]

Parameter	Ratings				
Discontinuity length (persistence/continuity)	<1 m	1–3 m	3–10 m	10–20 m	>20 m
	6	4	2	1	0
Separation (aperture)	None	<0.1 mm	0.1–1.0 mm	1–5 mm	>5 mm
	6	5	4	1	0
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided
	6	5	3	1	0
		Hard filling		Soft filling	
Infilling (gouge)	None	<5 mm	>5 mm	<5 mm	>5 mm
	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
	6	5	3	1	0

[a] *Note:* Some conditions are mutually exclusive. For example, if infilling is present, it is irrelevant what the roughness may be, since its effect will be overshadowed by the influence of the gouge.

Source: Bieniawski 1989, Chart E

RMR System

Effect of Discontinuity Strike and Dip Orientations in Tunneling

Strike Perpendicular to Tunnel Axis			
Drive with Dip		Drive against Dip	
Dip 45–90	Dip 20–45	Dip 45–90	Dip 20–45
Very favorable	Favorable	Fair	Unfavorable

Strike Parallel to Tunnel Axis		Irrespective of Strike
Dip 20–45	Dip 45–90	Dip 0–20
Fair	Very unfavorable	Fair

Source: Bieniawski 1989, Table 4-2

RMR System

Guidelines for Excavation and Support of Rock Tunnels in Accordance with the Rock Mass Rating System[a]

Rock Mass Class	Excavation	Support: Rock Bolts (20-mm Dia, Fully Grouted)	Support: Shotcrete	Support: Steel Sets
Very good rock I RMR:81–100	Full face 3-m advance	Generally, no support required except for occasional spot bolting		
Good rock II RMR:61–80	Full face 1.0–1.5-m advance Complete support 20 m from face	Locally, bolts in crown 3 m long, spaced 2.5 m, with occasional wire mesh	50 mm in crown where required	None
Fair rock III RMR: 41–60	Top heading and bench 1.5–3-m advance in top heading Commence support after each blast Complete support 10 m from face	Systematic bolts 4 m long, spaced 1.5–2 m in crown and walls with wire mesh in crown	50–100 mm in crown and 30 mm in sides	None
Poor rock IV RMR: 21–40	Top heading and bench 1.0–1.5-m advance in top heading. Install support concurrently with excavation 10 m from face	Systematic bolts 4–5 m long, spaced 1–1.5 m in crown and wall with wire mesh	100–150 mm in crown and 100 mm in sides	Light to medium ribs spaced 1.5 m where required
Very poor rock V RMR: <20	Multiple drifts 0.5–1.5-m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after blasting	Systematic bolts 5–6 m long, spaced 1–1.5 m in crown and walls with wire mesh. Bolt invert	150–200 mm in crown, 150 mm in sides, and 50 mm on face	Medium to heavy ribs spaced 0.75 m with steel lagging and fore-poling if required. Close invert

[a] Shape: horseshoe; width: 10 m; vertical stress: <25 MPa; construction: drilling and blasting.

Source: Bieniawski 1989, Table 4-4

Q-System

- **The Q-system uses 6 parameters to classify a rock mass**
  - **Rock quality designation (*RQD*)**
  - **Number of joint sets (J_n)**
  - **Roughness of the most unfavorable joint or discontinuity (J_r)**
  - **Degree of alteration or filling along the weakest joint (J_a)**
  - **Water inflow (J_w)**
  - **Stress condition, or stress reduction factor (*SRF*)**

$$Q = \frac{RQD}{J_n} \bullet \frac{J_r}{J_a} \bullet \frac{J_w}{SRF}$$

- **The value of Q increases with rock quality from 0.001 to 1000 on a logarithmic scale**

Q-System Parameter Assessment

Q-System Description and Ratings: Parameters RQD, J_n, J_r, J_a, SRF, and J_w[a]

Rock Quality Designation (RQD)

Very poor	0–25	*Note:*
Poor	25–50	(i) Where RQD is reported or measured as ≤10 (including 0), a nominal value of 10 is used to evaluate *Q*.
Fair	50–75	
Good	75–90	
Excellent	90–100	(ii) RQD intervals of 5, i.e., 100, 95, 90, etc., are sufficiently accurate

Joint Set Number J_n

Massive, none or few joints	0.5–1.0	*Note:*
One joint set	2	(i) For intersections, use ($3.0 \times J_n$)
One joint set plus random	3	
Two joint sets	4	(ii) For portals, use ($2.0 \times J_n$)
Two joint sets plus random	6	
Three joint sets	9	
Three joint sets plus random	12	
Four or more joint sets, random, heavily jointed, "sugar cube," etc.	15	
Crushed rock, earthlike	20	

Joint Roughness Number J_r

(a) Rock wall contact and		*Note:*
(b) Rock wall contact before 10-cm shear		(i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m
Discontinuous joint	4	
Rough or irregular, undulating	3	

Q-System Parameter Assessment

Smooth, undulating	2.0
Slickensided, undulating	1.5
Rough or irregular, planar	1.5
Smooth, planar	1.0[b]
Slickensided, planar	0.5
(c) No rock wall contact when sheared	
Zone containing clay minerals thick enough to prevent rock wall contact	1.0[b]
Sandy, gravelly, or crushed zone thick enough to prevent rock wall contact	1.0[b]

Note:
(ii) $J_r = 0.5$ can be used for planar slickensided joints having lineation, provided the lineations are favorably oriented
(iii) Descriptions B to G refer to small-scale features and intermediate-scale features, in that order

Joint Alteration Number J_a

(a) Rock wall contact	J_a	ϕ_r (approx)
A. Tightly healed, hard, nonsoftening, impermeable filling, i.e., quartz or epidote	0.75	
B. Unaltered joint walls, surface staining only	1.0	25–35°
C. Slightly altered joint walls. Nonsoftening 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, and 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-cm shear		
F. Sandy particles, clay-free disintegrated rock, etc.	4.0	25–30°

Q-System Parameter Assessment

Joint Alteration Number J_a

G. Strongly over-consolidated, nonsoftening clay mineral fillings (continuous, <5 mm in thickness)	6.0	16–24°
H. Medium or low over-consolidation, softening, clay mineral fillings. (continuous, <5 mm in thickness)	8.0	12–16°
J. Swelling clay fillings, i.e., montmorillonite (continuous, < mm in thickness). Value of J_a depends on percentage of swelling clay-sized particles, and access to water, etc.	8.0–12.0	6–12°
(c) No rock wall contact when sheared		
K. 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°
L. Zones or bands of silty or sandy clay, small clay fraction (nonsoftening)	5.0	
M. 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°

Note:

(i) Values of ϕ_r are intended as an approximate guide to the mineralogical properties of the alteration products, if present

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Q-System Parameter Assessment

Stress Reduction Factor (SRF)

(a) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated			
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
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			
	σ_c/σ_1	σ_t/σ_1	
H. Low stress, near surface	>200	>13	2.5
J. Medium stress	200–10	13–0.66	1.0

Note:

(i) Reduce these SRF values by 25–50% if the relevant shear zones only influence but do not intersect the excavation

(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 σ_c and 0.8 σ_t; when $\sigma_1/\sigma_3 > 10$, reduce σ_c and σ_t to

Q-System Parameter Assessment

Stress Reduction Factor (SRF)

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	0.6 σ_c and 0.6 σ_t (where σ_c = unconfined compressive strength, σ_t = tensile strength (point load), σ_1 and σ_3 = major and minor principal stresses)
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	
O. Heavy squeezing rock pressure			10−20	(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)
(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	

Q-System Parameter Assessment

Joint Water Reduction Factor J_w

	J_w	Approximate water pressure (kg/cm^2)
A. Dry excavations or minor inflow, i.e.,		
B. 5 L/min locally	1.0	<1
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

Note:
(i) Factors C–F are crude estimates. Increase J_w if drainage measures are installed

(ii) Special problems caused by ice formation are not considered

[a] After Barton et al. (1974).
[b] Nominal.

Q-System Excavation Support Ratio (ESR)

Excavation Category	ESR
A. Temporary mine openings	3–5
B. Vertical shafts:	
Circular section	2.5
Rectangular/square section	2.0
C. Permanent mine openings, water tunnels for hydropower (excluding high-pressure penstocks), pilot tunnels, drifts, and headings for large excavations	1.6
D. Storage caverns, water treatment plants, minor highway and railroad tunnels, surge chambers, access tunnels	1.3
E. Power stations, major highway or railroad tunnels, civil defense chambers, portals, intersections	1.0
F. Underground nuclear power stations, railroad stations, factories	0.8

Q-System Ground Support Guidelines

Q-System: Support Measures for *Q* Range 10 to 1000[a]

Support Category	*Q*	Conditional Factors RQD/J_n	J_r/J_n	Span/ESR (m)	P^b (kg/cm^2)	Span/ESR (m)	Type of Support [c]	Notes
1	1000–400				<0.01	20–40	sb (utg)	
2	1000–400				<0.01	30–60	sb (utg)	
3	1000–400				<0.01	46–80	sb (utg)	
4	1000–400				<0.01	65–100	sb (utg)	
5	400–100				0.05	12–30	sb (utg)	
6	400–100				0.05	19–45	sb (utg)	
7	400–100				0.05	30–65	sb (utg)	
8	400–100				0.05	48–88	sb (utg)	
9	100–40	⩾20			0.25	8.5–19	sb (utg)	
		<20					B (utg) 2.5–3 m	
10	100–40	⩾30			0.25	14–30	B (utg) 2–3 m	
		<30					B (utg) 1.5–2 m + clm	
11	100–40	⩾30			0.25	23–48	B (tg) 2–3m	
		<30					B (tg) 1.5–2 m + clm	
12	100–40	⩾30			0.25	40–72	B (tg) 2–3m	
		<30					B (tg) 1.5–2 m + clm	

Q-System Ground Support Guidelines

Support Category	Q	Conditional Factors RQD/J_n	J_r/J_n	Span/ESR (m)	P^b (kg/cm^2)	Span/ESR (m)	Type of Support [c]	Notes
13	40–10	≥10	≥1.5		0.5	5–14	sb (utg)	I
		≥10	<1.5				B (utg) 1.5–2 m	I
		<10	≥1.5				B (utg) 1.5–2 m	I
		<10	<1.5				B (utg) 1.5–2 m + S 2–3 cm	I
14	40–10	≥10		≥15	0.5	9–23	B (tg) 1.5–2 m + clm	I, II
		<10		≥15			B (tg) 1.5–2 m + S (mr) 5–10 cm	I, II
				<15			B (utg) 1.5–2 m + clm	I, III
15	40–10	>10			0.5	15–40	B (tg) 1.5–2 m + clm	I, II, IV
		≤10					B (tg) 1.5–2 m + S (mr) 5–10 cm	I, II, IV
16 [d]	40–10	>15			0.5	30–65	B (tg) 1.5–2 m + clm	I, V, VI
		≤15					B (tg) 1.5–2 m + S (mr) 10–15 cm	I, V, VI

Q-System Ground Support Guidelines

Q-System: Support Measures for Q Range 1 to 10[a]

Support Category	Q	Conditional Factors: RQD/J_n	Conditional Factors: J_r/J_a	Span/ESR (m)	P^b (kg/cm^2)	Span/ESR (m)	Type of Support [c]	Notes
17	10–4	>30			1.0	3.5–9	sb (utg)	I
		≥10, ≤30					B (utg) 1–1.5 m	I
		<10		≥6			B (utg) 1–1.5 m + S 2–3 cm	I
		<10		<6			S 2–3 cm	I
18	10–4	>5		≥10	1.0	7–15	B (tg) 1–1.5 m + clm	I, III
		>5		<10			B (utg) 1–1.5 m + clm	I
		≤5		≥10			B (tg) 1–1.5 m + S 2–3 cm	I, III
		≤5		<10			B (utg) 1–1.5 m + S 2–3 cm	I
19	10–4			≥20	1.0	12–29	B (tg) 1–2 m + S (mr) 10–15 cm	I, II, IV
				<20			B (tg) 1–1.5 m + S (mr) 5–10 cm	I, II
20[d]	10–4			≥35	1.0	24–52	B (tg) 1–2 m + S (mr) 20–25 cm	I, V, VI
				<35			B (tg) 1–2 m + S (mr) 10–20 cm	I, II, IV
21	4–1	≥12.5	≤0.75		1.5	2.1–6.5	B (utg) 1m + S 2–3 cm	I
		<12.5	<0.75				S 2.5–5 cm	I
			>0.75				B (utg) 1m	I
22	4–1	>10, <30	>1.0		1.5	4.5–11.5	B (utg) 1m + clm	I
		≤10	>1.0				S 2.5–7.5 cm	I
		<30	≤1.0				B (utg) 1 m + S (mr) 2.5–5 cm	I
		≥30					B (utg) 1 m	I
23	4–1			≥15	1.5	8–24	B (tg) 1–1.5 m + S (mr) 10–15 cm	I, II, IV, VII
				<15			B (utg) 1–1.5 m + S (mr) 5–10 m	I
24[d]	4–1			≥30	1.5	18–46	B (tg) 1–1.5 m + S (mr) 15–30 cm	I, V, VI
				<30			B (tg) 1–1.5 m + S (mr) 10–15 cm	I, II, IV

Q-System Ground Support Guidelines

Q-System: Support Measures for Q Range 0.1 to 1.0[a]

Support Category	Q	Conditional Factors RQD/J_n	Conditional Factors J_r/J_a	Span/ESR (m)	P^b (kg/cm^2)	Span/ESR (m)	Type of Support[c]	Notes
25	1.0–0.4	>10	>0.5		2.25	1.5–4.2	B (utg) 1 m + mr or clm	I
		≤10	>0.5				B (utg) 1 m + S (mr) 5 cm	I
			≤0.5				B (tg) 1 m + S (Mr) 5 cm	I
26	1.0–0.4				2.25	3.2–7.5	B (tg) 1 m + S (mr) 5–7.5 cm	VIII, X, XI
							B (utg) 1 m + S 2.5–5 cm	I, IX
27	1.0–0.4			≥12	2.25	6–18	B (tg) 1 m + S (mr) 7.5–10 cm	I, IX
				<12			B (utg) 1 m + S (mr) 5–7.5 cm	I, IX
				>12			CCA 20–40 cm + B (tg) 1 m	VIII, X, XI
				<12			S (mr) 10–20 cm + B (tg) 1 m	VIII, X, XI
28[d]	1.0–0.4			≥30	2.25	15–38	B (tg) 1 m + S (mr) 30–40 cm	I, IV, V, IX
				≥20, <30			B (tg) 1 m + S (mr) 20–30 cm	I, II, IV, IX
				<20			B (tg) 1m + S (mr) 15–20 cm	I, II, IX
							CCA (sr) 30–100 cm + B (tg) 1 m	IV, VIII, X, XI
29	0.4–0.1	>5	>0.25		3.0	1.0–3.1	B (utg) 1 m + S 2–3 cm	
		≤5	>0.25				B (utg) 1 m + S (mr) 5 cm	
			≤0.25				B (tg) 1 m + S (Mr) 5 cm	
30	0.4–0.1	≥5			3.0	2.2–6	B (tg) 1 m + S 2.5–5 cm	IX
		<5					S (mr) 5–7.5 cm	IX
							B (tg) 1 m + S (mr) 5–7.5 cm	VIII, X, XI
31	0.4–0.1	>4			3.0	4–14.5	B (tg) 1 m + S (mr) 5–12.5 cm	IX
		≤4, ≥1.5					S (mr) 7.5–25 cm	IX
		<1.5					CCA 20–40 cm + B (tg) 1 m	IX, XI
							CCA (sr) 30–50 cm + B (tg) 1 m	VIII, X, XI
32[d]	0.4–0.1			≥20	3.0	11–34	B (tg) 1 m + S (mr) 40–60 cm	II, IV, IX, XI
				<20			B (tg) 1 m + S (mr) 20–40 cm	III, IV, IX, XI

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Q-System Ground Support Guidelines

Q-System: Support Measures for Q Range 0.001 to 0.1[a]

Support Category	Q	Conditional Factors RQD/J_n	J_r/J_a	Span/ESR (m)	P^b (kg/cm^2)	Span/ESR (m)	Type of Support[c]	Notes
33	0.1–0.01	≥2			6	1.0–3.9	B (tg) 1 m + S (mr) 2.5–5 cm	IX
		<2					S (mr) 5–10 cm	IX
							S (mr) 7.5–15 cm	VIII, X
34	0.1–0.01	≥2	≥0.25		6	2.0–11	B (tg) 1 m + S (mr) 5–7.5 cm	IX
		<2	≥0.25				S (mr) 7.5–15 cm	IX
			<0.25				S (mr) 15–25 cm	IX
							CCA (sr) 20–60 cm + B (tg) 1 m	VIII, X, XI
35[d]	0.1–0.01			≥15	6	6.2–28	B (tg) 1 m + S (mr) 30–100 cm	II, IX, XI
				≥15			CCA (sr) 60–200 cm + B (tg) 1 m	VIII, X, XI, II
				<15			B (tg) 1 m + S (mr) 20–75 cm	IX, XI, III
				<15			CCA (sr) 40–150 cm + B (tg) 1 m	VIII, X, XI, III
36	0.01–0.001				12	1.0–2.0	S (mr) 10–20 cm	IX
							S (mr) 10–20 cm + B (tg) 0.5–1.0 m	VIII, X, XI
37	0.01–0.001				12	1.0–6.5	S (mr) 20–60 cm	IX
							S (mr) 20–60 cm + B (tg) 0.5–1.0 m	VIII, X, XI
38[e]	0.01–0.001			≥10	12	4.0–20	CCA (sr) 100–300 cm	IX
				≥10			CCA (sr) 100–300 cm + B (tg) 1 m	VIII, X, II, XI
				<10			S (mr) 70–200 cm	IX
				<10			S (mr) 70–200 cm	VIII, X, III, XI

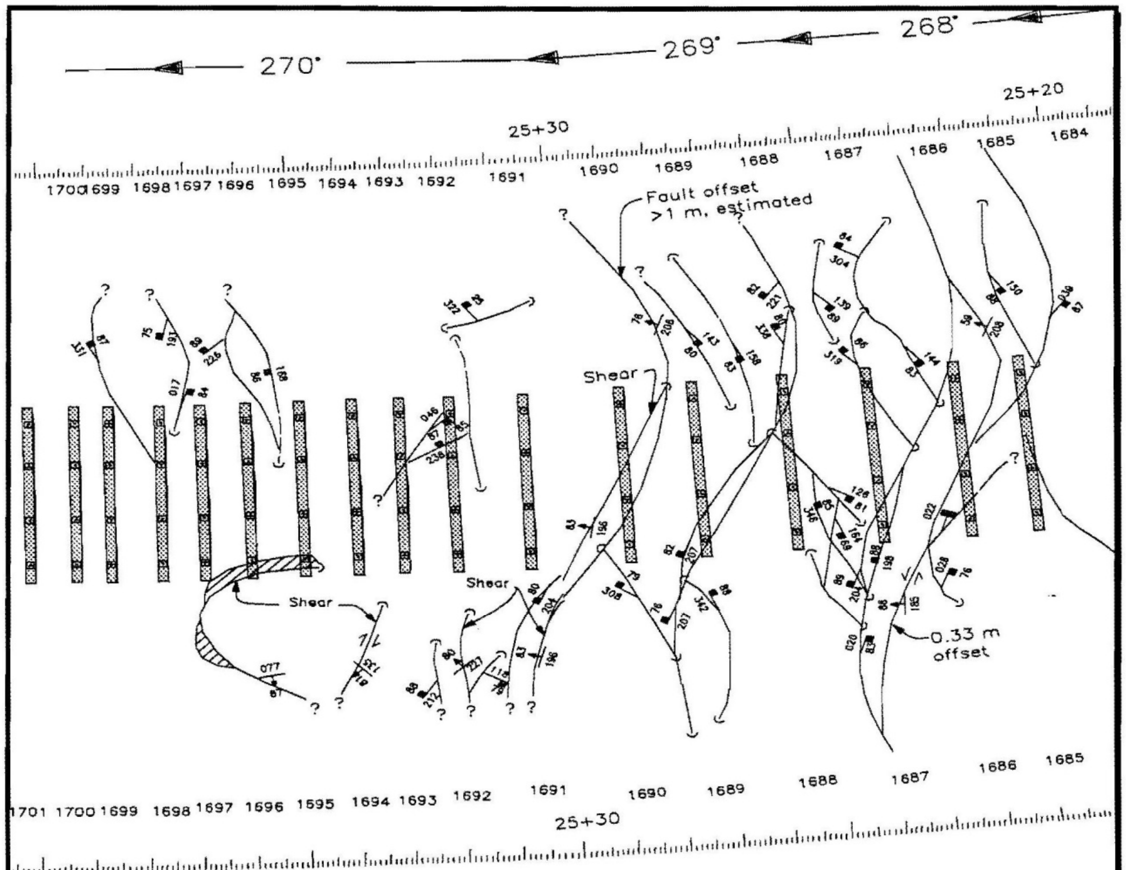
[a] After Barton et al. (1974).
[b] Approx.
[c] Key: sb = spot bolting; B = systematic bolting; (utg) = untensioned, grouted; (tg) tensioned (expanding-shell type for competent rock masses, grouted post-tensioned in very poor quality rock masses; S = shotcrete; (mr) = mesh-reinforced; clm = chain-link mesh; CCA = cast concrete arch; (sr) steel-reinforced. Bolt spacings are given in meters (m). Shotcrete or cast concrete arch thickness is given in centimeters (cm).
[d] See note XII
[e] See note XIII

Q-System Ground Support Guidelines

Q-System: Support Measures—Supplementary Notes

I. For cases of heavy rock bursting or "popping," tensioned bolts with enlarged bearing plates often used, with spacing of about 1 m (occasionally down to 0.8 m). Final support when "popping" activity ceases.
II. Several bolt lengths often used in same excavation, i.e., 3, 5, and 7 m.
III. Several bolt lengths often used in same excavation, i.e., 2, 3, and 4 m.
IV. Tensioned cable anchors often used to supplement bolt support pressures. Typical spacing 2–4 m.
V. Several bolt lengths often used in same excavation, i.e., 6, 8, and 10 m.
VI. Tensioned cable anchors often used to supplement bolt support pressures. Typical spacing 4–6 m.
VII. Several of the older-generation power stations in this category employ systematic or spot bolting with areas of chain-link mesh, and a free-span concrete arch roof (25–40 cm) as permanent support.
VIII. Cases involving swelling, e.g., montmorillonite clay (with access of water). Room for expansion behind the support is used in cases of heavy swelling. Drainage measures are used where possible.
IX. Cases not involving swelling clay or squeezing rock.
X. Cases involving squeezing rock. Heavy rigid support is generally used as permanent support.
XI. According to the authors' [Barton et al.] experience, in cases of swelling or squeezing, the temporary support required before concrete (or shotcrete) arches are formed may consist of bolting (tensioned shell-expansion type) if the value of RQD/J_n is sufficiently high (i.e., >1.5), possibly combined with shotcrete. If the rock mass is very heavily jointed or crushed (i.e., $RQD/J_n < 1.5$, for example, a "sugar cube" shear zone in quartzite), then the temporary support may consist of up to several applications of shotcrete. Systematic bolting (tensioned) may be added after casting the concrete (or shotcrete) arch to reduce the uneven loading on the concrete, but it may not be effective when $RQD/J_n < 1.5$, or when a lot of clay is present, unless the bolts are grouted before tensioning. A sufficient length of anchored bolt might also be obtained using quick-setting resin anchors in these extremely poor-quality rock masses. Serious occurrences of swelling and/or squeezing rock may require that the concrete arches are taken right up to the face, possibly using a shield as temporary shuttering. Temporary support of the working face may also be required in these cases.
XII. For reasons of safety, the multiple drift method will often be needed during excavation and supporting of roof arch. Categories 16, 20, 24, 28, 32, 35 (span/ESR $>$ 15 m only).
XIII. Multiple drift method usually needed during excavation and support of arch, walls, and floor in cases of heavy squeezing. Category 38 (span/ESR $>$ 10 m only).

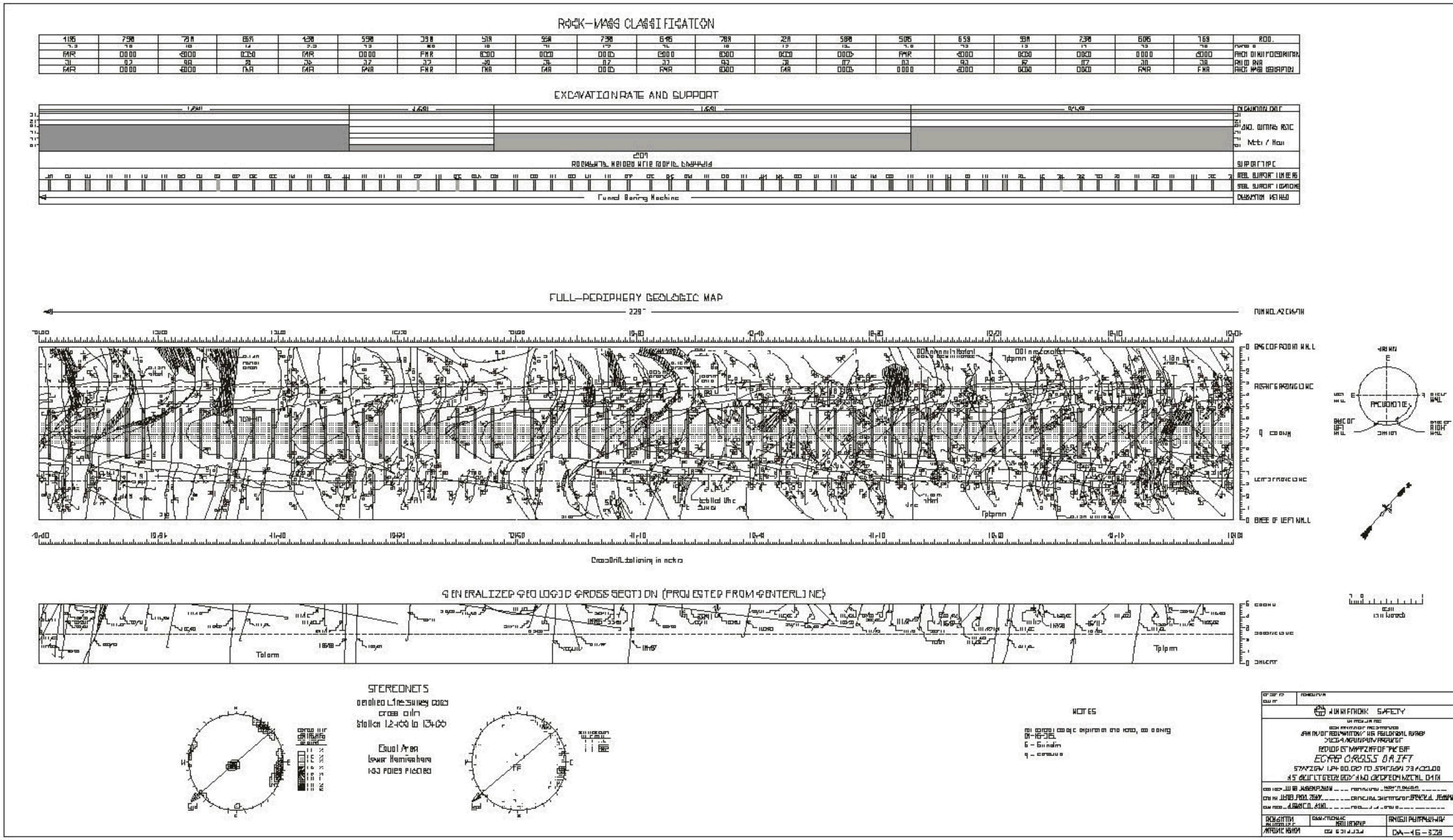
Example Rock Mass Classification at Yucca Mountain



RMR Rating Parameters				
Begin Station	2520	2525	2530	2535
End Station	2525	2530	2535	2540
RQD (Line Survey)	51.4	39.2	12.6	10
RQD Index	13	8	3	3
C	12	12	12	12
Js	10	10	15	10
Jcd	20	22	18	18
JwR	15	15	15	15
AJO	0	-5	-12	-12
RMR rating	70	62	51	46
Qualitative Description	Good	Good	Fair	Fair
Geologic Unit	Tptpln	Tptpln	Tptpln	Tptpln
Mechanical Unit	TSW2	TSW2	TSW2	TSW2

Q Rating Parameters				
Begin Station	2520	2525	2530	2535
End Station	2525	2530	2535	2540
RQD (Line Survey)	51.4	39.2	12.6	10
Jn	9	9	9	6
Jr	3	3	3	3
Ja	2	3	3	4
JwQ	1	1	1	1
SRF (Kirsten)	0.84	1.18	2.05	2.17
Q rating	10	3.7	0.68	0.58
Qualitative Description	Good	Poor	Very Poor	Very Poor
Installed Ground Support Category	CD1	CD1	CD1	CD1

Full Periphery Geologic Mapping at Yucca Mountain



Estimate Rock Mass Properties

- **Available methods for estimating various rock mass properties include**
  - **Q-system (Barton 2002b)**
  - **Rock Mass Index (RMi) (Palmström 1996)**
  - **Geological Strength Index (GSI) (Hoek et al. 2002)**

Estimate Rock Mass Properties

- Geological Strength Index (GSI) is the primary method used at Yucca Mountain
- GSI is estimated using both Q and RMR determined during tunnel mapping

$$GSI = 9 \ln Q' + 44$$

$$GSI = RMR' - 5$$

where $$Q' = \frac{RQD}{J_n} \bullet \frac{J_r}{J_a}$$

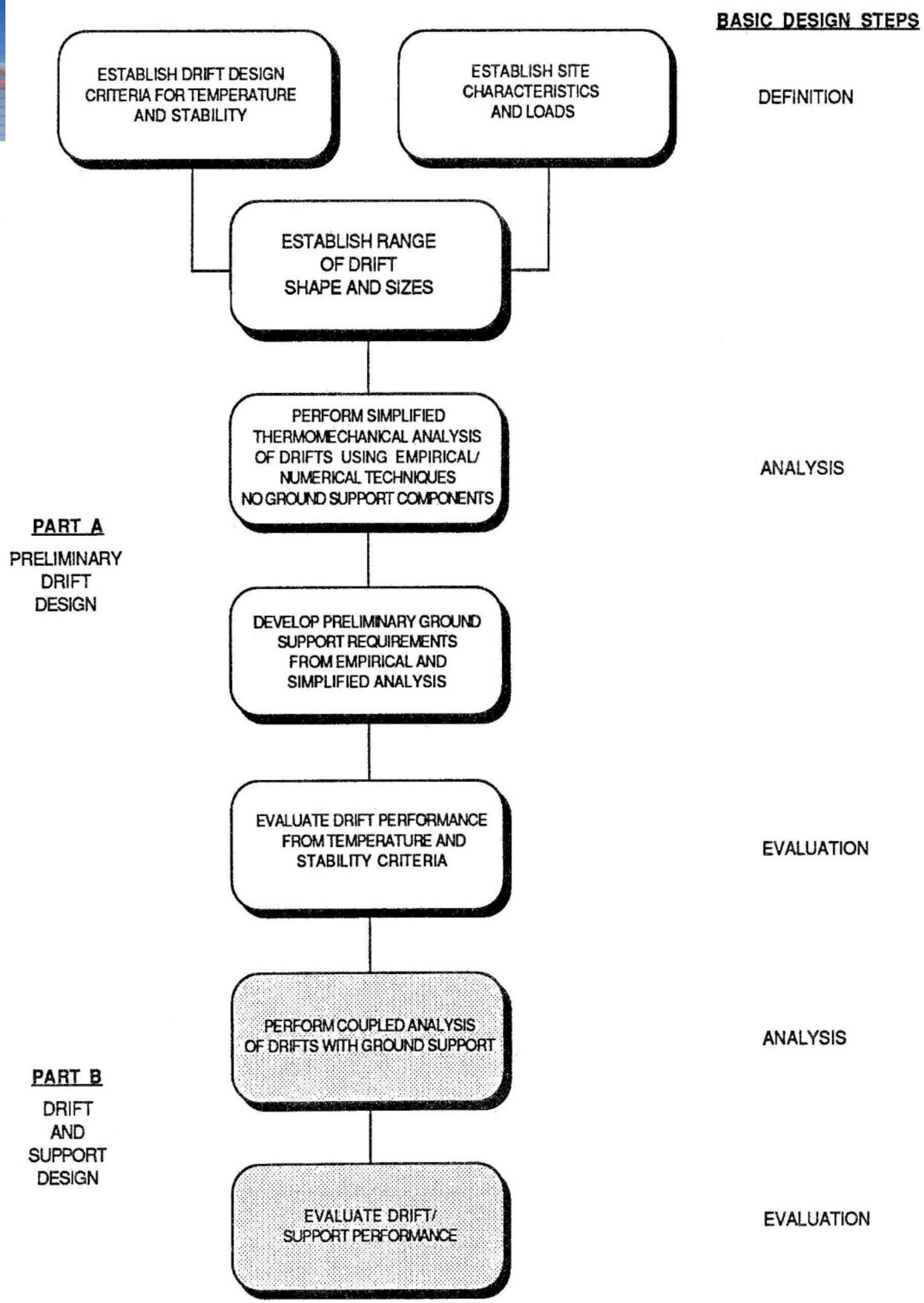
$$RMR' = C + RQD_i + JS + JC + JW'$$

- RockProps V1.0 — An Excel file to calculate rock mass properties

Drift Design Methodology

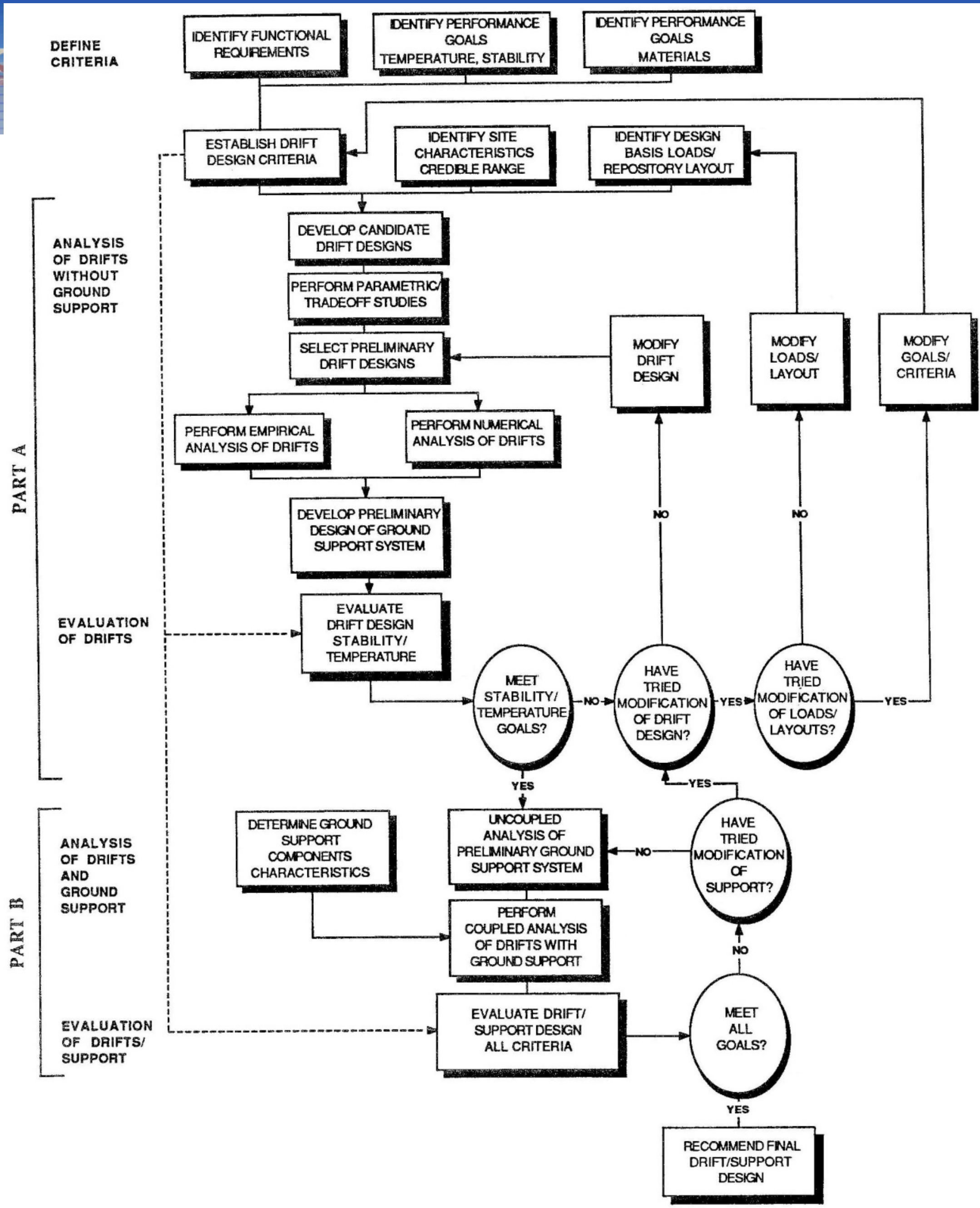
- Focus on excavation stability during all phases of the underground nuclear waste repository
  - Construction
  - Emplacement
  - Retrieval (if required)
  - Closure
- Keys to developing stable excavations
  - Excavation procedures
  - Design of room shape
  - Design and installation of ground support
  - Implementation of monitoring and maintenance programs

Summary of Drift Design Methodology



Source: Hardy and Bauer 1991, Figure 2-1

Logic Chart for Drift Design Methodology



Source: Hardy and Bauer 1991, Figure 2-2

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Output/Product from Each Design Step

Design Step	Output/Product
Define Criteria	
Identify the functional requirements (such as drift shape and area) and develop candidate drift cross sections.	List of functional requirements.
Identify performance goals for temperature, stability, and materials.	List of performance goals.
Identify design basis loads and repository layout.	Diagrams of repository layout and tables of loads for repository layouts.
Identify design input information over a credible range of site characteristics.	Assembly of Reference Information Base (RIB) information for use in design.
Establish drift design criteria.	List of criteria.
Analysis of Drifts	
Develop candidate drift designs.	Presentation of candidate drift shapes and dimension dependent on function.
Perform parametric/tradeoff studies.	Ranking of candidate drift designs.
Select preliminary drift design.	Recommended preliminary drift shape and dimensions.
Perform empirical and numerical analysis of drifts including sensitivity studies over a credible range of site characteristics.	Recommendations for ground support standup times, stresses, displacements, and temperatures around drift.
Assess stability of intersections and pillars.	Stresses, displacements, and temperatures around intersections and pillars.
Preliminary Ground Support Selection	
Develop preliminary ground support components based on empirical methods and support of yielded rock.	Preliminary ground support design.

Output/Product from Each Design Step

Design Step	Output/Product
<u>Evaluation of Drift Design</u>	
Evaluate the drift design stability and temperature performance goals.	Comparison of predicted drift performance with design criteria.
If the goals were not adequately met, modify drift shapes/ design. If this has been tried, modify the thermal panel load or layout (standoff distance to waste) and redo the analyses until goals are satisfied.	Recommended modification to drift shape design or thermal loads.
Compare analytical and empirical predicted drift performance with in situ tests and demonstrations when appropriate.	Comparison of predicted drift performance with demonstration field results.
Modify design models.	Recommendation of model changes.
<u>Analysis of Support</u>	
Calculate ground support loads from uncoupled analysis using analytical results.	Stresses in rockbolts and shotcrete.
Analyze the ground support components using coupled numerical methods to project performance over time.	Stresses, displacements and temperatures in drifts and ground support components.
<u>Evaluation of Support</u>	
Evaluate the drift and ground support design against all performance goals.	Comparison of predicted ground support loads versus performance goals.
If all goals are not met, then the option exists to modify the loads/layout and drift shape as before or modify the goals if they are overly conservative.	Recommendations/modifications to ground support, drift shape, size, or thermal loads.
A design that meets all goals constitutes a final design (drift geometry and ground support requirements).	Drawings showing drift shape, size, and ground support components for each type of ground expected.

Source: Hardy and Bauer 1991, Table 2-1

Design Basis

- Stress at drift location
  - In situ stress
  - Thermal stress
  - Stress induced by seismic motion
  - Design basis loads
- Information for design
  - Stratigraphy and rock structure
  - In situ conditions
  - Thermal properties
  - Mechanical properties
  - Waste characteristics
  - Ground support properties
- Repository layout

Analysis of Unsupported Drifts

- **Develop candidate drift designs**
- **Conduct parametric and tradeoff studies on candidate drift designs**
- **Select preliminary drift configuration**
- **Use empirical methods to**
  - **Quantify the rock quality**
  - **Assess opening stability**
    - **Stand-up time**
    - **What span is ground support required**
  - **Conduct preliminary assessment of ground support requirements**
  - **Estimate rock mass properties**

Analysis of Unsupported Drifts

- Use numerical methods to assess the behavior of the rock mass
  - Thermal model
  - Mechanical model
    - If no rock mass yield or joint slip is projected, no ground support is required
    - When yield or failure of intact blocks is projected, then the ground support should be designed to support the gravity load of the yielded material
- Evaluate fault zones and zones of poor rock quality
- Preliminary ground support selection based on empirical and numerical analyses

Ground Support Design

- **Use Q and RMR methods to define the ranges of ground support systems based on the expected in situ conditions**
- **The drift design will be verified by monitoring performance during construction of the repository**
- **Ground support materials will be selected for durability, strength, thermal compatibility, and recognition of chemical restrictions that might be imposed by long-term repository performance requirements**

Ground Support Analyses at Yucca Mountain

- Both empirical and analytical methods were used in design calculations
- Empirical methods were used to assess the need for ground support and the type of ground support
- Computer modeling was used to further analyze the stability of unsupported openings
- Applicable thermal and seismic loads were considered.
- Based on empirical estimates, design issues, and computer modeling, the final ground support system was developed

Ground Support Input Parameters

- **Time histories of rock temperatures**
- **Thermal and mechanical properties of the rock mass surrounding the emplacement drifts**
- **Rock bolt properties**
- **Seismic velocity histories**
- **Emplacement drift configurations**

Time Histories of Rock Temperatures

Time (years)	Temperatures (°C)		
	Drift Wall	50-m Above Drift Center[a]	50-m Below Drift Center[a]
0	22.28	21.68	23.08
0.01	36.64	21.68	23.08
1	71.80	21.68	23.08
2	72.22	21.68	23.08
5	70.42	21.71	23.10
7	68.63	21.81	23.19
10	66.32	22.09	23.45
20	59.88	23.42	24.72
30	54.32	24.68	25.96
50	46.78	26.53	27.81

Source: BSC 2007, Table 6-1

Thermal Properties

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

Temperature Range (°C)	CTE (10^{-6}/°C)[a]
20 - 25	7.34[b]
25 - 50	7.34
50 - 75	8.99
75 - 100	9.73
100 - 125	10.22
125 - 150	10.91
150 - 175	12.20
175 - 200	14.74
200 - 225	22.31

CTE = Coefficient of Thermal Expansion for Lithophysal and Nonlithophysal Rocks

Source: BSC 2007, Tables 6-2 and 6-3

Rock Mass Mechanical Properties for Lithophysal Rock

Parameter	Lithophysal Rock				
Rock Mass Category	1	2	3	4	5
Lithophysal Porosity (%)[a]	>30	25-30	15-25	10-15	<10
Poisson's Ratio[b]	0.22	0.22	0.22	0.22	0.22
Modulus of Elasticity (GPa)[c]	1.90	6.40	10.80	15.30	19.70
Bulk Modulus (GPa)	1.13	3.81	6.43	9.11	11.73
Shear Modulus (GPa)	0.78	2.62	4.43	6.27	8.07
Unconfined Compressive Strength (MPa)[c]	10	15	20	25	30
Cohesion (MPa)	2.60	3.90	5.21	6.51	7.81
Friction Angle (degrees)	35	35	35	35	35
Tensile Strength (MPa)[d]	1.0	1.5	2.0	2.5	3.0

Source: BSC 2007, Table 6-4

Rock Mass Mechanical Properties for Nonlithophysal Rock

Parameter	Nonlithophysal Rock (Tptpmn)				
Rock Mass Category	1	2	3	4	5
Geologic Strength Index (GSI)	51	59	62	68	72
Poisson's Ratio	0.19	0.19	0.19	0.19	0.19
Modulus of Elasticity (GPa)	10.59	16.79	19.95	28.18	35.48
Bulk Modulus (GPa)	5.69	9.03	10.73	15.15	19.08
Shear Modulus (GPa)	4.45	7.05	8.38	11.84	14.91
Unconfined Compressive Strength (MPa)	26.90	32.02	34.28	39.57	43.90
Cohesion (MPa)	7.36	8.33	8.75	9.73	10.52
Friction Angle (degrees)	32.64	35.02	35.91	37.65	38.79
Tensile Strength (MPa)	0.27	0.50	0.63	0.99	1.33

Source: BSC 2007, Table 6-5

Stability of Unsupported Emplacement Drifts

- The stability assessment is based on numerical analysis using the FLAC computer code
- The analysis evaluates
  - Temperature increases in rock following waste emplacement
  - Displacement and stress in the vicinity of an unsupported emplacement drift
  - Factor of safety
  - Ground reaction curves

Empirical Analysis of Ground Support Needs

- Calculate RMR values, GSI values, and E_m (elastic modulus) values for various categories
- Determine the unconfined compressive strength (σ_c) of intact representative nonlithophysal rock (Tptpmn), which is about 165 MPa.
- Estimate the major principal stress (σ_1) of rock adjacent to emplacement drifts, which is estimated to be about 25 to 40 MPa
- Calculate the ratio σ_c / σ_1 to be in the ranges of 4 to 7
- The joint water reduction factor J_w is set to 1 for dry rock condition
- A SRF value ranging from 0.5 to 2 is considered appropriate.
- Calculate Q values for various categories

Estimate of Ground Support Needs for Emplacement Drifts in Nonlithophysal Rock Based on RMR and Q Systems

Rock Mass Category	E_m (GPa)	RMR	SRF	Q	Ground Support Needs
1	10.59	51	0.5 – 2.0	1.09 – 4.35	Bolts: 3 m long, spaced 1.7-2.1 m in crown and walls, with Bernold-type sheet, or wire mesh and 40-60 mm shotcrete
2	16.79	59	0.5 – 2.0	2.65 – 10.59	Bolts: 3 m long, spaced 1.8-2.3 m in crown and walls, with Bernold-type sheet, or wire mesh and 30-50 mm shotcrete
3	19.95	62	0.5 – 2.0	3.69 – 14.78	Bolts: 3 m long, spaced 2.0-2.3 m in crown and walls, with Bernold-type sheet, or wire mesh and 30-50 mm shotcrete
4	28.18	68	0.5 – 2.0	7.20 – 28.78	Bolts: 3 m long, spaced 2.2-2.4 m in crown and walls, with Bernold-type sheet, or wire mesh and 30-50 mm shotcrete
5	35.48	72	0.5 – 2.0	11.22 – 44.89	Bolts: 3 m long, spaced 2.2-2.6 m in crown and walls, with Bernold-type sheet, or wire mesh and 30-40 mm shotcrete

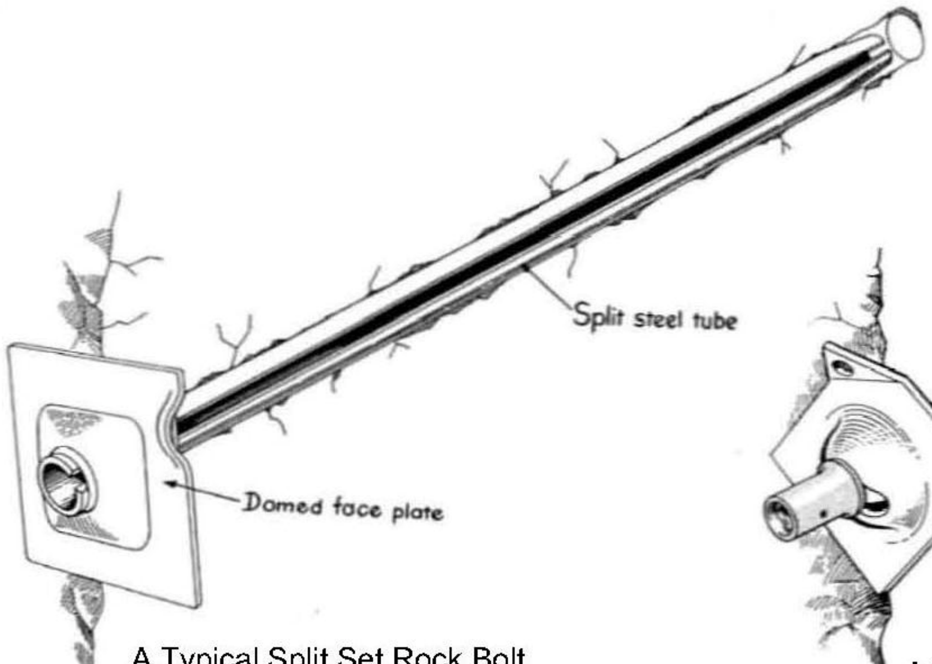
Source: BSC 2007, Table 6-7

Selection of Ground Support Methods

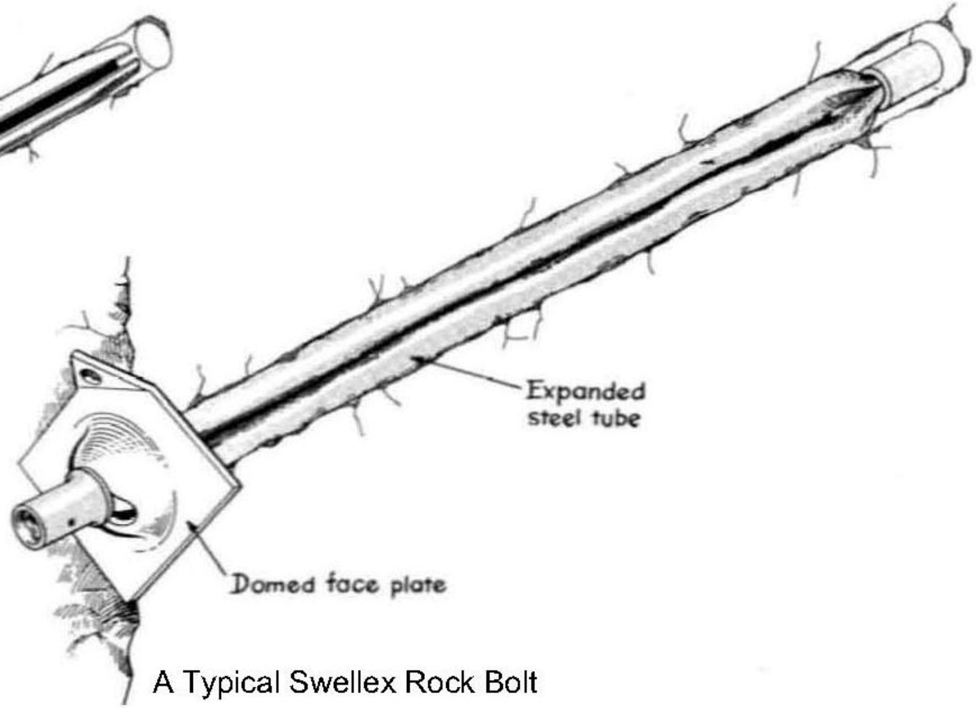
- Ground support installed in emplacement drifts must
  - Ensure stable conditions required for operational worker safety
  - Limit the potential rockfall which might damage waste packages
  - Be functional with little or no planned maintenance throughout the preclosure period of 100 years
  - Have acceptable long-term effect on waste isolation
- Cementious materials are ruled out for use in emplacement drifts due to their potential adverse impact on the long-term waste isolation

Selection of Ground Support Methods

- **Friction-type rock bolts**



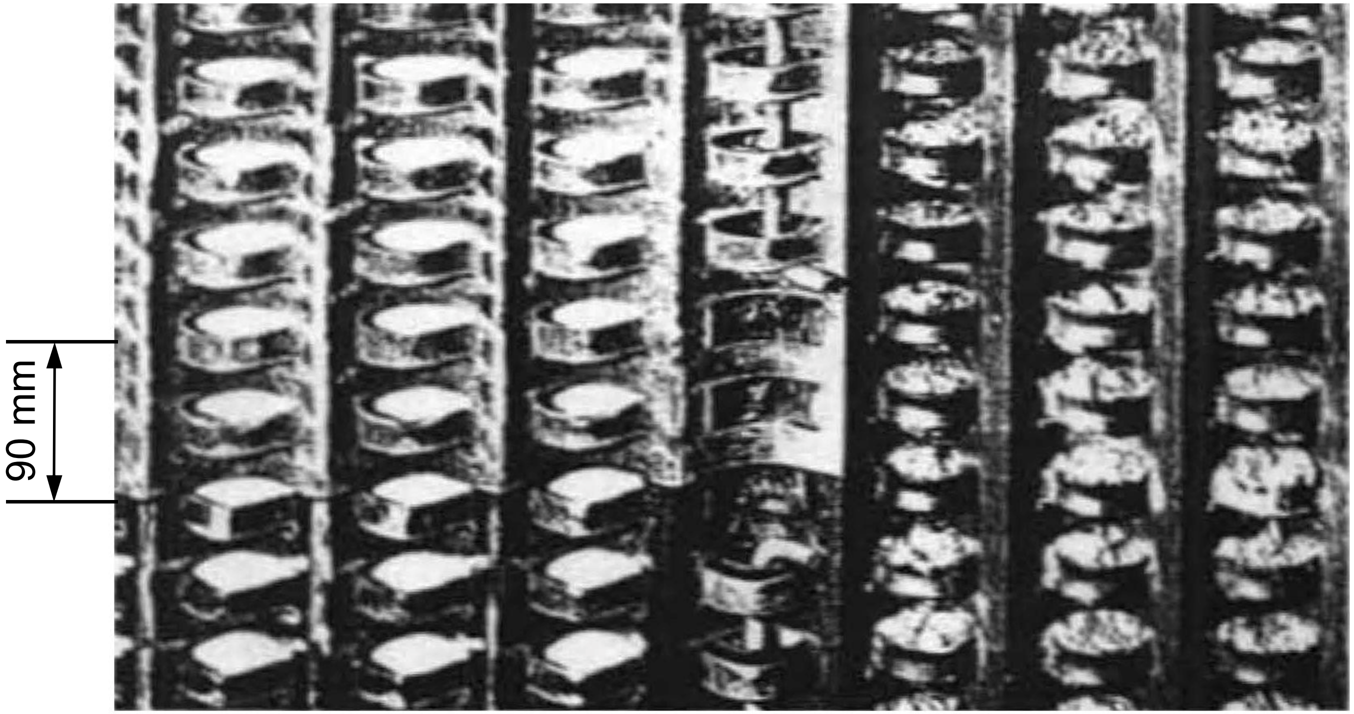
A Typical Split Set Rock Bolt



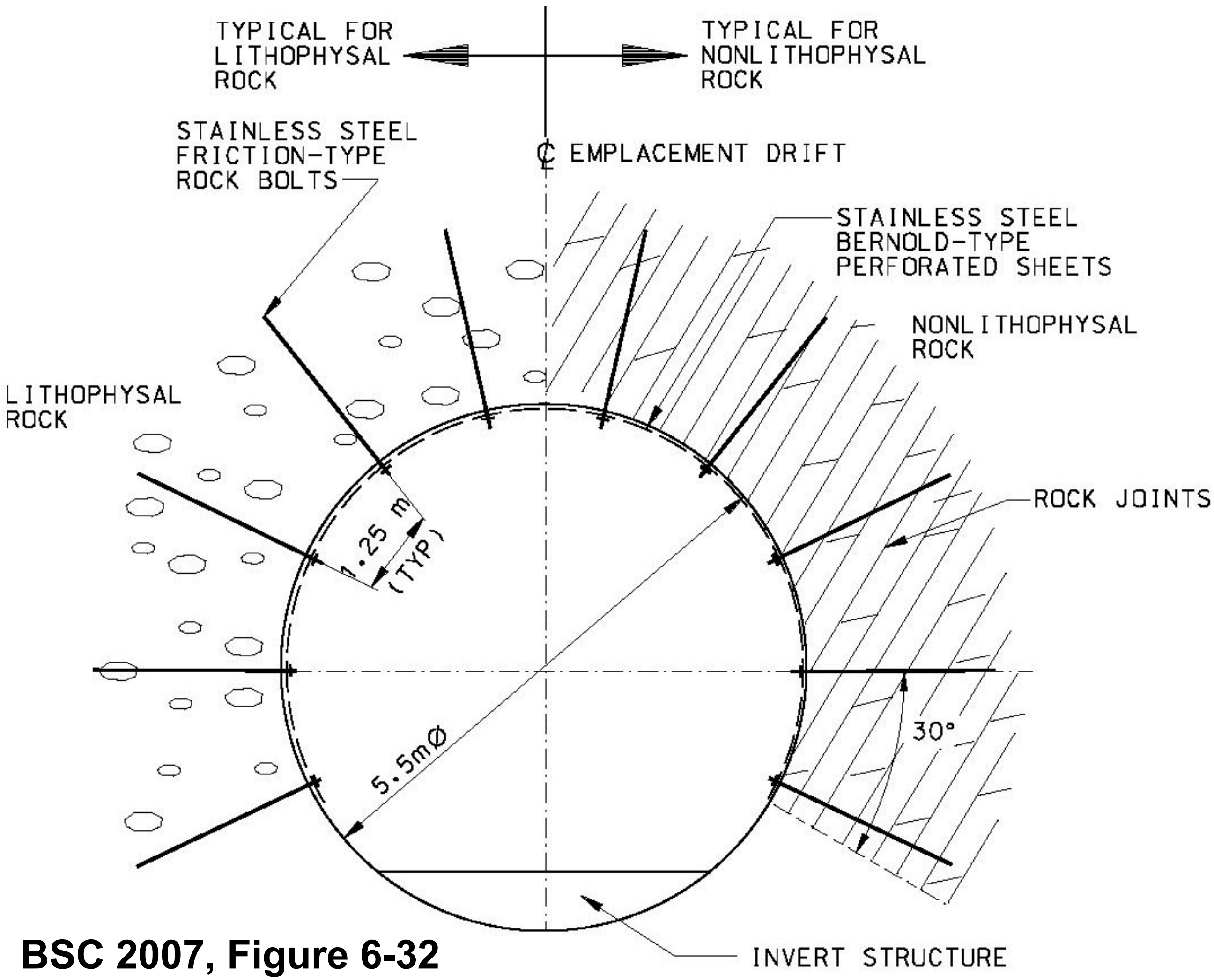
A Typical Swellex Rock Bolt

Selection of Ground Support Methods

- **Perforated steel sheets — consist of thin (2 to 3 mm thick), slotted and slightly corrugated steel sheets that can be bolted tight to the drift surface using friction-type rock bolts**



Ground Support Methods Recommended for Emplacement Drifts at Yucca Mountain

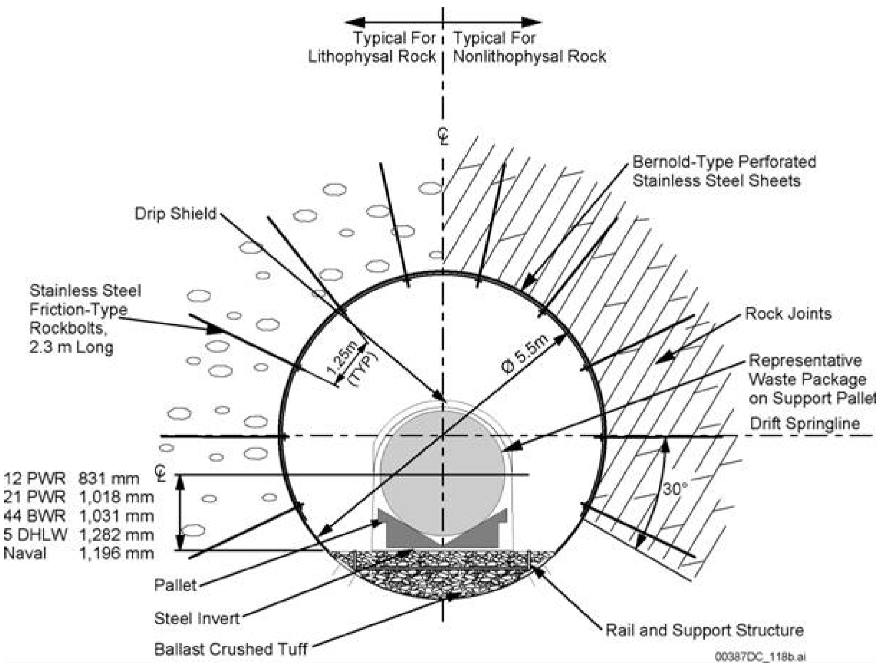


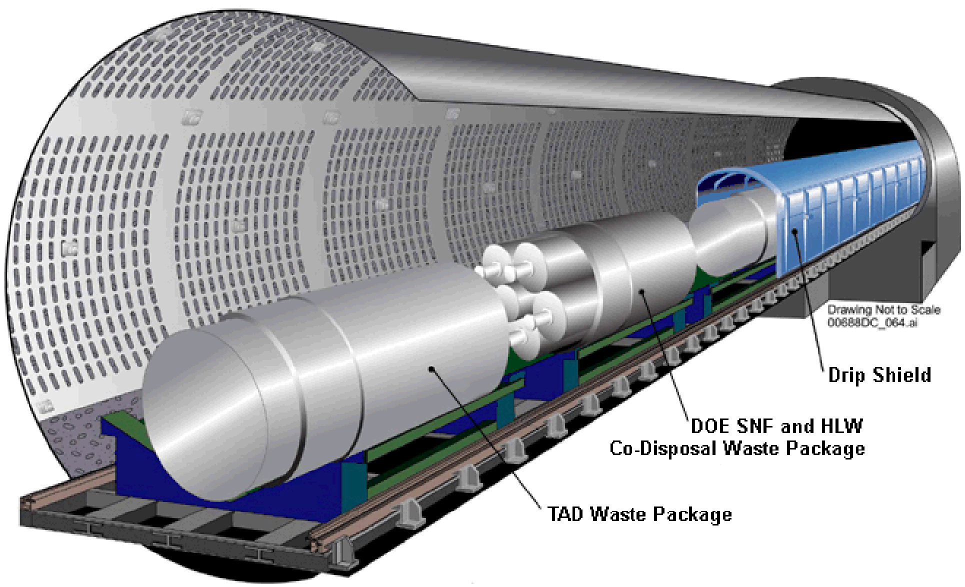
Source: BSC 2007, Figure 6-32

Drift Degradation Analyses at Yucca Mountain

- **Summary of the general approach used for assessment of emplacement drift degradation under in situ, thermal and seismic loading**
- **Estimation of the thermal and mechanical properties and strength of tuff**
  - **nonlithophysal rock**
  - **lithophysal rock**
- **Numerical model for drift degradation assessment and its validation**
- **Seismic response of drifts**
- **Based on *Drift Degradation Analysis* (BSC 2004a), which is summarized by Lin et al. (2007) and Damjanac et al. (2007)**

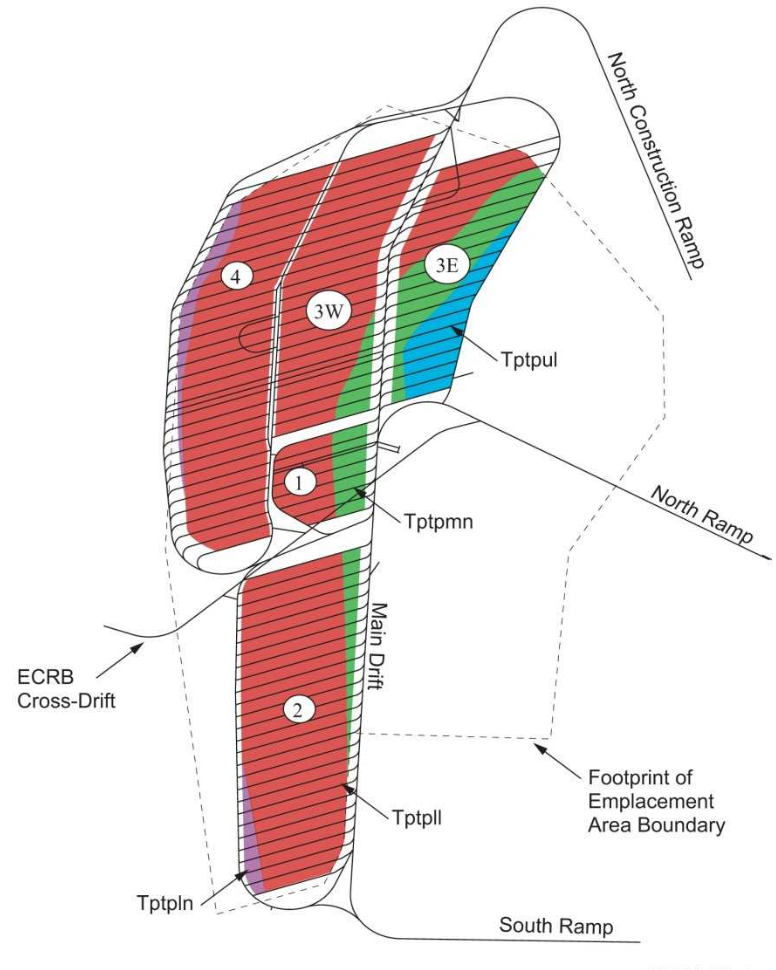
Emplacement Drift Configuration





Repository Layout

- **The proposed repository is constructed in two basic units of the Topopah Spring tuff:**
  - **~ 85% of repository drifts in lithophysal tuff**
  - **~ 15% of repository drifts in nonlithophysal tuff.**
- **Depth of repository is ~ 300 m.**
- **Vertical gravitational stress is maximum, ~ 7.8 MPa.**



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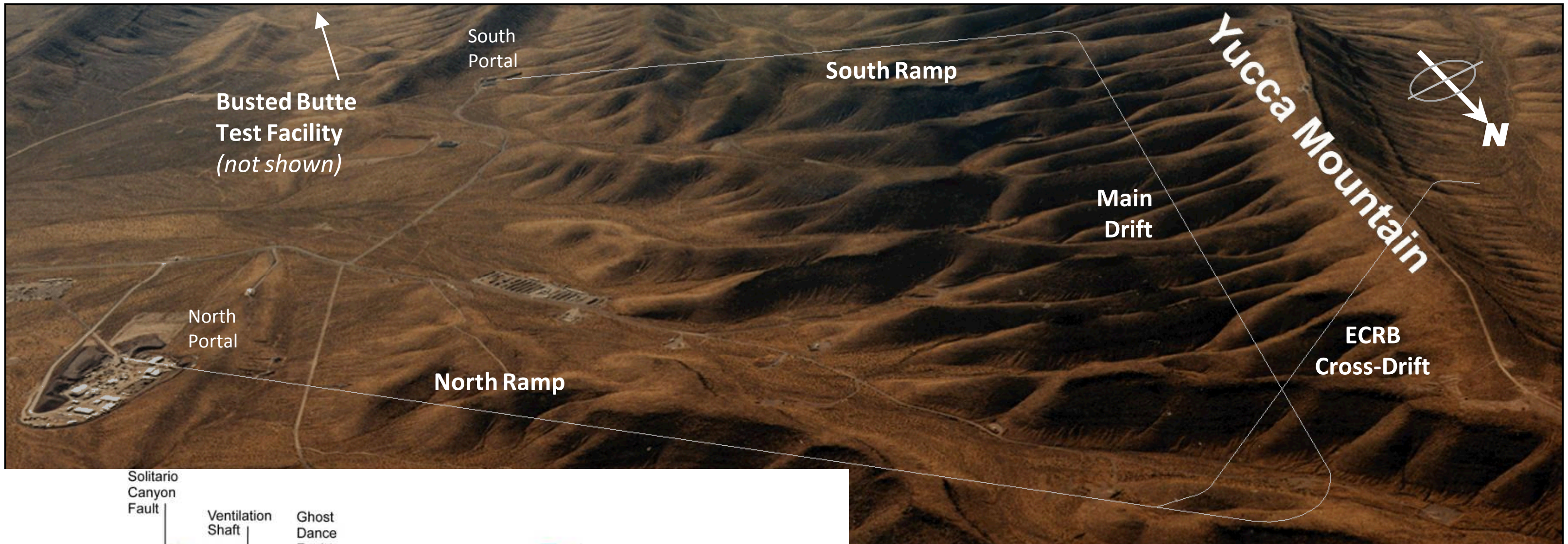
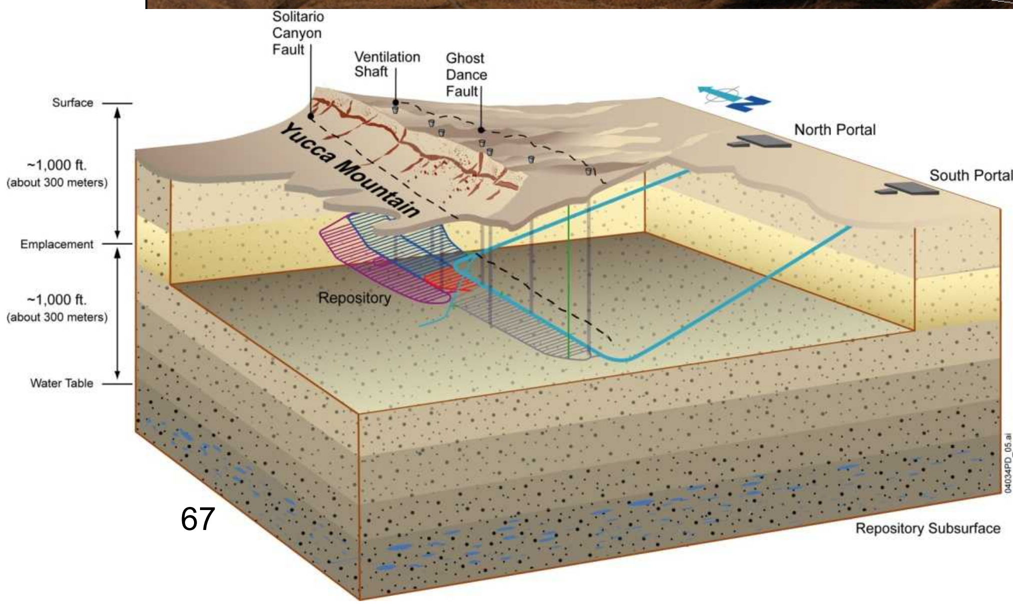
Repository Layout

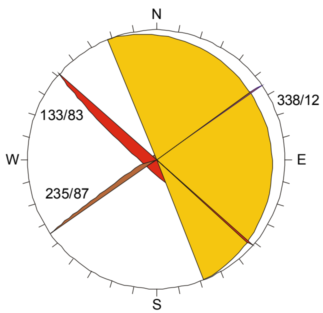




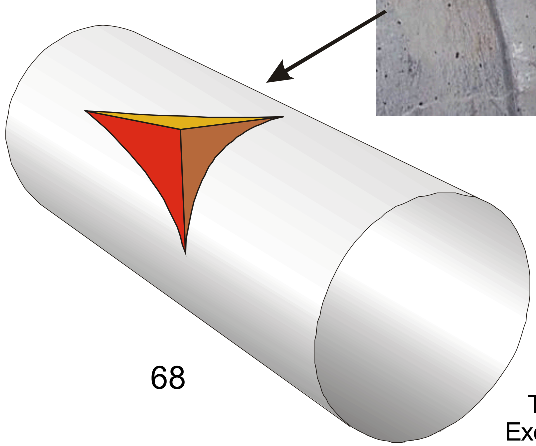
In the North Ramp/Main Drift curve

Nonlithophysal Tuff

Stereographic Projection of
Key-Block-Forming Fracture Planes



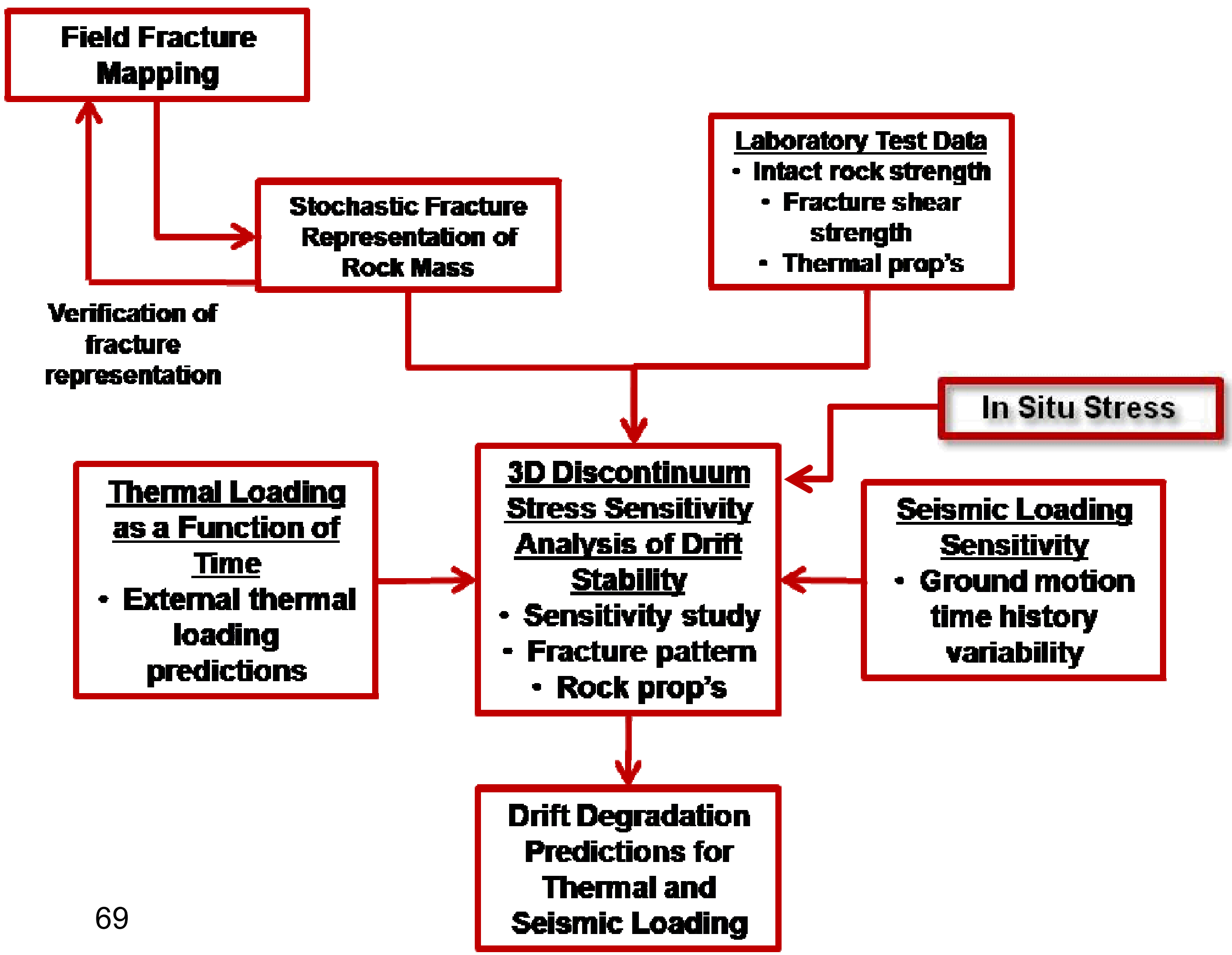
Key Block Formed by the Intersection of an
Excavation with
Three Fracture Planes



Tunnel
Excavation

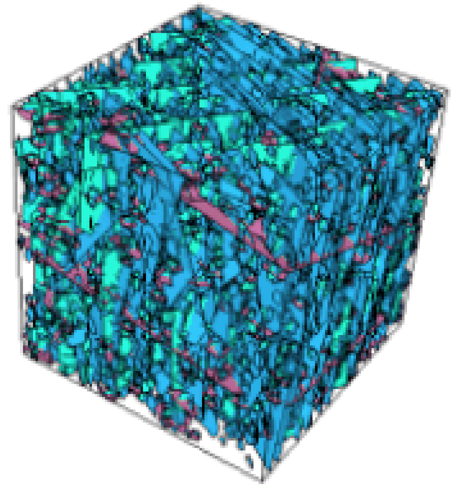
- Good quality, fine-grained, massive and strong rock.
- Fracture sets mapped in detail throughout Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) Cross-Drift. Four well-developed, short trace length (less than the drift diameter) fracture sets – generally discontinuous in nature.
- Approximately 500 unconfined and confined lab compression strength tests have been completed, including testing to 200ºC and saturated conditions.
- Fracture strength determined from direct shear testing on joints.
- Rock strength estimates:
  - Unconfined intact rock strength approximately 200 MPa
  - Unconfined rock block strength estimated to be approximately 70-75 MPa.

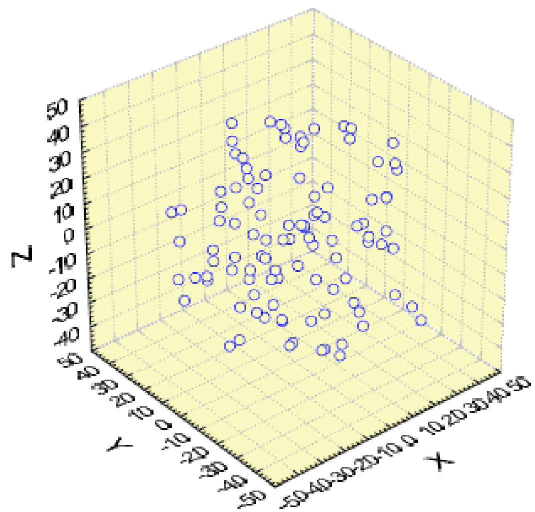
Approach to Drift Degradation Assessment in Nonlithophysal Rock



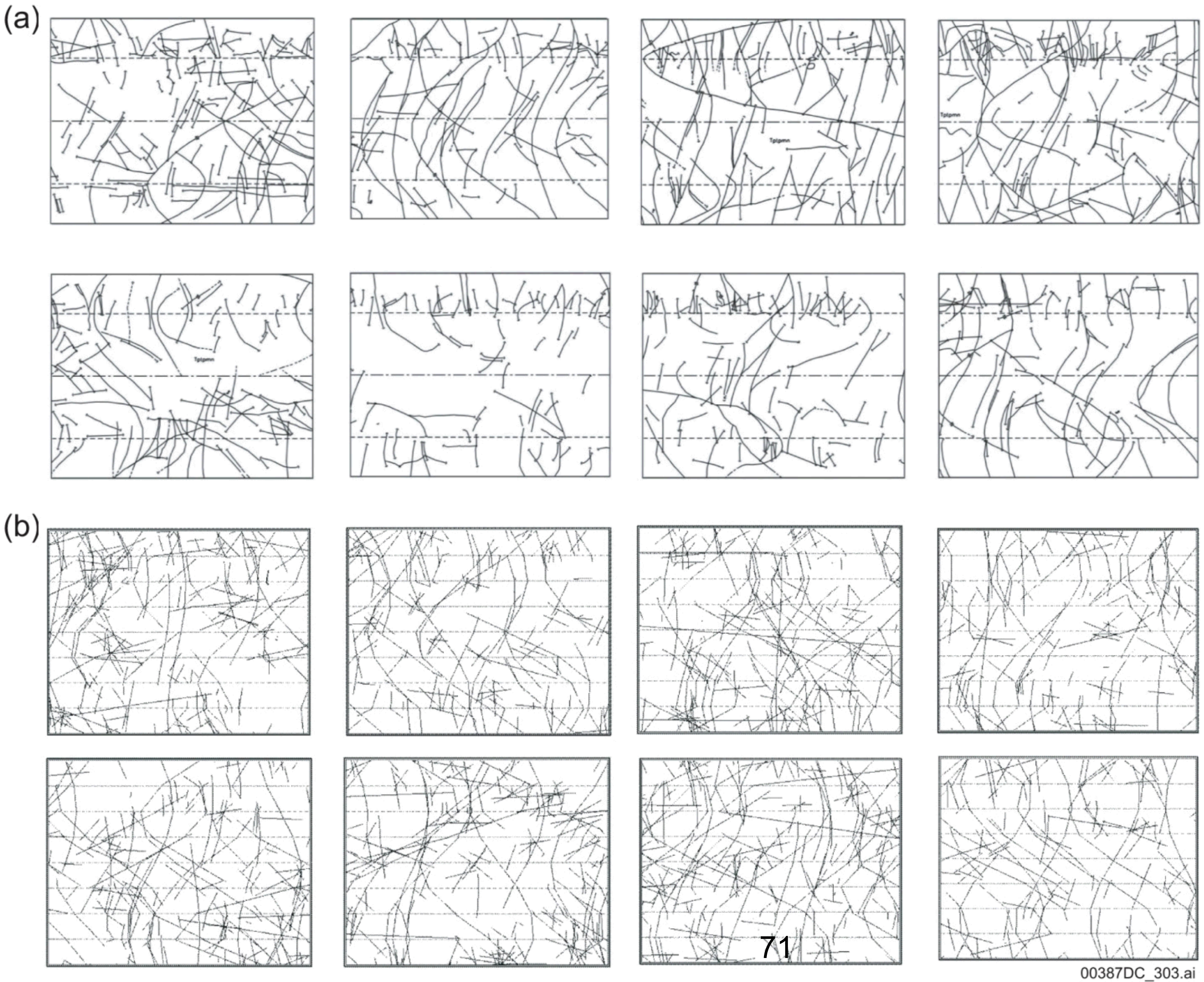
Stochastic Fracture Representation of the Rock Mass

- **Emplacement drifts are randomly located and “excavated” within the 100-m cube rock mass generated by FracMan, such that the stochastic nature of the jointed medium and its impact on rockfall is adequately sampled.**
- **A random emplacement drift centroid coordinate is chosen within the cube, and a 25-m × 25-m × 25-m volume, oriented at the emplacement drift 72° azimuth, is extracted to contain the model emplacement drift.**





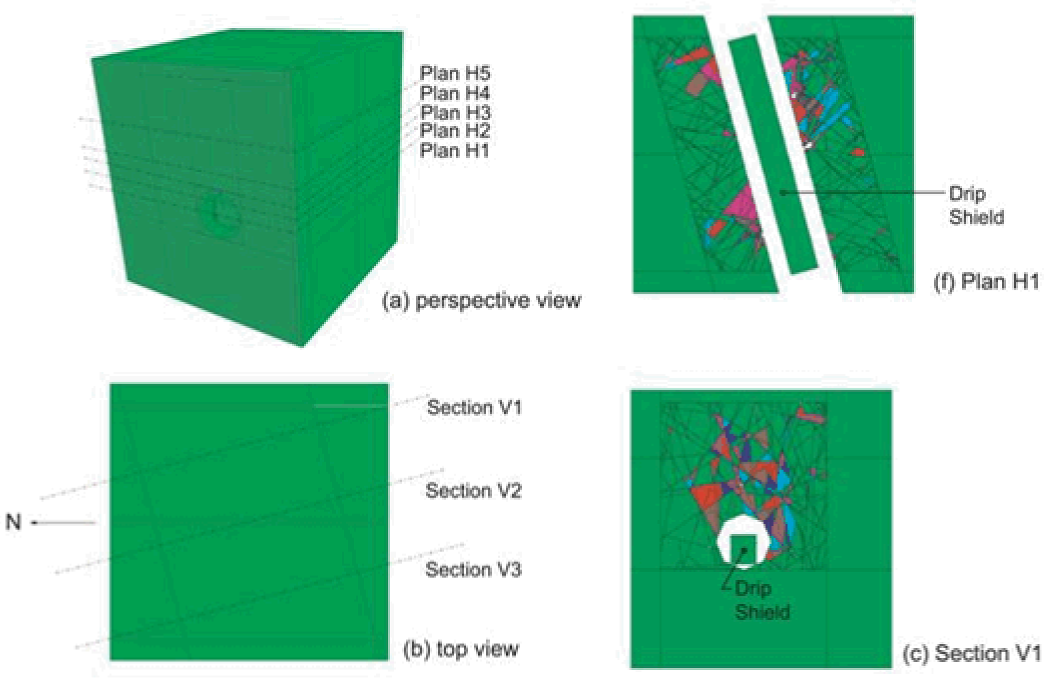
Fracture Modeling



(a) Full periphery geologic maps from the Tptpmn in the Exploratory Studies Facility

(b) Simulated full periphery geologic maps from the FracMan cube

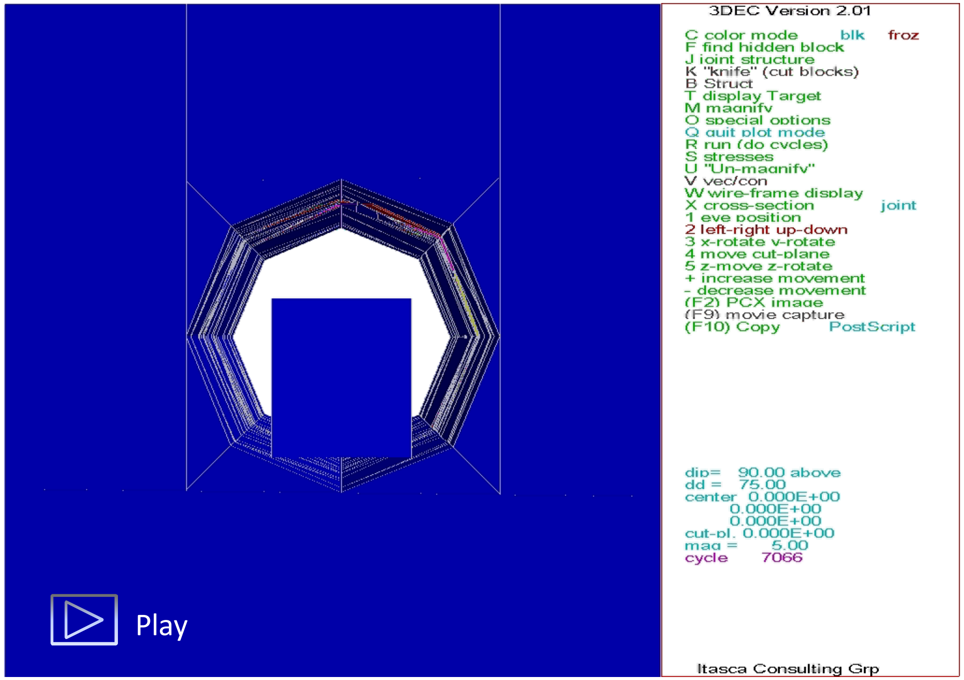
3DEC Rockfall Model



- **An algorithm was developed for applying the FracMan fracture geometry to the 3DEC model.**
- **The algorithm allows incomplete fractures to be cut within a block, or to terminate against other fractures, thus creating realistic fracture patterns within the rock mass.**
- **In other words, portions of a fracture plane could be assigned a standard Coulomb slip behavior, whereas others could be bonded to the opposing surface with the strength of the adjacent rock blocks, thereby creating fractures that have rock "bridges" along their surface. In this case, the rock bridge acts as a strong bond along the fracture surface, but can still fail in shear or tension if the stresses so dictate.**
- **In this manner, it is possible to represent a discontinuous fracture system, but one in which breakage of solid rock can occur.**

3DEC Rockfall Model

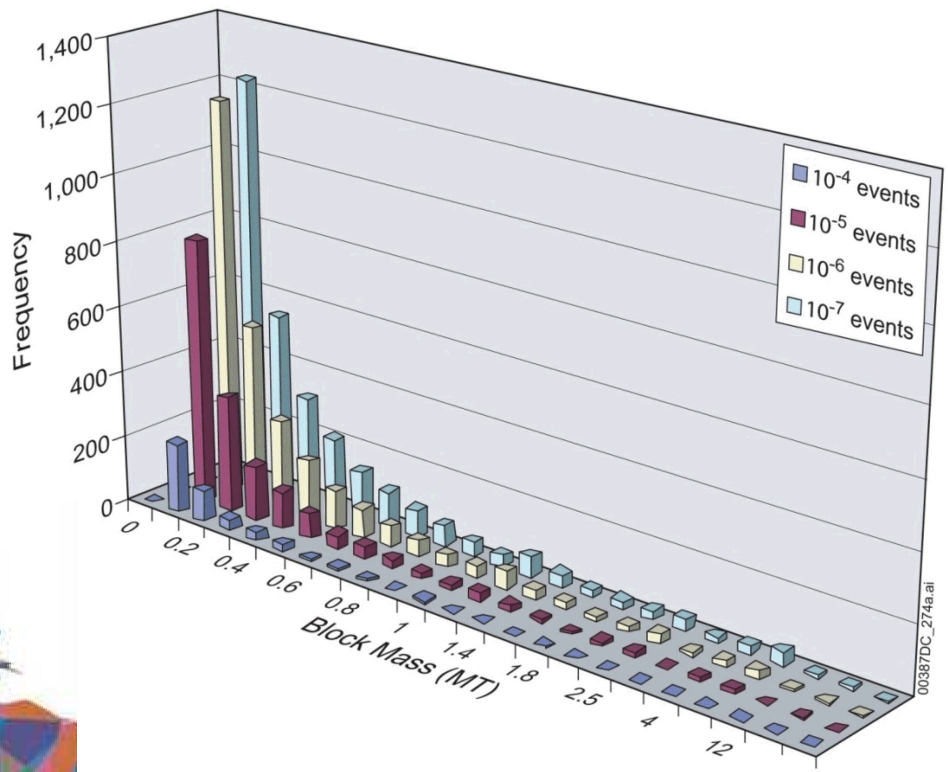
- The initial state of stress was included at the model consolidation stage.
- Site-specific ground motions were developed for Yucca Mountain through use of a formal process of expert elicitation resulting in ground motion time histories for four levels of annual probability of exceedance.
- A total of 15 sets of ground motion time histories were developed at the repository horizon for each annual postclosure hazard level.
- A simple Latin Hypercube sampling scheme was used for the pairing of ground motion and fracture modeling region.

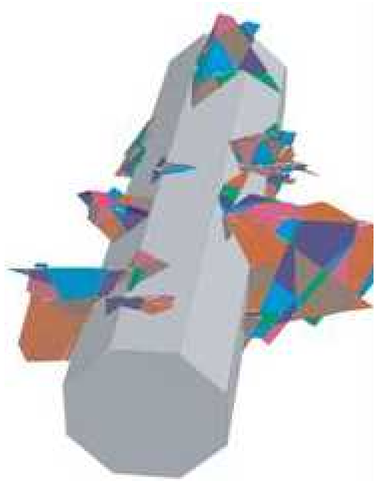


Rockfall Results in Nonlithophysal Rock

Rockfall data from seismic analyses include the following:

- **block size**
- **block relative impact velocity**
- **block impact momentum**
- **block impact**
- **drift profile.**





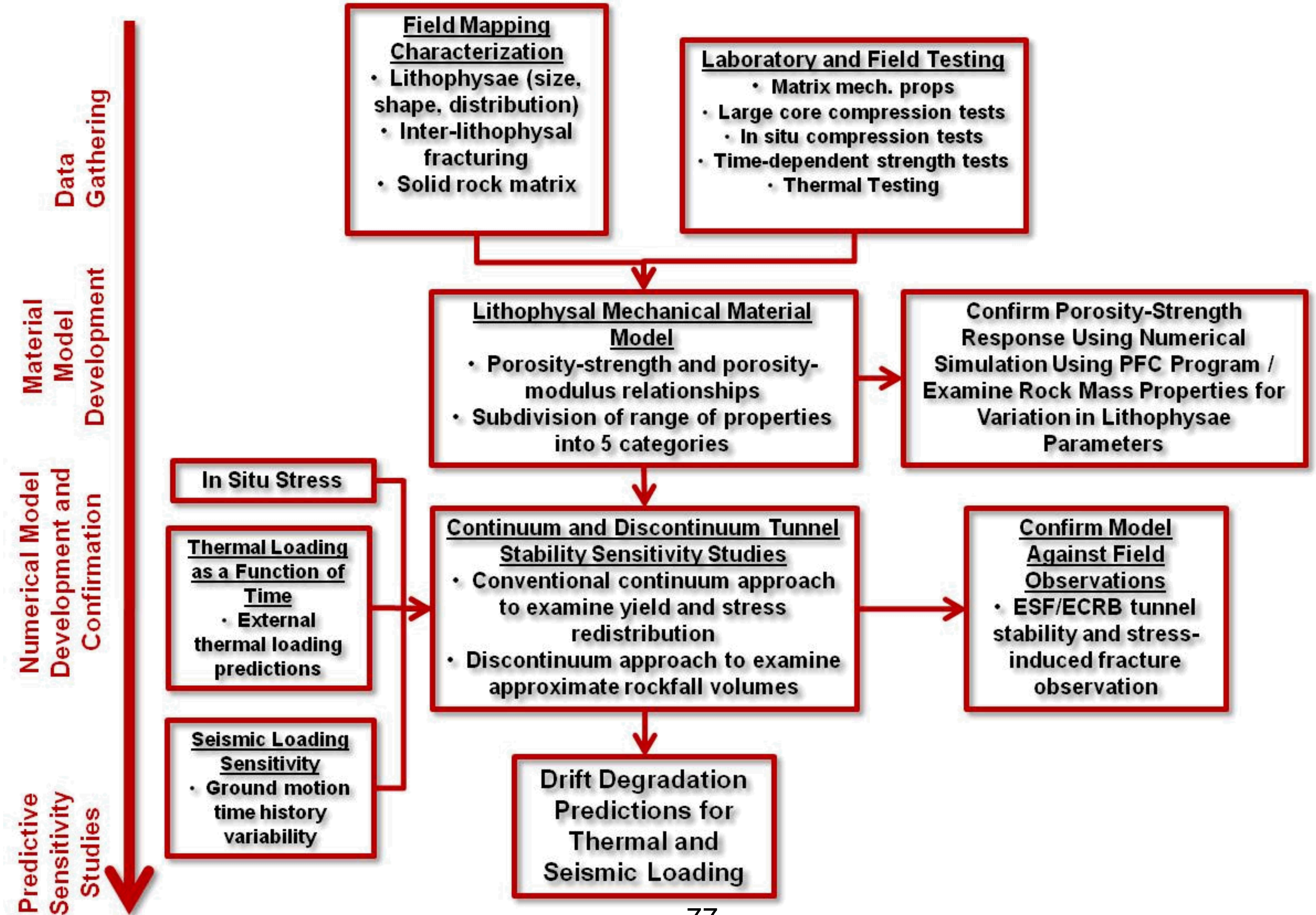
Lithophysal Tuff

- Matrix material is mechanically similar to nonlithophysal rock.
- Fracture sets are not as distinct as in nonlithophysal units and are discontinuous.
- Fracture spacing is relatively small: less than 1 m, and very often on the order of 0.1 to 0.2 m; trace lengths are short.
- Lithophysal porosity varies from ~ 10 to 30%.
- Block sizes produced on failure expected to be roughly equal to average fracture spacing.

Geotechnical Characterization of Lithophysal Unit

- **Mechanical Properties**
  - Approximately 500 uniaxial and triaxial compression tests on small (~2") cores at temperatures to 200ºC and saturated conditions
  - 10.5" core samples from Busted Butte
  - 11.5" core samples from Tptpul and Tptpll in the ESF and ECRB Cross-Drift
  - Approximately 30 time-dependent strength tests at 200ºC and saturated conditions conducted on tuff core matrix to determine time-to-failure as a function of applied stress
- **Thermal Properties**
  - Extensive laboratory testing of thermal conductivity, expansion and heat capacity as function of temperature
  - In situ heat probe tests to determine field effects of porosity
  - Verification of thermal properties from drift scale test and in situ block test

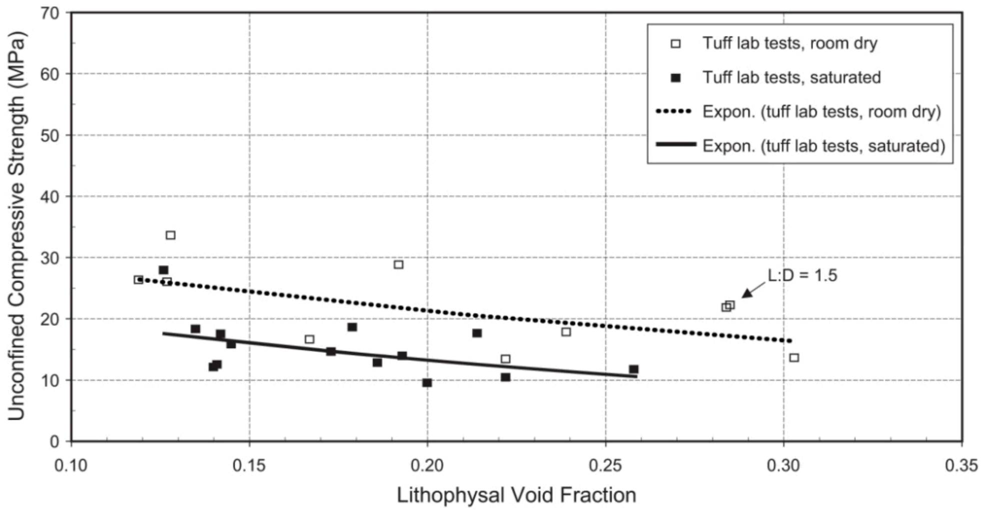
Approach to Drift Degradation Assessment in Lithophysal Rock

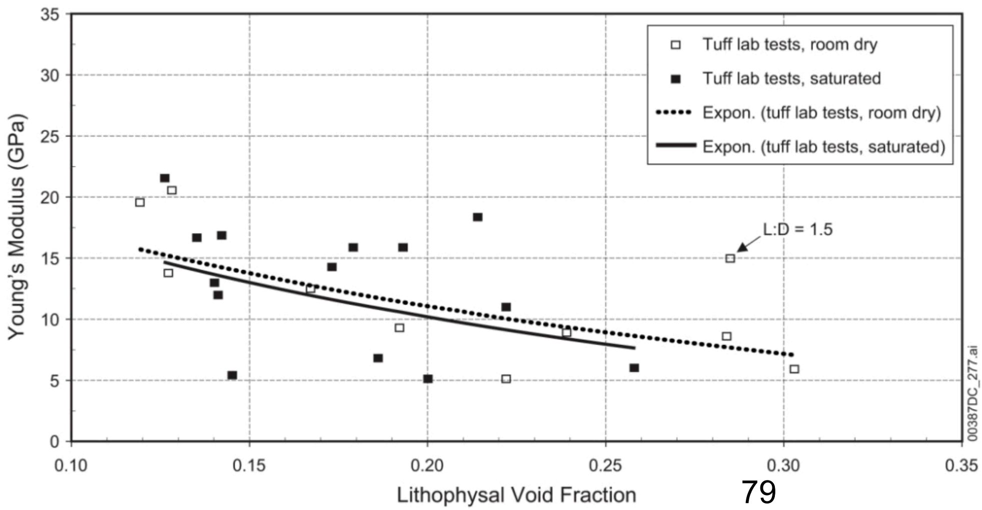


Justification for a 2D Isotropic Model of Lithophysal Rock

- **The size of the internal lithophysae structure and fracture spacing is much smaller than the drift size (i.e., 5.5-m diameter).**
- **There is no preferred direction in the fracture or lithophysae orientation that would justify introduction of anisotropy into drift scale modeling.**

Laboratory Testing on Large Samples



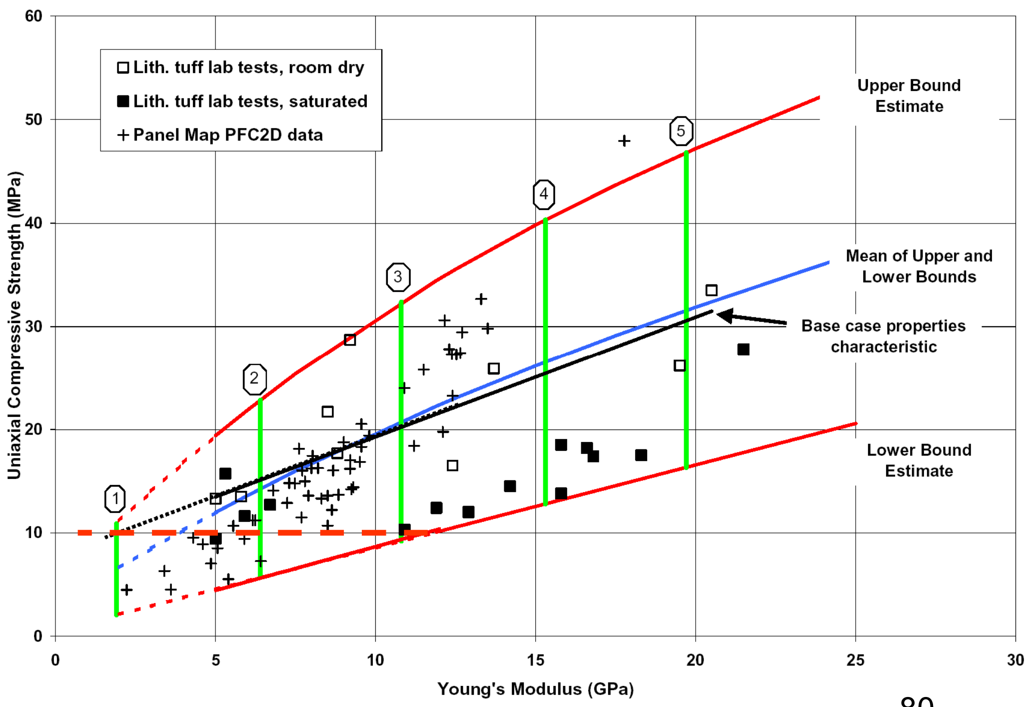


(a)

(b)

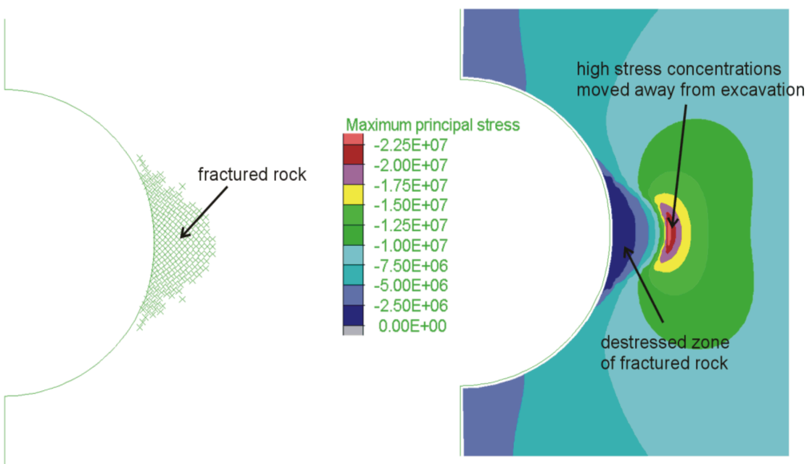
Range of Strength and Stiffness for Lithophysal Rock Mass Used in Drift Degradation Analyses

Category	~ % of Tptpll	~% lith porosity
1	6	>25
2	15	20-25
3	26	15-20
4	27	10-15
5	26	<10



Modeling Approaches Used for Drift Degradation Assessment in Lithophysal Rock

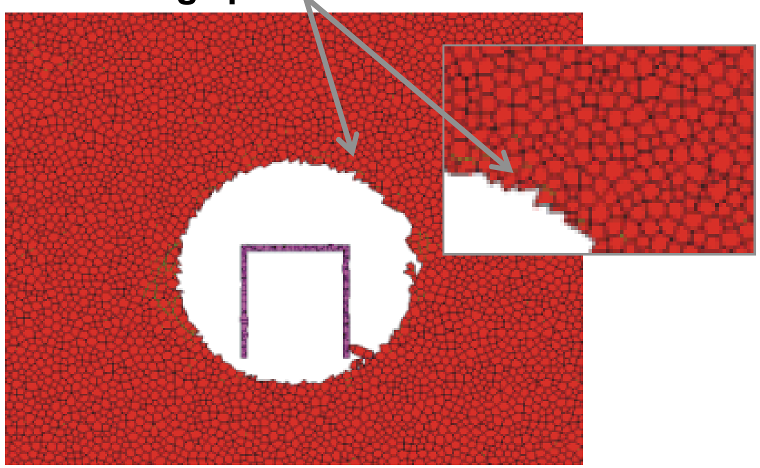
Continuum



- **Material response represented as an elastic-plastic material with Mohr-Coulomb failure criteria defined by rock mass shear and tensile strength.**
- **Rock mass progressively fails when stress state satisfies failure criteria.**
- **Rock cannot dislodge and fall due to continuum assumption.**

Discontinuum

Yield represented by shear or tensile failure along "potential" surfaces



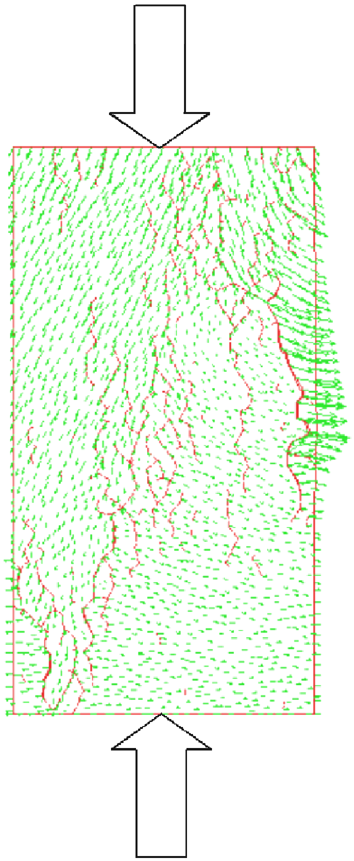
- **Rock mass represented by a large number of small, randomly-shaped elastic blocks bonded at contacts with rock mass shear and tensile strength.**
- **Bonds between blocks may progressively fail when stress satisfies failure criteria.**
- **Rock blocks may dislodge and fall under gravity or seismic load – allows estimate of the ultimate equilibrium shape of the excavation and failed rock volume.**

Discontinuum Model Calibrated to Stress-Strain Response in Unconfined Compression

- Three material parameters are of particular importance to stress level and mechanical stability of the drifts:
  - Modulus
  - Uniaxial compressive strength
  - Post-peak strength brittleness.
- Model stiffness and block interface strength adjusted to achieve a calibration of the Young's modulus and uniaxial compressive strength for range of lithophysal rock categories.
- Post-peak behavior of rock mass is highly random and dependent on a large number of parameters (e.g., sample size).
- We do not attempt to specifically calibrate the model to post-peak behavior; instead we made sure that numerical model is more brittle than observed behavior from the tests as this conservatively predicts more extensive drift failure.

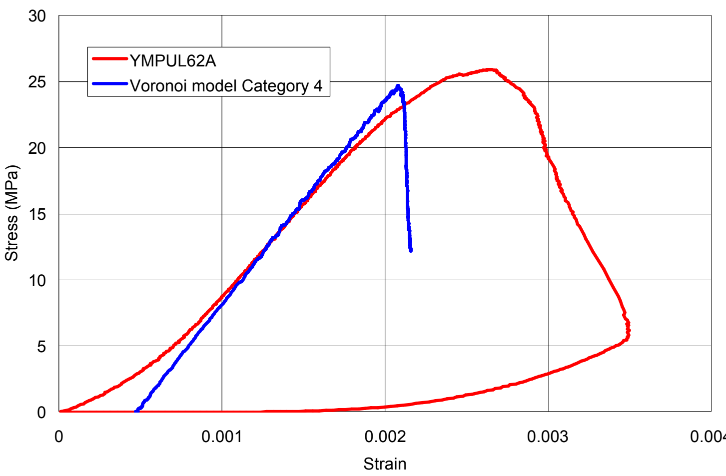
Calibration of Lithophysal Model to Laboratory Compression Testing on Large Rock Core Samples

Applied Axial Load

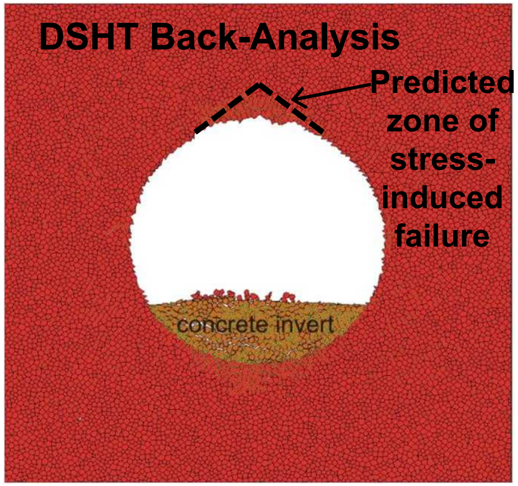


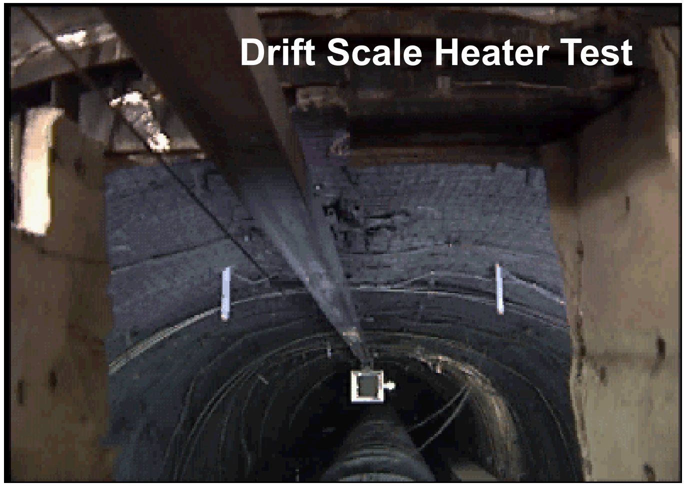
Axial splitting parallel to applied stress

Example of UDEC Model Calibration to Laboratory Compression Test

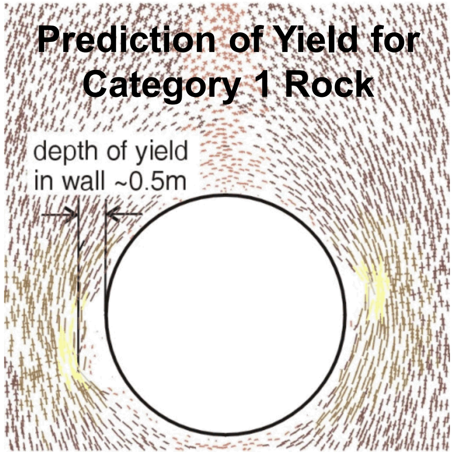


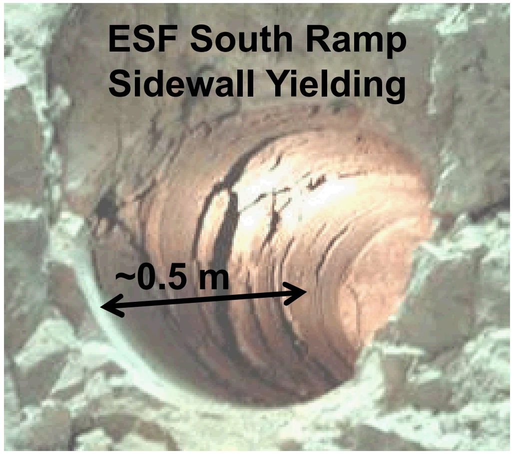
Comparison of Model Predictions to Observations of Fracturing and Drift Stability in the ESF





- Model verified against observed Drift Scale Heater Test (DSHT) roof spalling timing and extent during thermal overdrive





- Model verified against observations of depth of fracturing in approximately 60 large diameter boreholes in ESF and ECRB

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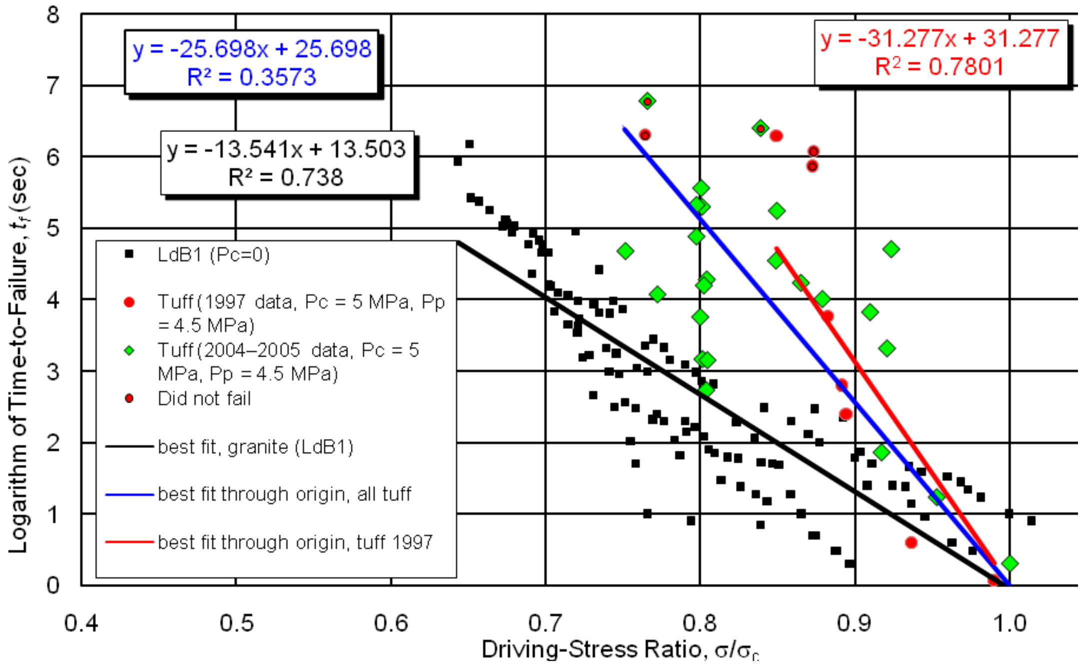
Impact of Time-Dependency on Drift Stability in Lithophysal Rock

- **Time-dependent strength reduction of rock mass estimated from laboratory testing of time-to-failure for various ratios of applied stress to short term strength at 150ºC and saturated conditions.**
- **Sensitivity study of drift stability conducted for range of lithophysal rock mass strength categories.**



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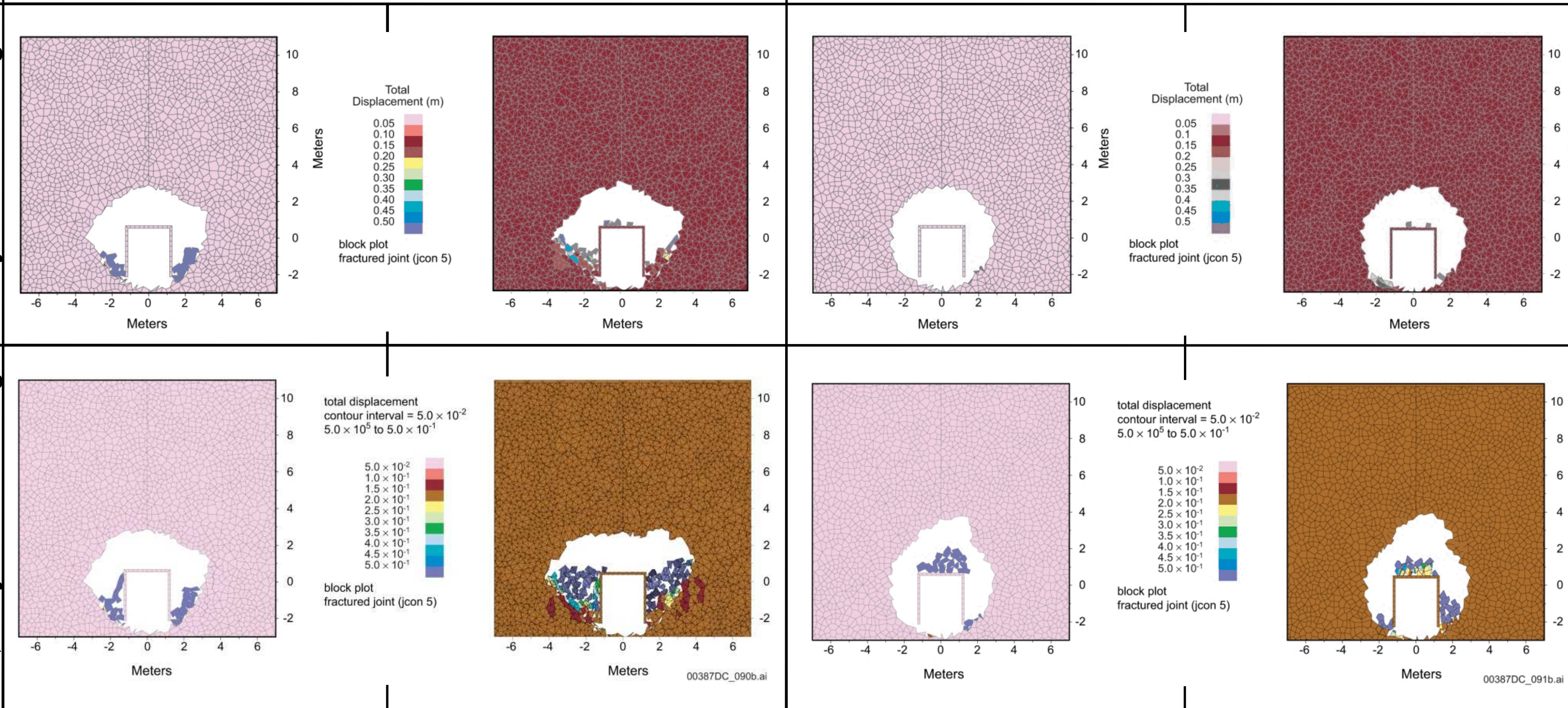
Drift Profiles for Combined Thermal, Time-Dependency, and 1×10^{-4} Seismic Ground Motion

	Rock Mass Strength Category 2		Rock Mass Strength Category 5	
80 years of heating				
10,000 years of heating				
	before seismic shaking	after seismic shaking	before seismic shaking	after seismic shaking



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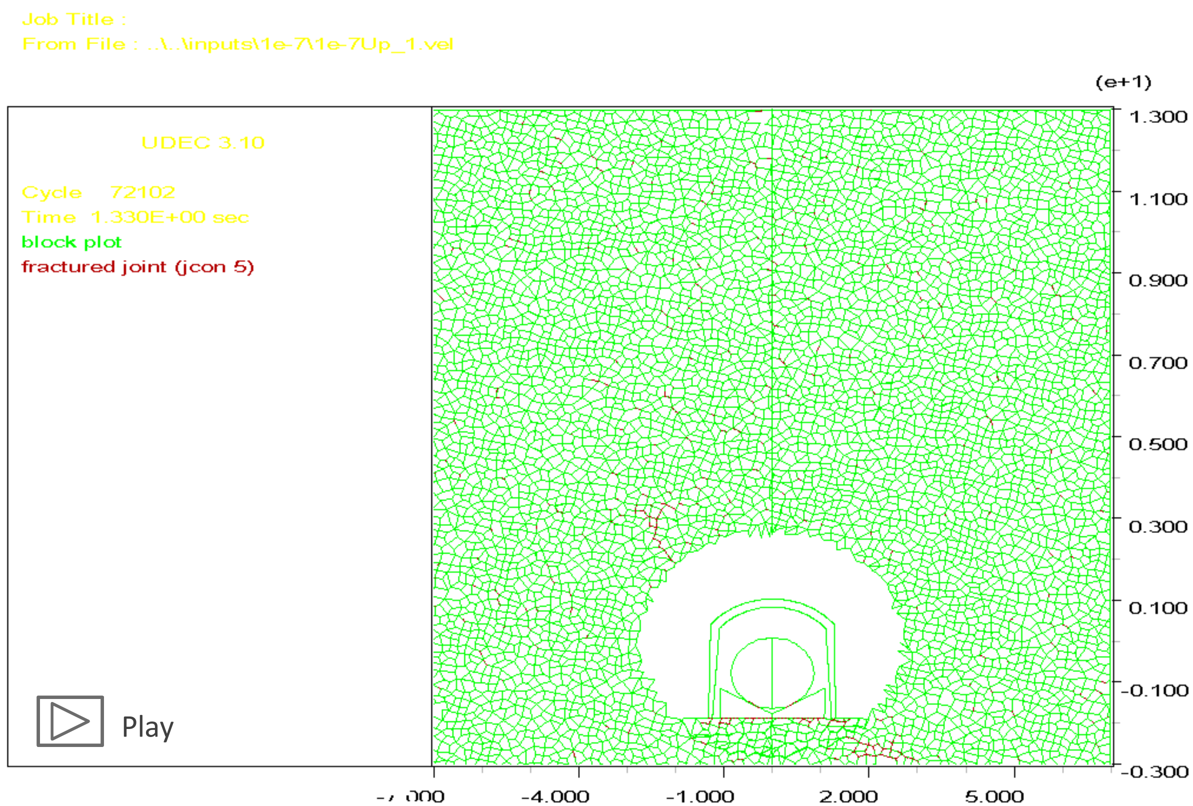
Seismic Response of Drifts in Lithophysal Rock

- **2D dynamic simulations of the drift subjected to seismic ground motions of different intensity were carried out.**
- **Different PGV levels (0.4 m/s, 1.05 m/s and 2.44 m/s) and multiple ground motions at each PGV level were considered.**



- **Analyses show minor rockfall at the 0.4 m/s PGV level and total drift collapse at the 2.44 m/s PGV level.**
- **Transition is observed at the 1.05 m/s PGV level.**

Rockfall Results in Lithophysal Rock

- Detailed underground mapping and laboratory and field testing of Yucca Mountain tuffs have been carried out at a range of temperature and saturation conditions.
- Numerical models have been validated against results from large-scale laboratory and field testing, and predictions are consistent with observations of drift response observed in the ESF and ECRB.
- Multiple modeling approaches were used. Discontinuum approach is consistent with results of continuum methods, but also capable of predicting rockfall volume.
- No significant rockfall predicted due to thermally induced stresses, time-dependency results in small amounts of rockfall through thermal pulse phase of repository.
- No significant rockfall in lithophysal rock predicted for seismic ground motions from the 0.4 m/s PGV level; drift completely collapses at the 2.44 m/s PGV level.

Key Requirements of Performance Confirmation

- **Confirm that subsurface conditions, geotechnical and design parameters are as anticipated and that changes to these parameters are within assumed limits.**
- **Confirm that the waste retrieval option is preserved.**
- **Evaluate information used to assess whether natural and engineered barriers function as intended.**
- **Evaluate effectiveness of design features intended to perform a postclosure function during repository operation and development.**
- **Monitor waste package condition.**

Approach for Developing a Performance Confirmation Program

1. Select performance confirmation parameters and test methods
2. Predict performance and establish a baseline
3. Establish bounds and tolerances for key parameters
4. Establish test completion criteria and variance guidelines
5. Plan activities, and construct and install the performance confirmation program
6. Monitor, test, and collect data
7. Analyze and evaluate data
8. Recommend corrective action in the case of variance.

Focus on Public Health and Safety

- **Three primary questions use risk insights to focus attention on issues important to public health and safety:**
  - **What can go wrong?**
  - **How likely is it?**
  - **What are the consequences?**

Selection Criteria to Confirm Postclosure Performance

- How sensitive are barrier capability and system performance to the parameter?
- What is the level of confidence in the current knowledge about the parameter?
- How accurately can information be obtained by a particular test activity?

General Requirements
Testing and Monitoring

Activity	Description
• Precipitation monitoring	Monitoring of precipitation and composition analysis.
• Seepage monitoring	Seepage monitoring and laboratory analysis of water samples.
• Subsurface water and rock testing	Laboratory analysis of chloride mass balance and isotope chemistry based on samples taken at selected locations of the underground facility.
• Drift inspection	Regular inspection of non-emplacement drifts and periodic inspection of emplacement drifts, a thermally accelerated drift, and other underground openings using remote measurement techniques, as appropriate.
• Thermally accelerated drift near-field monitoring	Monitoring of near-field coupled processes (thermal-hydrologic-mechanical-chemical), properties, and parameters associated with a thermally accelerated drift.
• Thermally accelerated drift in-drift environment monitoring	Monitoring and laboratory testing of gas composition; water quantities, composition, and ionic characteristics (including thin films); microbial types and amounts; and radiation and radiolysis within a thermally accelerated drift.

Geotechnical and Design Monitoring and Testing

Activity	Description
• Subsurface mapping	Mapping of faults, fractures, and stratigraphic contacts.
• Seismicity monitoring	Monitoring regional seismic activity. Observation of surface and subsurface (large magnitude) fault displacement after significant local or regional events.
• Construction effects monitoring	Monitoring construction deformation to confirm mechanical rock properties.
• Thermally accelerated drift thermal-mechanical monitoring	Monitoring drift and invert shape and integrity in a thermally accelerated drift.

Design Testing
(Other than Waste Packages)

Activity	Description
• Seal testing	Laboratory testing of effectiveness of borehole seals followed by field testing of effectiveness of gallery and shaft seals. Testing, as appropriate, to evaluate the effectiveness of backfill placement.

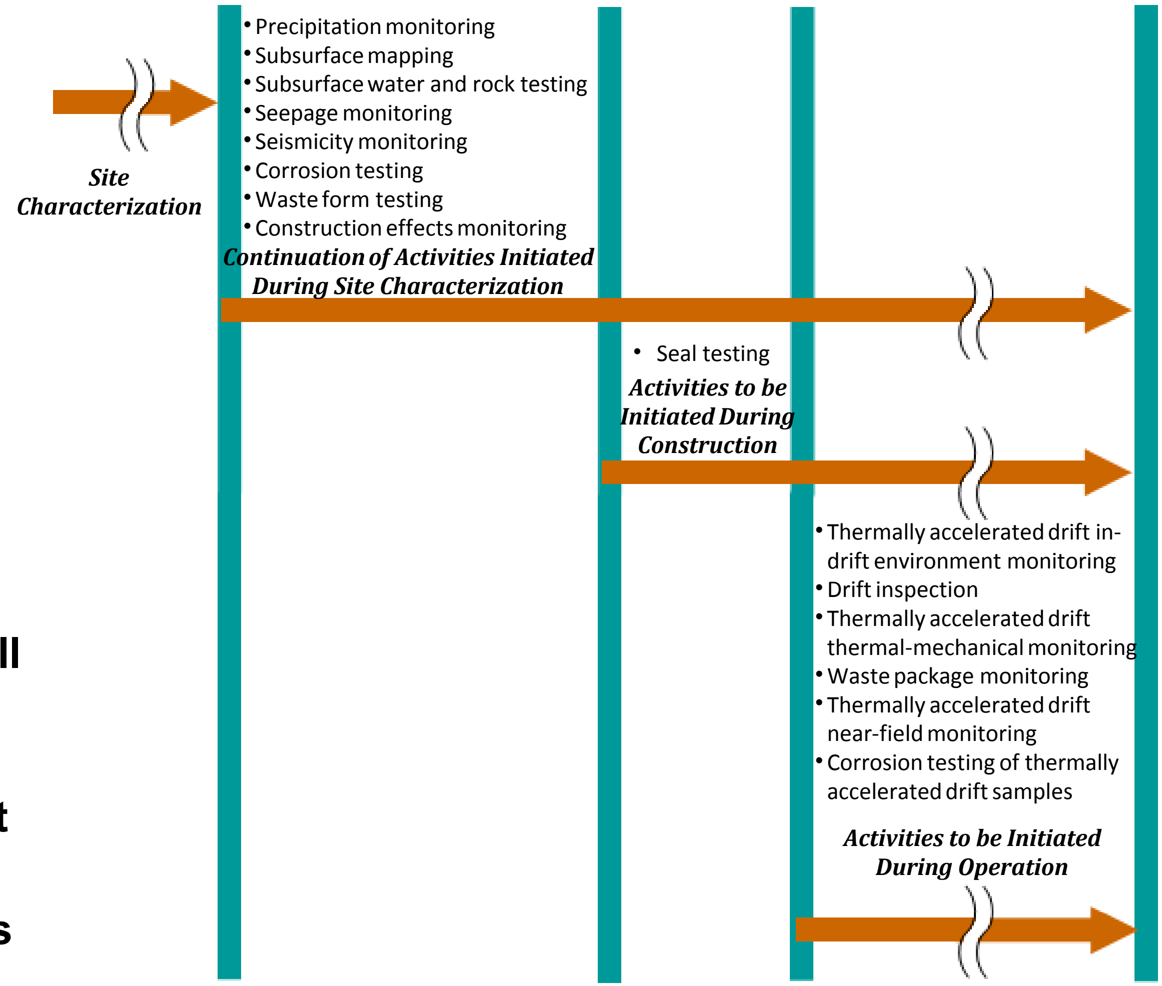
Monitoring and Testing of Waste Packages

Activity	Description
• Waste package monitoring	Remote monitoring for evidence of external corrosion of the waste package.
• Corrosion testing	Corrosion testing in the laboratory of waste package samples in the range of representative repository thermal and chemical environments. Includes laboratory testing of general corrosion and localized corrosion.
• Corrosion testing of thermally accelerated drift samples	Corrosion testing in the laboratory of waste package samples exposed to conditions in a thermally accelerated drift. Includes corrosion model applicability and laboratory testing of general corrosion and localized corrosion.
• Waste form testing	Waste form testing (including waste package coupled effects) in the laboratory under internal waste package conditions.

Source: BSC 2004c, Table 3-2

Performance Confirmation Testing/Monitoring Activity Timelines

- **Planning for currently identified candidate performance confirmation activities is ongoing; methods and approaches other than those discussed here may be employed.**
- **Monitoring and testing methodologies for performance confirmation activities conducted during site characterization are well developed.**
- **Construction period activities require refinement and finalization.**
- **Operational period activities are general conceptualizations.**



Source: BSC 2004b, Figure 6-1

Program Response to Change

- **Advances in technology are likely to occur over the life of the program**
- **The monitoring program should permit re-evaluation and modification of activities as the state of understanding and technology changes**
- **An integration group and workshop approach is recommended to facilitate evaluation of new data and program effectiveness, including technological advancement, and ensure the flexibility needed to accommodate necessary changes**

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