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SEISMIC PERFORMANCE OF UNDERGROUND FACILITIES

by

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ABSTRACT

A workshop was held in Augusta, GA, February 11-13, 1981 to review and assess the state-of-the-art for determining and predicting earthquake damage to underground facilities. The papers presented related to data collection and analysis, modeling, and repository design. Discussion groups addressed (1) seismology (2) rock mechanics and hydrology, (3) modeling, (4) design, and (5) licensing, siting, and tectonics.

Most scientists in attendance believed that enough was known to proceed with site selection, design, and licensing of a waste repository. However, there was recognition of several items of research that would enhance understanding of the subsurface effects of seismicity.

In general, the subsurface effects of earthquakes are substantially less than their surface effects. This conclusion is supported by both observation and by modeling studies. The absence of wave reflections, the absence of high flexural stresses, and the absence of poor soil conditions contribute to the improved seismic performance of subsurface facilities.

Seismic considerations for geologic disposal of nuclear waste vary with the phase of operation. During construction and waste loading, the primary concern is for the safety of onsite personnel. However, during long-term waste storage, the principal interest is in the migration of contaminants due to seismic cracking and enhancement of permeability. Backfilling the storage facility will mitigate this effect.

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SEISMIC PERFORMANCE OF UNDERGROUND FACILITIES

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A workshop was held in Augusta, GA, February 11-13, 1981, with 55 scientists and engineers in attendance. The objective of this workshop was to review and assess the state of the science of determining and predicting damage to underground facilities from earthquakes, with particular emphasis on the ultimate goal of developing criteria for the siting and design of mined geologic nuclear waste repositories. The workshop consisted of one day of presentations to review the status of current work on the subsurface effects of earthquakes. These talks fell into four categories -- Introduction, Data Collection and Analysis, Modeling, and Design. The second day consisted of discussions and assessments by subgroups divided along discipline lines. These are Seismology; Rock Mechanics and Hydrology; Modeling; Licensing, Siting, and Tectonics; and Design.

The following issues were suggested for discussion:

1. What is the nature of seismic motions that cause damage in the subsurface?

2. What is the importance of in-situ stress in localizing earthquakes in a mined environment?

3. What is the role of in-situ stress in mine stability?

4. What are the seismic effects on shafts, particularly those that cross lithologic discontinuities?

5. At what depth do surface waves develop? What effect do they have on shaft design?

6. What is the effect of seismic motions on permeability of the rock, particularly near a mined facility?

The purpose of the workshop was not to list research needs. The most important goal of the workshop was to evaluate the significance of each issue discussed to the safety, licensing, and siting of a subsurface nuclear waste repository.

A questionnaire was distributed both before and after the workshop to poll the opinions of the attendees on whether the level of knowledge was sufficient to move forward on site selection, licensing, and design, (M.R. Wigley). This questionnaire was broken down into six levels of confidence -- three in the category of yes and three in the category of no. In the pre-workshop poll, 63% believed that knowledge was adequate, (Figure 1). In the post-workshop poll, there was a general migration of opinion in the direction of greater confidence as indicated by changes in the six levels of confidence. In the post-workshop poll, 89% believed knowledge was adequate, (Figure 2).

A similar workshop was held in Seattle Washington in February 1980 (J. A. Caggiano) although its focus was more specifically related to the Hanford and Nevada Test sites. The discussion sessions were divided into (1) tectonics and seismology, (2) subsurface ground motion, and (3) analysis and design.

Data Collection and Analysis

Data presented in several talks (H. R. Pratt, C. R. McClure) indicated that subsurface effects are substantially less than surface effects from the same or similar earthquakes. The absence of abundant data to support these conclusions is, in itself, an indication that seismic effects in the subsurface are minimal. More data is available for tunnels than for deep mines (Figures 3, 4, and 5).

The ratio of peak acceleration at depth to that at the surface can be calculated (G. N. Owen), but the decrease is not uniform due to interference between the incident (upward-traveling) wave and the reflective (downward-traveling) wave which depend on the duration of the wave train, (Figure 6). The fact that acceleration actually decreases with depth is shown by the comparison of the acceleration history from the same nuclear event (Meg=5.4) as observed at the surface, 61 m, and 343 m, (Figures 7, 8, and 9)(L. J Vortman). The medium consists of 312 m of alluvium over a layer of basalt to 350 m, which in turn overlies tuff below. There is little difference between the observation at the surface and at 61 m, but a substantial decrease at the 343 m station. Another example from the Nevada test site shows substantial reduction with depth, (Figure 10 and 11).

One paper (D. M. Perkins) addressed the manner in which probabilistic ground motions change with increasing return period. The larger the ground motion values, the less that the increase of these values at longer return periods depends on the conventional seismicity parameters, such as magnitude and distance, and the more the increase depends on the statistical variability of these factors. Because of the lack of statistics in quiet areas compared to seismically active areas, this variability is greater, making it more difficult to predict the return period for large earthquakes.

Modeling

This category dealt with numerical and physical modeling to enhance the understanding of processes and effects. The first paper (K. K. Wahi) presented the results of a parametric numerical modeling contracted by SRL to study earthquake effects on tunnels for a nuclear waste repository. Modifications had to first be made to existing numerical methods in order to handle joint slip and tensile fracture. The actual records of three earthquakes were used to excite the finite difference grid. The simulated history included instantaneous excavation at a depth of 600 m followed by a 6-month time period to approach equilibrium, then instantaneous emplacement of the waste accompanied by a thermal load of 60 kilowatts per acre. After 4.5 years (5 years total time) the earthquake struck. Three rock types - salt, granite, shale - were investigated. Parametric variations were also made in in situ stress and pore pressure. For salt, only the motion from a small earthquake of high acceleration (0.95g) and high frequency caused instability in the facility, (Figure 12). For granite, the same earthquake caused instability, (Figure 13). In addition, a moderate earthquake (0.41g) caused an instability when horizontal stress was equal to twice the vertical stress. For shale, a number of parametric situations caused instability of the tunnel, (Figures 14 and 15).

The second paper (B. C. Trent) compared the results of the parametric modeling described in the previous paper to empirical results from mine support studies. The modeling results were consistent with empirical calculations of tunnel stability.

The third paper (N. Barton) described the results of physical scale modeling of tunnels in joint systems using 20,000 discrete blocks of weak brittle material. Conclusions were drawn on how to treat joint strength and stiffness in modeling.

Design

There were three talks in the category of design. The first of these (G. N. Owen) was on considerations in developing seismic design criteria. Empirical methods have always played a major role in design of underground openings. However, licensing procedures have served to increase the rigors of seismic analysis, but the state of quantitative methods is not yet as sophisticated for subsurface structures as it is for surface structures. Figure 16 shows potential damage modes during the operational phase and during the decommissioned phase.

Underground facilities in rock may experience higher acceleration with smaller amplitudes at higher frequency than surface facilities, (T. R. Kuesel). Flexible elements of the underground facility will have a smaller response and stiff elements will have a greater response than for a surface facility. In the cross section view of a tunnel, the facility vibrates as a unit with no out-of-phase motions. In the longitudinal dimension, out-of-phase motions may develop. The above statements apply generally to tunnels, but two additional considerations have to be given to a repository which is very deep and operating at elevated temperatures. The first is the in situ tectonic stress field coupled with the strains unlocked by excavation of the facility. The second is the alteration of the mechanical properties of the rock at high temperatures. The analysis must consider the combination of static, dynamic, and thermal loads and the response of the rock to these loads, which will not be simply additive.

A seismic evaluation of the proposed headframe structure and the cable/hoist system was presented, (H. Kamil). Seismic input motions were developed. Recommendations were made to improve the design of the head frame structure. The cable/hoist system was structurally adequate but there was a possibility that the cages might impact the shaft walls or adjacent cables.

SUMMARY

The summary of the first day's talks (G. A. Young) concluded that ample qualitative evidence had been given that underground openings have better seismic perforance than surface structures. It therefore seems that little additional benefit is to be gained in pursuing further qualitative documentation of this fact. However, elucidation as to why this is true, particularly in regard to quantitative measures, is worthy of pursuit. A partial answer to this question was given.

There are three reasons for improved subsurface seismic performance, (Figure 17); (1) the absence of wave reflections at the surface, (2) surface structures respond as unsupported vertical cantilever elements as opposed to underground openings which are not subjected to high flexural stresses, and (3) seismic failure of surface structures is commonly associated with poor soil conditions that should not be present at depth. Instrumentation of deep underground openings will be helpful in providing the quantitative information that is needed, but, in the meantime, existing analytical procedures are adequate. Some studies of underground response to nuclear tests are helpful, but it must always be kept in mind that there are substantial differences in the source mechanisms of earthquakes and nuclear tests.

The tools are at hand to design underground storage facilities for reliable performance in a seismic environment, but such design will probably be overly conservative. It is probable that considerations for the thermal load may have greater impact on the design than those for seismic loads. A probablistic treatment of seismicity should be adequate.

In regard to licensing and siting studies, current investigational seismic studies as performed for surface nuclear facilities are adequate except the additional rock properties at depth will be needed as will the in situ lateral-to-horizontal stress ratio. Classically, mines are designed as conditions are encountered by the advancing mine; however, for a nuclear waste repository, licensing procedures will require greater reliance on analytical procedures to show conservatism in the design.

Subgroup Deliberations

On the second day the workshop divided into five subgroups to consider particular aspects of the seismic performance of underground facilities, (Figure 18).

Seismology

There is no lack of critical seismic data or theory that would prevent proceeding with the site selection process. If a site can be licensed through the normal procedures that have been developed for licensing a surface nuclear facility, it can probably also be licensed in regard to the subsurface aspects of seismicity provided that the rock type is suitable for other stress considerations. Some research will, however, enhance the transferability of studies for the surface effects of earthquakes to those concentrating on the subsurface. The following recommendations were made:

1. Additional measurements of ground motion as a function of depth.
2. More explicit descriptions of mine tremors.
3. More studies of in situ stress.
4. Studies of earthquake parameters in relation to subsurface damage.
5. A centralized data repository for studies of subsurface effects of seismicity.
6. Studies of the relation between permeability and seismicity.

Rock Mechanics and Hydrology

The state of the art is such that enough is known to design repositories against the anticipated earthquake loadings. The repository should not be sited close to active faulting. Backfilling for the decommissioned phase is an important mitigating design feature as it renders the effects of an earthquake unimportant in periods greater than 100 years. Earthquakes are most important when other stresses (mechanical-thermal) cause the facility to approach closest to the failure envelope. This is expected in the period 25-100 years. The additional load factor for dynamic design is expected to be between 10-20% of the static load factor. The disturbed zone around a tunnel caused by an earthquake is unlikely to exceed 2 tunnel diameters; hence regional permeability enhancement due to seismicity is unlikely to be a problem. Siting should avoid areas where the horizontal to vertical stress ratio is greater than 2.

Modeling

All the computational tools needed to begin site-specific seismic-response analyses are available, even though design methodologies are yet to be determined and some of the data bases are sparse. Additional generic earthquake studies are not expected to yield significant dividends. The weakest link in the analytic data base is the definition of the seismic input motion. The greatest strength is the availability of numerous numerical models and analytical procedures. Continuing research in determining material mechanisms and material properties for modeling the thermomechanical and hydrological response of the geologic media is needed for all phases of the analysis. This includes dynamic properites for seismic response.

Licensing, Siting, and Tectonics

All issues should be considered licensing issues unless mitigating action can be taken. Such actions might be 1) mitigation through site selection, 2) solution by focused research, and 3) conservative engineering measures. Most issues can be mitigated by proper siting.

Licensing issues that have impact on site selection and conservative engineering design are:

1. Uncertainity of our knowledge of geologic and tectonic processes during time intervals of concern in repository siting.

2. Absence of an observed data base to confirm analytical models.

3. Development of an accepted probablistic methodology to replace current deterministic approaches.

4. A general low level of public confidence of existing technology for investigating the suitability of a host rock for a radioactive waste repository.

5. The lack of specific and detailed information about the relationship between tectonic activity and geohydrologic conditions.

6. Guaranteeing the long term stability of the geologic repository environment.

7. The absence of local and subregional knowledge of the current tectonic regime.

Design

If a site is chosen away from capable faults and major stress zones, such that shaking and not fault displacement is the major consideration, a repository facility can be adequately designed from a safety and licensing point of view. It is likely that seismic stresses will be small compared to in situ and thermal stresses. Historic data on the seismic performance of mines indicates that problems are not severe. A clear statement of performance requirements and acceptance criteria is needed so that inapplicable cases can be rapidly eliminated from consideration. Seismic performance and acceptance criteria are different for the operating and post operating phases. The performance requirement during the operating phase is that of mine safety with permeability enhancement not being a significant consideration. In the post operating phase, backfill will mitigate permeability enhancement as a consideration except perhaps around the shaft. Shafts should be designed with flexible or ductile linings to mitigate possible shear displacements at geologic discontinuties. Rock properties, as well as earthquake characteristics, should be presented as a probablistic format rather than as determistic values. Design of underground facilities requires flexibility to make adjustment for conditions encountered. Approval procedures should be similarly flexible and should contemplate a range of expected site conditions.

Summation

As several stated, it appears that the level of knowledge is sufficient to proceed with the investigations, analyses, design, and construction of an underground nuclear waste isolation facility. The subgroups provided a series of recommendations that appear compatible with each other. The next step is to translate and expand these recommendations into engineering criteria.

CONCLUSIONS

A central fact needs to be reemphasized--that there is ample documentation of the fact that subsurface damage from an earthquake is far less than surface damage from the same earthquake, (Figure 19). Thus, to apply the same seismic criteria to subsurface facilities as to surface facilities would appear to be overly conservative. In the early stages of a repository, seismic protection is a matter of industrial safety not public safety. In the later stages, backfilling the tunnels will have the important effect of decreasing the void space that might enhance cracking. Thus, although there remain scientific aspects of the subsurface effects of earthquakes that are not completely understood, the level of knowledge appears to be adequate to proceed with siting and licensing a repository from a seismic point of view. However, research should continue to enhance this understanding.

REFERENCES

1. Marine, I. W., Editor, **Proceedings - Workshop on Seismic Performance of Underground Facilities.** USDOE Document DP-1623, Savannah River Laboratory, Aiken, SC.

DO WE KNOW ENOUGH?

Percent		YES	Percent		NO
7	3	YES! OUR UNDERSTANDING IS COMPLETE. ALL THAT WE NEED FOR A PARTICULAR SITE IS THE RAW DATA TO ASSESS THE SEISMIC ENVIRONMENT AND ANALYZE ITS EFFECT ON THE WASTE ISOLATION SYSTEM.	16	7	NO, BUT WE BELIEVE THAT WE ARE NOT FAR AWAY. IF WE PURSUE A MODEST RESEARCH PROGRAM ON ISSUE(S) NUMBER(S) ______________, WE WILL BE THERE.
33	14	YES, FOR THE PRESENT. HOWEVER, WE RECOMMEND THAT WHEN A SPECIFIC SITE IS CHOSEN, THIS CONCLUSION BE REEVALUATED.	14	6	NO, FOR THE PRESENT. HOWEVER, IF WE ACTIVELY INVESTIGATE ISSUE(S) NUMBER(S) ______________, WE HAVE A CHANCE OF GETTING THERE.
23	10	YES, BUT TO DIMINISH THE UNCERTAINTY ASSOCIATED WITH ISSUE(S) NUMBER(S) __________, WE RECOMMEND THAT A RESEARCH PROGRAM BE INSTITUTED.	0	0	NO! AND WE NEVER WILL!
63	27	Total Yes	30	13	Total No

7 3 None of the above or No opinion

43 Total Respondents

FIGURE 1. Pre Workshop Poll

DO WE KNOW ENOUGH?

Percent		YES	Percent		NO
19	9	YES! OUR UNDERSTANDING IS COMPLETE. ALL THAT WE NEED FOR A PARTICULAR SITE IS THE RAW DATA TO ASSESS THE SEISMIC ENVIRONMENT AND ANALYZE ITS EFFECT ON THE WASTE ISOLATION SYSTEM.	11	5	NO, BUT WE BELIEVE THAT WE ARE NOT FAR AWAY. IF WE PURSUE A MODEST RESEARCH PROGRAM ON ISSUE(S) NUMBER(S) ____________, WE WILL BE THERE.
39	18	YES, FOR THE PRESENT. HOWEVER, WE RECOMMEND THAT WHEN A SPECIFIC SITE IS CHOSEN, THIS CONCLUSION BE REEVALUATED.	0	0	NO, FOR THE PRESENT. HOWEVER, IF WE ACTIVELY INVESTIGATE ISSUE(S) NUMBER(S) ____________, WE HAVE A CHANCE OF GETTING THERE.
14	14	YES, BUT TO DIMINISH THE UNCERTAINTY ASSOCIATED WITH ISSUE(S) NUMBER(S) ____________, WE RECOMMEND THAT A RESEARCH PROGRAM BE INSTITUTED.	0	0	NO! AND WE NEVER WILL!
89	41	Total Yes	11	5	Total No

0 0 None of the above or no opinion

46 Total Respondents

FIGURE 2. Post Workshop Poll

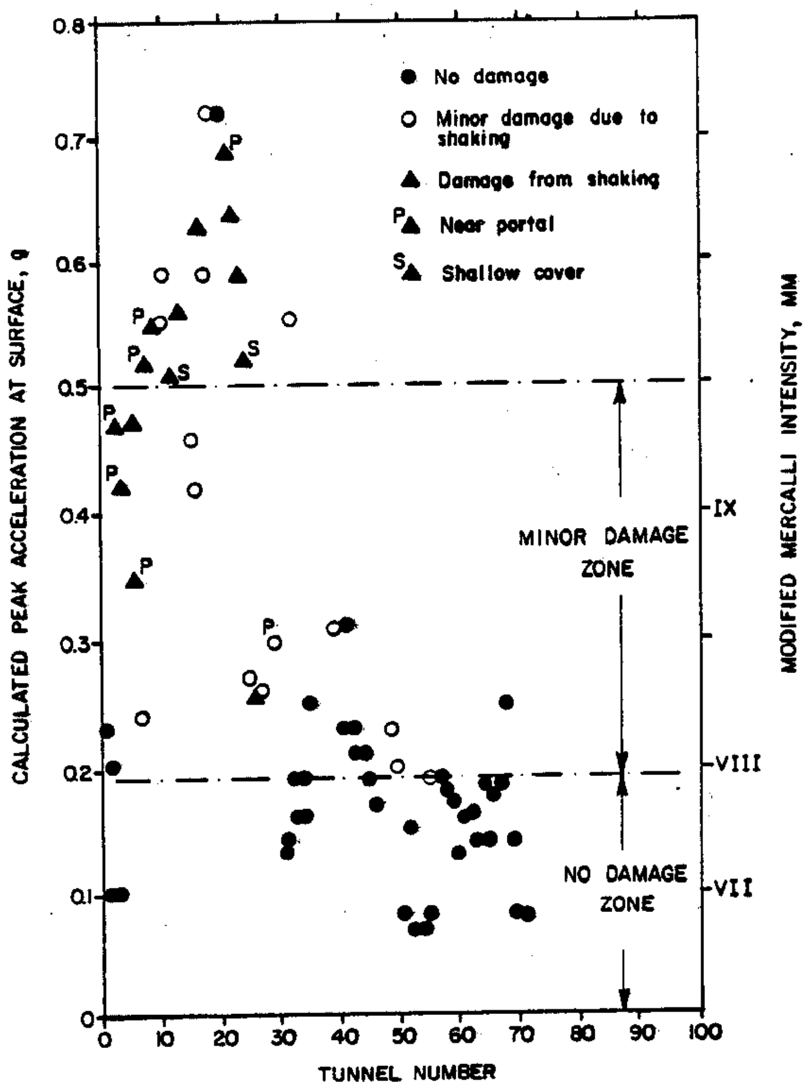


FIGURE 3. Calculated Peak Surface Accelerations and Associated Damage Observations (From Dowding and Rozen, 1978)

Total Number of Openings	Damage: None	Slight	Moderate	Heavy
82	45	27	4	6

SUMMARY OF UNDERGROUND OPENINGS IN ROCK WITH RESPECT TO DAMAGE

Number of Earthquakes	Total Number of Openings	Damage: None	Slight	Moderate	Heavy
46	72	51	13	6	2

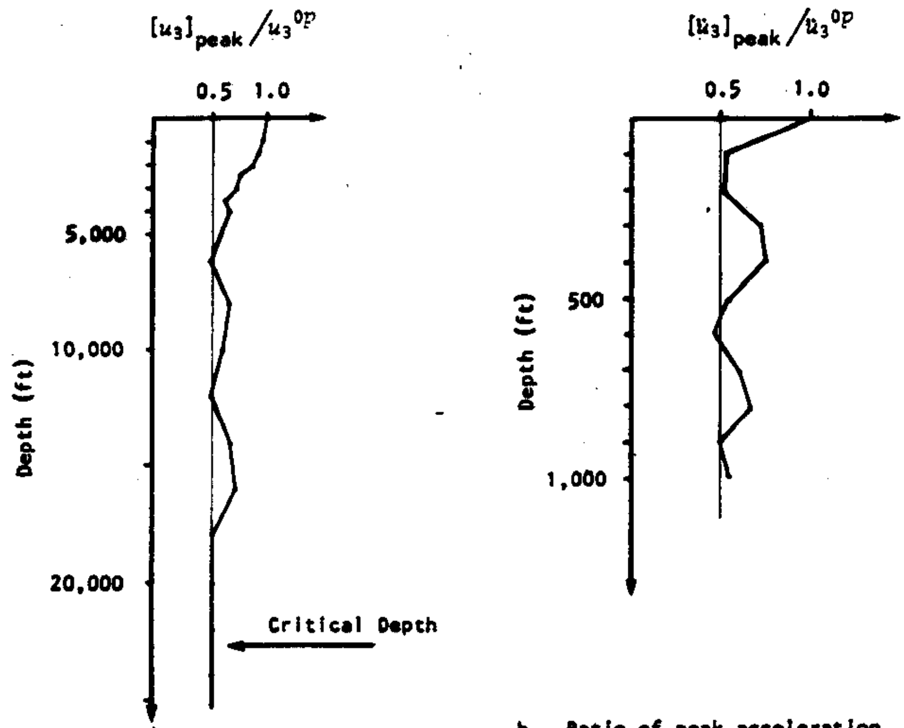
FIGURE 4. Summary of Underground Openings With Respect to Damage

Total Number of Openings Meeting Criteria*	Damage			
	None	Slight	Moderate	Heavy
18	10	6	2	0

*Selected Criteria are as follows;

1) Opening must be in rock,
2) Opening must have at least 300 ft of cover,
3) Opening has not suffered displacement due to faulting or landsliding.

FIGURE 5. Summary of Underground Openings Meeting Selected Criteria with Respect to Damage

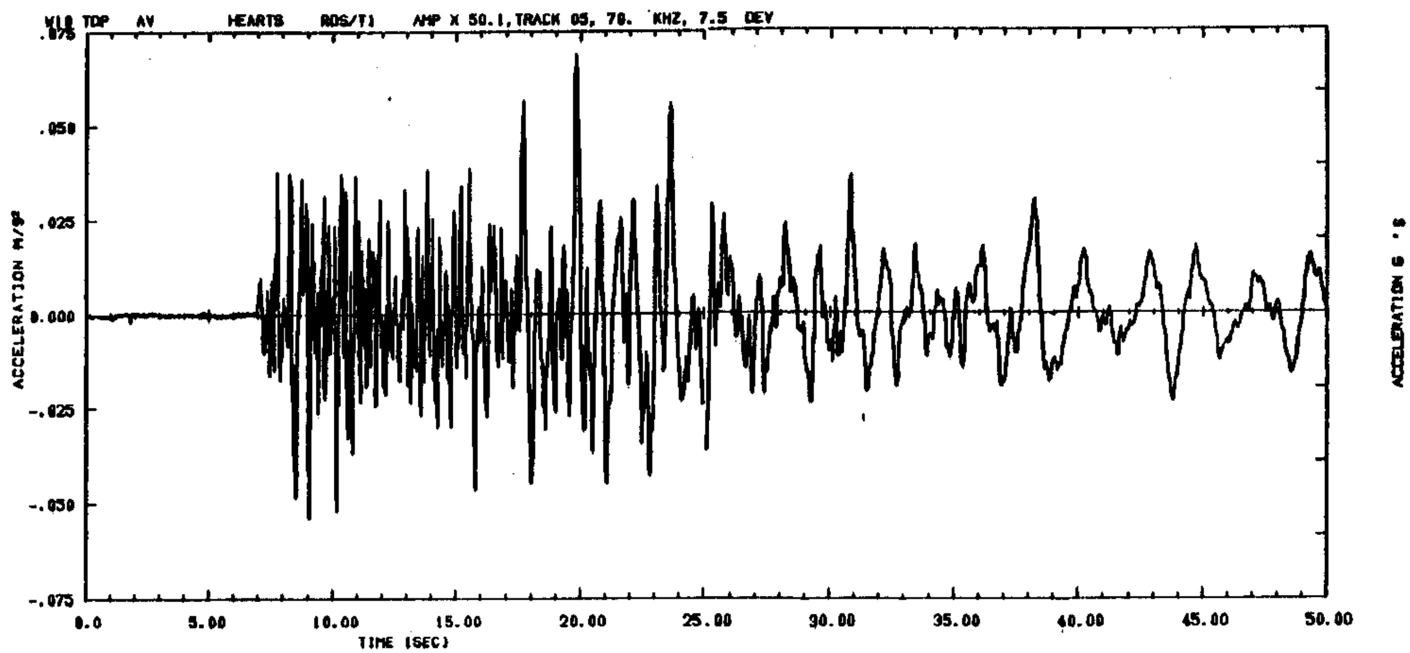


b. Ratio of peak acceleration at depth to peak acceleration at the surface

a. Ratio of peak displacement at depth to peak displacement at the surface

NOTE: 1 ft = 0.3048 m.

FIGURE 6. Variation of Peak Displacement and Peak Acceleration With Depth for the 1966 Parkfield (California) Earthquake.



FIRFIL IDT=.0020 HPF= .25 LPF= 27. VTB=.250 DPB=0.

ODT=.005 BWH= .16 BWL= 8. VTE=.166 DPE=93.

FIX= HLH= 167 HLL= 2399 FLL= -20. FLH= 0

AAS= 0. ASB= ASE= VSE= 0. DSE= 0.

14.34.35 02/06/81 14.34.35

FIGURE 7. Acceleration History at Surface, Vertical Component, Station W-10

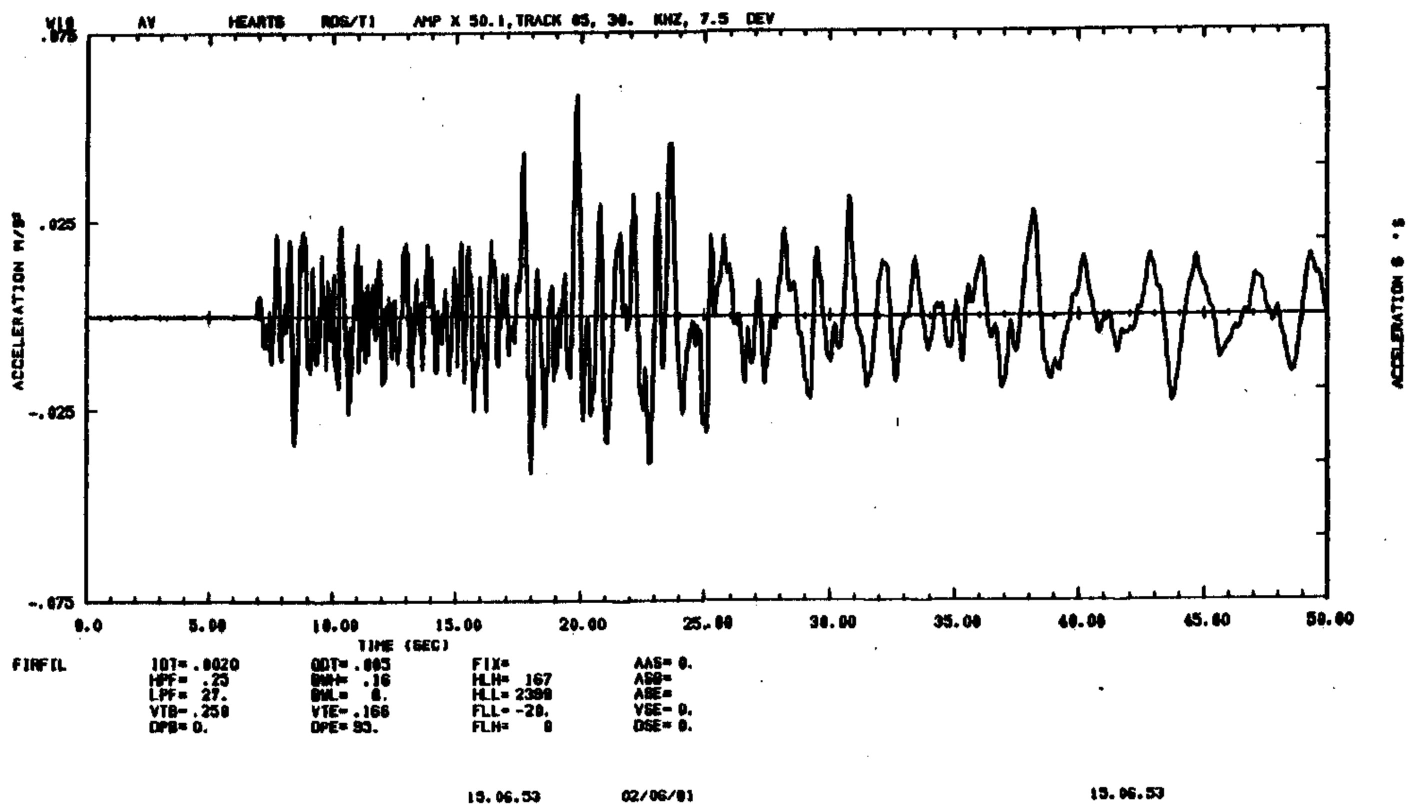


FIGURE 8. Acceleration History at 61 Meters, Vertical Component, Station W-10

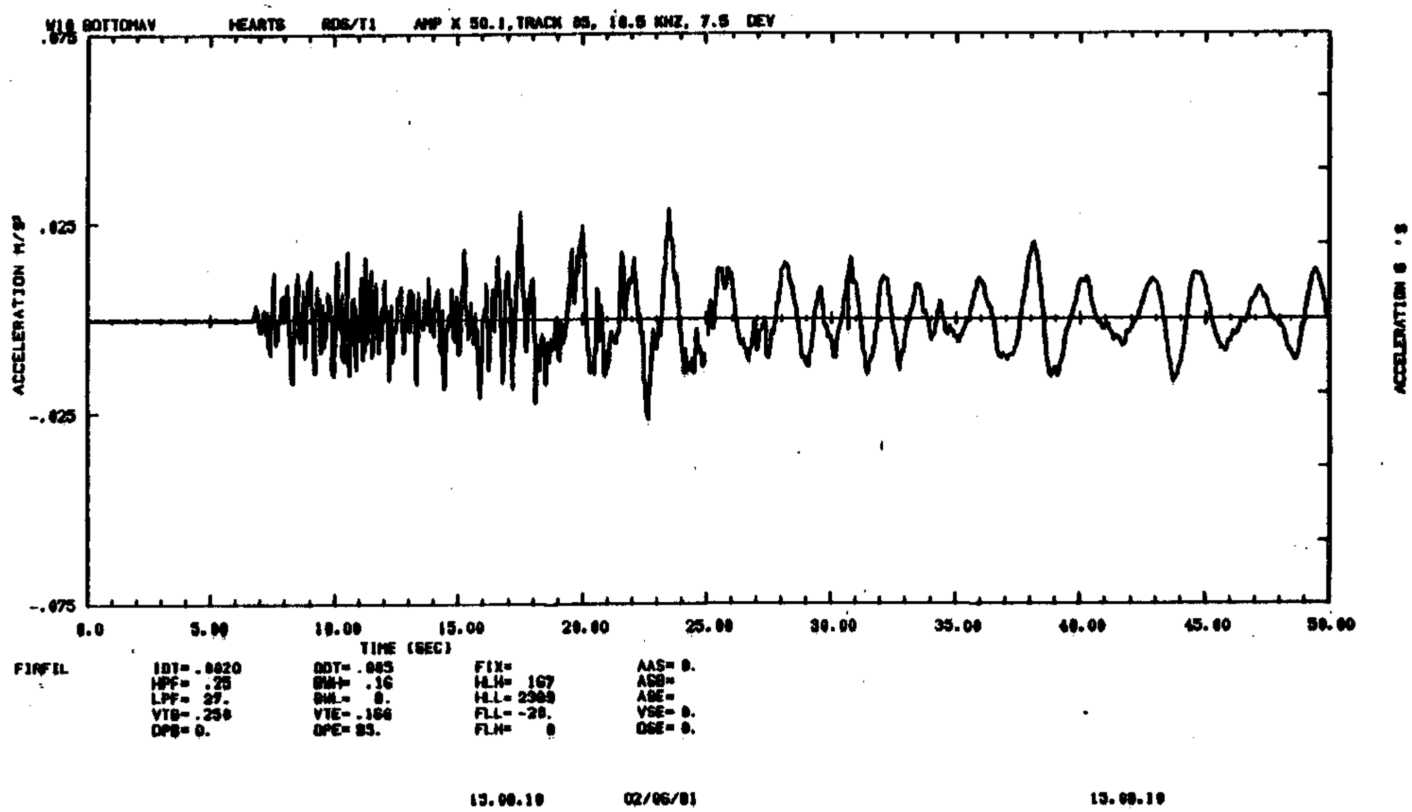


FIGURE 9. Acceleration History at 342.6 Meters, Vertical Component, Station W-10

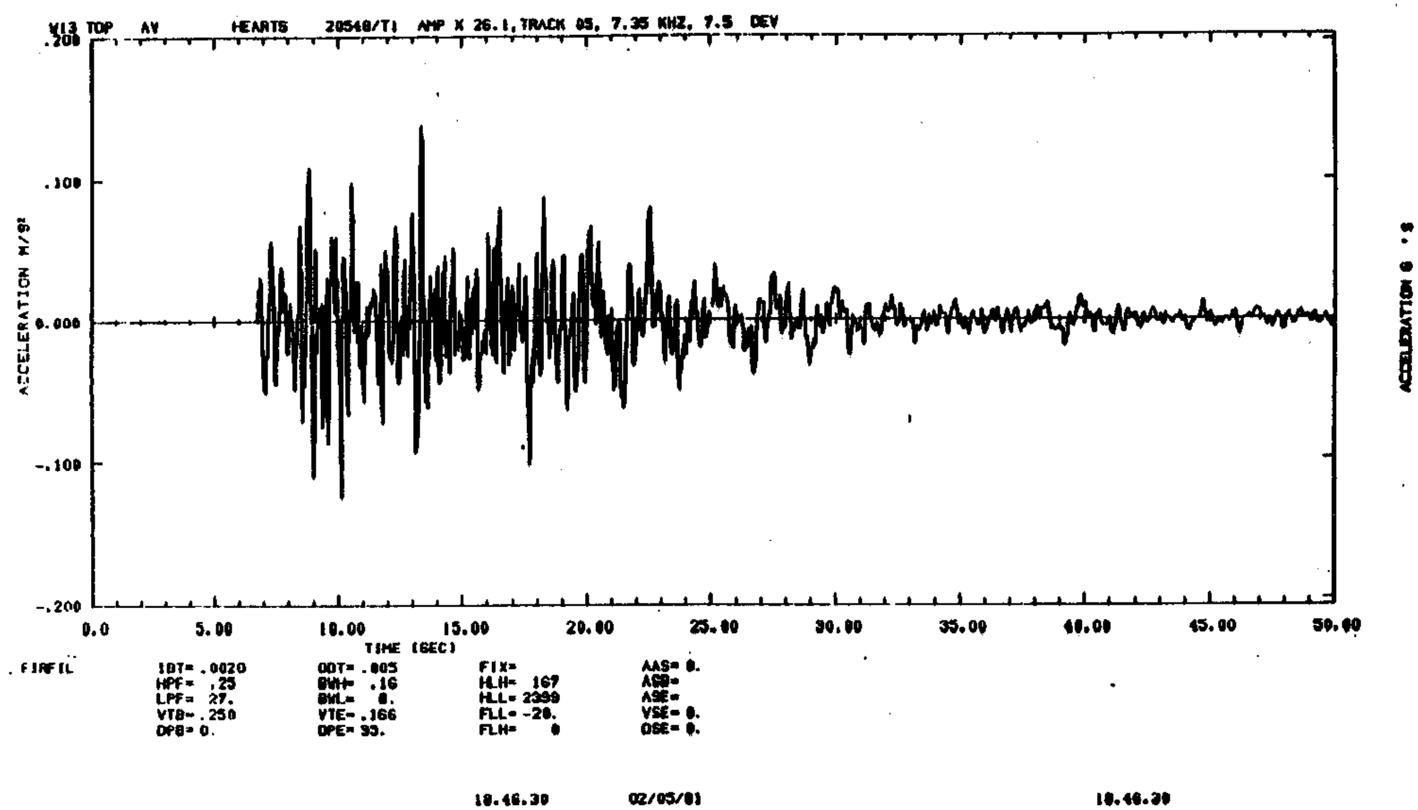


FIGURE 10. Acceleration History at Surface, Vertical Component at Timber Mountain

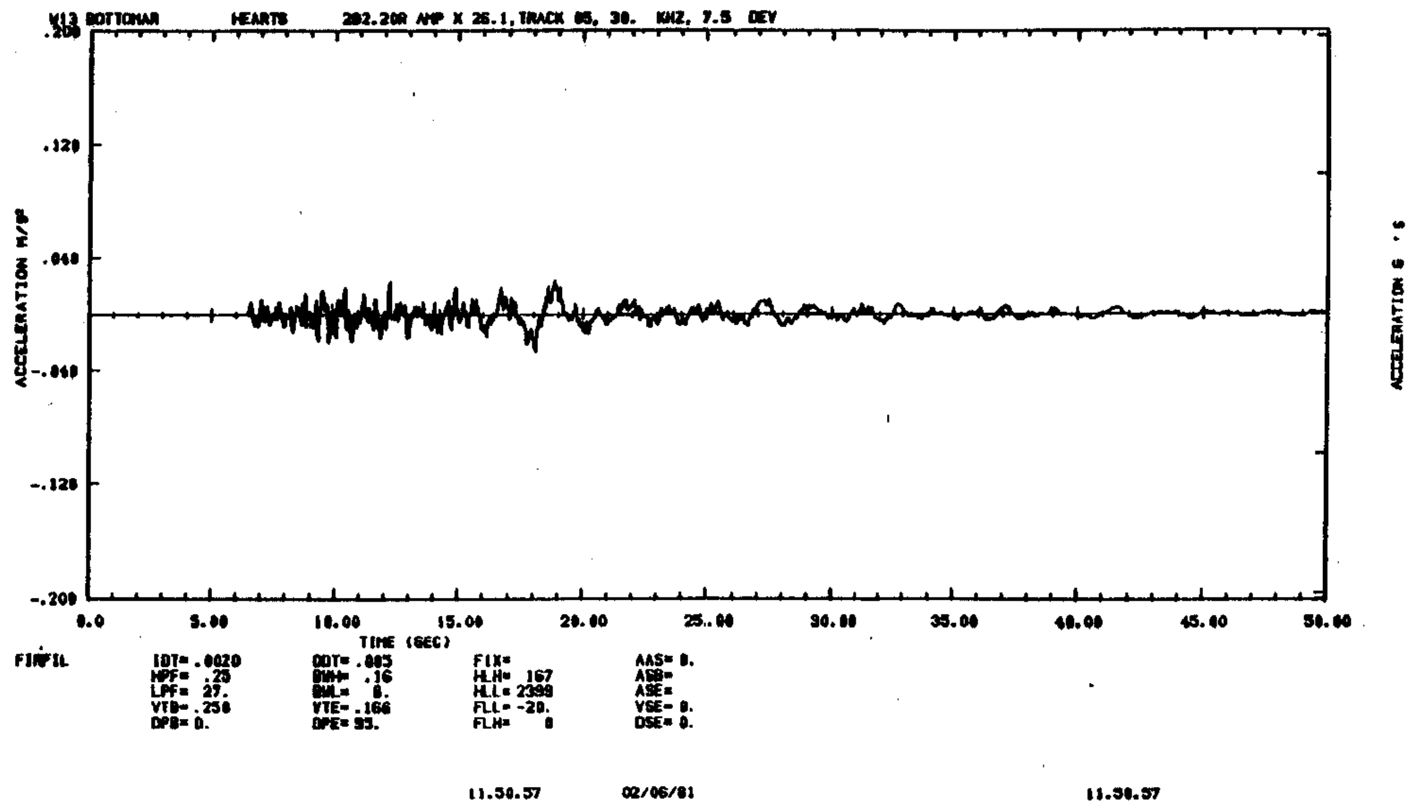


FIGURE 11. Acceleration History at 762 Meters, Vertical Component at Timber Mountain

Property \ Simulation		Case 1	Case 2	Case 3	Case 4	Case 5
	Joint Geometry	X	X	X	X	X
	Pore Pressures	X	X	X	X	X
	In Situ Stresses	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$
	Shear Zone	X	X	X	X	✓
	Thermal Loading (60 kW/acre)	✓	✓	✓	X	✓
	Earthquake	Oroville (0.41g)	Parkfield (0.35g)	EPRM (0.95g)	Oroville (0.41g)	Oroville (0.41g)
CRITERIA	FAILURE CRITERION	O	O	FAILED (Earthquake Phase)	O	O
CRITERIA	DAMAGE CRITERIA	FRACTURING VOID STRAIN	O	FRACTURING VOID-STRAIN	O	O
CRITERIA	PERMEABILITY CRITERION	O	O	O	O	O

X = None, ✓ = Yes, O = Does not exceed criterion

FIGURE 12. Results for Salt Compared With Defined Criteria

Property \ Simulation	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Joint Geometry	G_1	G_1	G_1	G_1	G_1	G_1	G_1	G_1
Pore Pressure	X	X	X	H1	H2	X	X	X
In Situ Stresses	$\sigma_H = \sigma_V$	$\sigma_H = \frac{1}{2}\sigma_V$	$\sigma_H = 2\sigma_V$	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$	$\sigma_{H1} = 2\sigma_V$ $\sigma_{H2} = \sigma_V$	$\sigma_H = \frac{3}{2}\sigma_V$
Shear Zone	X	X	X	X	X	X	X	X
Thermal Loading	✓	✓	✓	✓	✓	✓	✓	✓
Earthquake	Oroville (0.41g)	Oroville (0.41g)	Oroville (0.41g)	Oroville (0.41g)	Oroville (0.41g)	ERPM (0.95g)	Oroville (0.41g)	Oroville (0.41g)
FAILURE CRITERION	0	0	FAILED (Before Earthquake Phase)	0	0	FAILED (Earthquake Phase)	FAILED (Before Earthquake Phase)	0
DAMAGE CRITERIA	0	0	SLIP	0	0	FAILED (Earthquake Phase)	SLIP	0
PERMEABILITY CRITERION	0	0	EXCEEDED	0	0	EXCEEDED	EXCEEDED	0

X = None, ✓ = Yes, 0 = Does not exceed criterion

FIGURE 13. Results for Granite Compared With Defined Critera

	Property \ Simulation	Case 1	Case 2
	Joint Property	S_1	S_1
	Pore Pressures	X	H1
	In Situ Stresses	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$
	Shear Zone	X	X
	Thermal Loading (60 kW/acre)	✓	✓
	Earthquake	Oroville (0.41g)	Oroville (0.41g)
	Anisotropy	✓	✓
CRITERIA	FAILURE CRITERION	FAILED (Earthquake Phase)	FAILED (Heating Phase)
CRITERIA	DAMAGE CRITERIA	SLIP VOID-STRAIN	SLIP VOID-STRAIN
CRITERIA	PERMEABILITY CRITERION	EXCEEDED	EXCEEDED

X = None, ✓ = Yes, 0 = Does not exceed criterion

FIGURE 14. Results for Shale Compared With Defined Criteria.

Property \ Simulation	Case 3	Case 4	Case 5a	Case 5b	Case 6a	Case 6b
Joint Geometry	S_1	S_2	S_1	S_1	S_1	S_1
Pore Pressure	X	H1	X	H1	X	H1
In-Situ Stresses $\sigma_H = \sigma_V$	✓	✓	✓	✓	✓	✓
Shear Zone	X	X	X	X	X	X
Thermal Loading (60 kW/acre)	✓	✓	15kW/acre	15kW/acre	✓	✓
Earthquake Oroville(0.41g)	✓	✓	✓	✓	✓	✓
Anisotropy	✓	X	✓	✓	✓	✓
Opening Size	8mX8m	8mX8m	8mX8m	8mX8m	4mX4m	4mX4m
CRITERIA: FAILURE CRITERION	FAILED (Earthquake Phase)	O	FAILED (Earthquake Phase)	FAILED (Heating Phase)	FAILED (Earthquake Phase)	FAILED (Heating Phase)
CRITERIA: DAMAGE CRITERIA	Fracuring Void Strain	EXCEEDED	SLIP VOID-STRAIN	SLIP VOID-STRAIN	EXCEEDED	SLIP VOID-STRAIN
CRITERIA: PERMEABILITY CRITERION	EXCEEDED	EXCEEDED	EXCEEDED	EXCEEDED	EXCEEDED	EXCEEDED

X = None, ✓ = yes, O = Does not exceed criterion

FIGURE 15. Results for <u>Shale</u> Compared With Defined Criteria

Damage Mode	Possible Consequence During Operational Phase	Possible Consequence During Decommissioned Phase
<u>Underground Structures</u>		
Rock Fall (extent depends on seismic loading, rock quality, and support)	Injure personnel Block transportation Block ventilation Disrupt water management Damage canister Damage shaft wall	
Rock Slabbing (bursting)	Same as for rock fall	
Existing Rock Fractures and Seams Open, Rock Blocks Shift	Increase permeability -- increase water inflow Weaken rock structure	Increase permeability -- speed up transport of radioactive waste to the biosphere
Cracking of Waterproofing Liners in Shafts (if used)	Increase permeability -- increase water inflow	
Spalling of Shotcrete or Other Surfacing Material	Lead to rock fall if extensive	
Unraveling of Rock-Bolted Systems	Same as for rock fall	
Steel Set Collapse	Same as for rock fall	
<u>Equipment</u>		
Failure of Hoist Systems	Drop canister Injure personnel Canister sticking in shaft	
Damage to Ventilation Machinery	Accumulation of gases Heat build-up Preclude personnel access	

FIGURE 16. Seismic Damage Modes

FIGURE 17. Reasons for Improved Subsurface Seismic Performance

1. Absence of wave reflections at the surface.
2. Surface structures respond as unsupported cantilver elements.
3. Surface structures are commonly associated with poor soil conditions.

FIGURE 18. Subgroups for Discipline Oriented Deliberations

- Seismology
- Rocks Mechanics and Hydrology
- Modeling
- Licensing, Siting, and Tectonics
- Design

FIGURE 19. Conclusions

1. That subsurface seismic damage is far less than surface damage is amply documented.

2. For siting, general criteria used for surface facilities would appear conservative for subsurface facilities.

3. Measurements of in situ stress may have greater significance to subsurface facilities than to surface facilities.

4. In the early period of a geologic repository, industrial safety is the principal interest.

5. In the long term, permeability enhancement is the principal interest, but can be mitigated by backfill.