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NNWSI PROJECT

Nevada Nuclear Waste Storage Investigations Project

TECTONIC STABILITY AND EXPECTED GROUND MOTION AT YUCCA MOUNTAIN

REPORT OF A WORKSHOP AT SAIC – LA JOLLA
AUGUST 7-8, 1984

PRELIMINARY REPORT

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION
LA JOLLA, CALIFORNIA
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INTRODUCTION

At the direction of DOE a workshop was convened on August 7 and 8, 1984 to discuss effects of natural and artificial earthquakes and associated ground motion as related to repository siting at Yucca Mountain, Nevada. A panel of experts in seismology and tectonics was assembled to review available data and analyses and to assess conflicting opinions on geological and seismologic data.

The objective of the meeting was to advise the Waste Management Program about how to present a technically belanced and scientifically credible evaluation of Yucca Mountain for the NNWSI EA.

The group considered two central issues: (1) the magnitude of ground motion at Yucca Mountain due to the largest expected earthquake, and (2) the overall tectonic stability of the site given the current geologic and seismologic data base. To focus the discussion, Drs. W. F. Brace and G. A. Frazier raised a series of questions about each issue, as given below. The group examined each question and prepared responses, which often included major recommendations for more geologic or seismologic studies. These responses have been edited by Brace, Frazier and Pratt and are collected in this report. A more complete document with detailed recommendations will follow.

The workshop participants are listed in Appendix 1. The experts brought to La Jolla for the workshop were W. F. Brace, G. A. Frazier, H. R. Pratt, C. B. Raleigh, R. B. Smith and B. P. Wernicke. Their resumes are included in Appendix 1.

EXECUTIVE SUMMARY

- In situ stress measurements at Yucca Mountain neither rule out, nor are strong evidence for an impending major earthquake near the site. Other regions in the United States have similar stress conditions and are completely aseismic.

- Crustal extension rates inferred from contemporary seismicity and Quaternary geologic slip rates in the Basin-Range can not yet provide detailed recurrence intervals for earthquakes at Yucca Mountain. Limitations, primarily because of a short historical seismic record and a lack of detailed slip rate data in the immediate site vicinity, preclude an accurate assessment using this method to the limited area of Yucca Mountains.

- There is a high probability that fault scarps associated with faults capable of producing large earthquakes ($M_s \geq 7$) have been located and mapped.

- The Death Valley region, about 50 kilometers from Yucca Mountain, has heretofore not been considered a major source region of large earthquakes for assessing seismic risk at the site. This region may have a potential for producing large earthquakes, but more study is required to assess it's earthquake capability.

- An earthquake within 15 km of the site of magnitude 6.0 could plausibly occur unassociated with a known fault and could possibly be a threat for exceeding 0.40 acceleration at the site.

- The relationship between earthquake magnitude and fault length and displacement for normal, oblique, and strike slip faults appears to be one of the most,tenuous links for earthquake hazard assessment at Yucca Mountain.

- The historic seismic record at Yucca Mountain is too brief and incomplete to provide an accurate assessment of the frequency-magnitude relationship of the quality required to extrapolate future seismicity.

- Present estimates of peak ground acceleration at Yucca Mountain are based on empirical relationships that were not specifically derived for normal, oblique slip, or strike slip faults within an intraplate extensional regime. Thus, they should be re-evaluated for application to the Yucca Mountain region and assessed for standard error and uncertainties.

- Attenuation of ground motion appears to increase with depth and with frequency, but the site-specific attenuation properties at the Yucca Mountain are poorly understood. To ignore potential changes with depth appears to be conservative and is probably the best approach to apply at this time.

- Ground motion in compressional regimes like Southern California may have little relevance for an extensional region like Yucca Mountain.

THE ISSUES: TECTONIC STABILITY AND GROUND MOTION

TECTONIC STABILITY

Before turning to actual seismic effects at Yucca Mountain, such as ground motion due to an earthquake, it is important to assess the likelihood of a major earthquake near the site. What is the tectonic stability of the region, in view of the conflicting indications cited by Rogers et al., 1983, for example? This question was discussed from a number of points of view, emphasized in the following six questions:

1. The United States Geological Survey has recently completed <u>in situ</u> stress measurements in several boreholes at Yucca Mountain. <u>What does the stress state at and near Yucca Mountain imply about future earthquakes near the site?</u>

2. Rogers, et al. (1983) cite an argument in favor of large magnitude earthquakes, based on the size of Great Basin scarps. <u>What is the evidence for this as it applies to Yucca Mountain?</u>

3. Weapons tests over the years at Nevada Test Site may provide an important test of the tectonic stability of the region. The tests have apparently induced slip on faults at distances not exceeding 15 km from the test site. <u>Are these observations relevant in the present context?</u>

4. The recent estimates of extension rate from geologic and seismic data for the Southern Great Basin might be used to predict earthquake recurrence rate. <u>What would this rate be for Yucca Mountain?</u>

5. The existence of stable and unstable regions side-by-side seems quite in line with modern ideas about tectonics in the Western United States (Hill, 1982). Stable, more or less intact blocks are bounded

by faults; the blocks are stronger than the faults, and so motion is concentrated along the latter. By inference, earthquakes will be localized along block boundaries. <u>In the present context, have the block boundaries been correctly located?</u> In more concrete terms, <u>are currently active fault zones well located in Yucca Mountain?</u>

6. From an overall geologic standpoint, tectonic stability may be assessed from diverse observations of geomorphology, Holocene activity on faults, the geologic settings of recent great earthquakes, etc. <u>From such a point of view, which area in the southern Great Basin has the greatest potential for a major earthquake?</u>

1. In Situ Stress

Stress measurements in boreholes at the Yucca Mountain (Stock et al., 1984) indicate that the region is characterized by a stress state in which both the least and greatest horizontal principal stresses are less than the vertical stress. The observed stress state corresponds to a normal faulting regime; the magnitude of the horizontal stresses indicate that frictional sliding on pre-existing fault surfaces could be expected to occur if the coefficient of the friction along such faults were close to 0.6. According to Morrow and Byerlee (1984), the coefficient of static friction for repository tuff is about 0.85. In spite of the uncertainties in both these values, we would have to conclude that fictional failure on faults correctly oriented for slip could be induced by small changes in regional applied stress or pore pressure. It will be important to verify this possibility with future still deeper stress measurements.

Observations by Smith and Bruhn (1984) and Das and Scholz (1982) suggest that large, M7+, earthquakes nucleate at depths of the maximum extent of seismicity. For the Basin-Range this appears to be at midcrustal values of approximately 15 km (Smith and Bruhn, 1984). Because of the limited depth of drilling, the state of stress at Yucca Mountain is only known to 1.5 km. We do not know how to extrapolate such shallow measurements to depths of 10 km or more. In other parts of the world, such as South Africa, where measurements to nearly 4 km are available, no simple rules for extrapolation are evident.

Accepting the conclusions above that failure on correctly oriented faults is imminent, does it follow that a large earthquake is also imminent? This is certainly one possibility. Another possibility is that failure causes aseismic slip, that is, fault creep, or many small, non-damaging earthquakes. Our current knowledge of the Basin and Range is insufficient to choose among these three alternatives.

From the standpoint of seismic hazard, it is perhaps reassuring that in situ stress measurements in the Gulf Coast and in certain deep sedimentary basins within the U.S. (McGarr & Gay, 1978; Brace & Kolstedt, 1980) might lead one to a similar conclusion, that frictional failure on correctly oriented faults is imminent. Current seismic activity in these regions is negligible.

In summary, _in situ_ stress measurements suggest that frictional failure on correctly oriented faults at Yucca Mountain, might be induced by small changes in regional stress or pore pressure. Failure would not necessarily be accompanied by large earthquakes, but could induce aseismic slip or nuumerous small earthquakes.

2. Large Scarps

Association of large scarps with large earthquakes in the Great Basin has been suggested by Rogers et al., (1983), Buchanan and others (1980). The working group was not convinced that further studies will support this observation, particularly in light of recent information from the Wasatch Fault (Schwartz and Coppersmith, 1984, Swan et al., 1980) indicating large scarps have been produced by recurrent displacements along the same fault. An additional complication is that the nature of motion (dip-slip/strike-slip) on the fault will influence the likelihood that a large scarp is generated by a large earthquake.

3. Weapons Testing

Seismic signals resulting from cavity and chimney collapse and from relief of the stress cage surrounding the cavity are associated with underground nuclear explosions (UNE's). The evidence indicates that the seismic waves generated by the explosion have rarely been effective in triggering incipient earthquakes beyond about 15 km.

Also, weapon tests do not provide a demonstration of tectonic stability for the region because (1) underground nuclear explosions produce radiation which may not be a good "trigger" for a tectonic earthquake, (2) it is difficult to separate nearby simultaneous test and resulting induced seismicity and (3) underground nuclear explosions do not exceed 1 to 2 km in depth, whereas, large earthquakes probably nucleate 10 to 15 km deeper (Wallace et al., 1983; Dicky, 1968, McKeown et al., 1969; and Aki et al., 1969).

4. Extension Rates in the Basin Range

A potentially important indicator of seismic risk at Yucca Mountain is the regional extension rate across the southern Great Basin between the central Colorado Plateau and the southern Sierra Nevada Mountains. If the current extension rate for the province could be determined using geological information, seismic strain release data, and geodetic surveys, then an estimate of the strain across Yucca Mountain for the next 100,000 years could be made.

Long-term extension rates across the province at latitude 37°N are of the order of 1 cm/year (Wernicke et al., 1982). Reconstruction of strike-slip fault systems across the province indicates at least 140 km of east-west separation between the Colorado Plateau and the southern Sierra Nevada (Wernicke et al., 1982). Extension began approximately 15 million years ago, thus the extension rate is about 1 cm/year averaged across the province for the last fifteen million years. Seismic moment studies indicate release on an order of magnitude less, approximately 1 mm/year (Greensfelder et al., 1980, Smith, 1982, Smith, 1983). This may indicate that the current rate is considerably less than the 15 million year-average, but is more likely either a reflection of the inefficiency of seismicity in accommodating strain, an artifact of a lull in seismicity during the historical seismic record, or both. Local extension rates in highly extended areas in the Basin and Range can approach 2 cm/year every several million years (calculated from data in Anderson et al., (1972) and Miller et al., (1983)). A key geological observation is that the extension at any given time is localized confined to narrow belts as appears to be the case today in the Death Valley region, rather than being uniformly distributed across the province. In addition to this, it is clear that some large blocks have remained strain-free during Basin-Range tectonism. The Yucca Mountain area is not within a strain-free block, and its structural style is akin to ancient examples which have experienced high extension rates; thus, from a geological standpoint, a high rate across Yucca Mountain at the present time cannot be ruled out. It is unreasonable, however, to place bounds on the extension rate in the Yucca Mountain area via interpolation of province-wide strain rates because of the extreme inhomogeneity of strain accommodation apparent from the geologic record.

The above approach utilizes a 15 million-year average for extensional displacement. An alternate procedure is to consider the current extensional rates as determined by precise surveying.

Trilateration networks were established in Yucca Flat and Pahute Mesa in 1971 and were re-occupied in 1972, 1973 and 1983. The geodolite measurements were conducted by Savage and co-workers at the USGS in Menlo Park, California. The data from Yucca Flat (W. Prescott, pers. comm., 1984) measured over a block about 40 km in a N-S direction and 20 km E-W for the entire period can be fitted to a uniform strain field with the maximum principal strains being almost exactly N-S and E-W to within the error of the measurements. The N-S strain rate is -0.10×10^{-6} per year and the E-W strain rate is $+0.08 \times 10^{-6}$ per year. The same rates for the 15 million-year averages cited above are about $+0.07 \times 10^{-6}$ per year, a value which is remarkably close to the E-W strain of $+0.08 \times 10^{-6}$ per year.

For estimating recurrence times of major earthquakes, the most conservative assumption would have the strains accumulating entirely as elastic distortions and to assume that all the shear strain is released by displacement in a single strike-slip event on a N45W (or N45E) fault. As an example, the diagonals of a 20 km by 20 km block would accumulate a potential shear displacement of 1 meter in 400 years on a fault having the 28 km length of the block diagonal. In another calculation, if major earthquakes are accompanied by shear strain release of about 10^{-4}, it would require about 1,000 years to accumulate the necessary elastic strain. Thus, an earthquake of this size (1-meter strike-slip displacement, or 10^{-4} strain change) would occur in the measurement area at NTS every 400 to 1000 years.

Strain rates estimated by cumulative moment tensors of historic seismicity for the Basin-Range (Smith, 1982 and unpublished data) suggest maximum displacement rates of approximately 2-4 mm/yr associated with the large M7+ earthquakes in the central Nevada seismic belt, then decreasing rapidly to rates of 1 mm/yr or less across the Yucca Mountain region. Greensfelder et al., (1980), also suggests relatively low strain rates, 2 x 10^{-8} per year for the Yucca Mountain region but increasing by an order of magnitude to southward toward the Garlock fault to 10^{-7} per year.

5. Location of Potential Fault Zones

The NTS and its surroundings are one of the most scrutinized areas of the Basin and Range province and although the surface mapping is very detailed, it does not preclude the existence of faults without surface expression. Many of the small earthquakes observed by the USGS net cannot be associated with mapped faults. However, there is a high probability that all Quaternary-Holocene scarps associated with faults capable of producing large earthquakes are known.

When long zones in normal fault regimes (Madison, Wasatch, Borah Peak) have failed during large earthquakes, they break along segments rather than along their entire length (Swan and others, 1980). The Working Group noted that analyses associated with NNWSI have assumed failure over the entire fault length, whereas for other analyses, one-half the length has been used. Effort should be made to see if faults of concern can be segmented on the basis of end points, intersection of pre-existing structures (lateral terminations) or other features. It is recommended that significant surface faults with Quaternary-Holocene scarps within about 30 km of the site be trenched to determine slip rate.

The potential of active faulting associated with seismicity can be examined using regional network data from southern Nevada and from detailed network studies in the immediate vicinity of the nuclear test site. In general, the seismicity of the Yucca Mountain region appears to be associated with the western end of a general E-W trending zone of seismicity that extends across southern Nevada at approximate latitude 37°. To the west of Yucca Mtn. seismicity decreases westward toward the Furnace Creek-Death Valley region. Further west increased activity is associated with the central Nevada and Walker Lane trend. A notable E-W gravity lineament of approximately 15 mgal (Eaton, 1978) is coincident with the E-W zone of seismicity; both trends are generally orthogonal to the N-S structural grain of Quaternary-Holocene Basin-Range topography. This raises a question regarding the source of the E-W seismic belt in terms of a deep crustal feature that is not known at this time.

The historical seismic record for the Great Basin is marked by a sparseness of data because of the incompleteness of both personal felt reports for the early intensity reports and the short length of time that regional networks have been established. It would be imperative to examine the historical earthquake record for its completeness in order to ascertain the level of confidence for the assignment of statistical parameters such as the a and b values.

Focal depth distribution of earthquakes can provide information regarding correlations between surface geology and faulting at depth. In general the focal depth control requires that a station be located in epicentral distance within a distance of a focal depth in order to have an accurate measurement of the focal-depth parameter. In general, detailed station distributions in the immediate vicinity of Yucca Mountain have not been sufficient to assess focal depth, and thus, it is difficult to correlate focal depths with surface faulting, except perhaps for the deepest events.

The site specific seismicity of the Yucca Mountain region is somewhat limited in comparison to that inferred from the long term seismic record at the neighboring NTS site. This problem may be partially addressed by making statistical analyses of the completeness of the seismic record, but, nonetheless, is a limitation for long time seismicity assessments.

Much of the intraplate deformation of the western United States has been attributed to "block" tectonics where coherent and stable volumes of the upper crustal are bounded by or partially decoupled from adjacent blocks producing a mosaic of volumes bounded by active faults that accommodate regional displacement. Thus, at seismogenic depths, 0-15 km, the boundaries should be resolved by seismicity. Even small earthquakes, although not related to large strain release, may provide estimates of boundary zones and maximum focal depths can elucidate the depth of brittle seismogenic volumes.

Fault plane solutions for central and western portions of the Basin-Range including the Yucca Mountain site show varied distributions of pure normal, oblique normal and strike slip solutions (Smith and Lindh, 1978; Vanwormer and Ryall, 1980; Rogers, 1981). While Quaternary faulting shows significant oblique lateral slip, large earthquake solutions show major components of E-W extension on normal faulting. The smaller events show N-S to NW, to W extension on a variety of nodal planes. However, the consistent parameter of the general fault plane solution distribution for the southern Great Basin is the general northwest-southeast direction of the minimum stress in accordance with extension in that direction (Smith, 1978; Zoback and Zoback, 1980). Most large historic earthquakes in the western Great Basin that produce surface faulting show the primary displacement in the down-dip direction. What significance the strike slip solutions have, cannot be ascertained yet; they simply may be the accommodation of strain release along pre-existing fault plains that are not now favorably oriented for S-S faulting, or they may represent the potential of large lateral slip along such fault systems as the Death Valley-Furnance Creek zone.

6. Nearby Areas with High Potential for a Great Earthquake

The Death Valley region contains numerous long, Quaternary normal and strike-slip faults associated with mountain-block uplifts 2000-3000 high. The large historical earthquakes in the Basin and Range Province (Dixie Valley-Fairview Peak, Owens Valley, Borah Peak) are associated with similar faults bounding large topographic escarpments. Although the Death Valley is considered to be relatively aseismic in the historical record, there is abundant evidence for major Quaternary displacements on these faults (Hunt and Maybe, 1966). It is highly significant that the Borah Peak event (Mag. 7.1) occurred in a region of little seismicity. In view of the youthfulness and large topographic escarpment associated with the Death Valley region, especially the Furnace Creek and Black Mountain fault zones, the likelihood of a number of large events (M7 or greater) on these faults within the next hundred thousand years should be considered high until otherwise proven.

GROUND MOTION

The tectonic stability of the region was reviewed in the previous section with a focus on its earthquake-generating characteristics. The review of ground motion in this section focuses on issues relevant to the establishment of ground motion criteria for the repository, utilizing information developed within the review of tectonic stability. Some of the same issues are re-examined in an effort to resolve differences in the estimates of fault characteristics, potential earthquake magnitudes and credible levels of ground motion.

The largest credible earthquake for the Yucca Mountain site should follow procedures and definitions set forth in 10CFR Part 100, Appendix A. Specifically, the determination should provide the following:

1. A map of tectonic provinces contained within the area of 200 miles around the site.
2. A catalog of historical seismicity within each tectonic province, any part of which, is located within the area of 200 miles around the site; and
3. An evaluation of association of historical seismic events with capable faults, any part of which is situated within the area of 200 miles around the site.

As with tectonic stability, discussion of ground motion was focused on a number of questions:

1. What are the largest unassociated earthquakes to be expected within 15 km?
2. What is the largest earthquake of any sort within 50 km?
3. What will be the future recurrence of large earthquakes?
4. What is the attenuation of ground motion appropriate for Yucca Mt?
5. How will surface ground motion be attenuated at repository depth?

1. Unassociated Earthquakes

Yucca Mountain is interspersed with faults ranging outward from within a few hundreds of meters of the site. While there is no clear evidence to indicate that any of the faults within 10 km have moved within 35,000 years, significant earthquakes cannot be ruled out with the information currently available. The experts concluded that an earthquake of magnitude approximately 6 could plausibly occur at depth in this area without significant surface manifestations.

As a result of this evaluation, the issue of earthquakes unassociated with known seismogenic faults was reviewed. To assess the importance of unassociated earthquakes, an extremely rough estimate was made for the return period of a magnitude 6 earthquake within 15 km of the repository site. Convenient assumptions were made in arriving at the estimate, namely:

a. The Basin Range structure was assumed to be undergoing spatially uniform extension at the rate of 0.2 mm/yr per 1° x 1° area, which yields about .02 mm/yr within 15 km of the site. Smith (1982) provided estimates of extension rates that varied from undiscernable values to as high as approximately 4 mm/yr per along the active central Nevada seismic zone per 1° x 1° area.

b. All extension is assumed to be manifested by uniformly distributed magnitude 6 earthquakes. Furthermore, each earthquake is assumed to produce 150 mm (Bonilla, 1982) of offset over a length of 11 km (Mark and Bonilla, 1977).

With these convenient assumptions, the recurrence interval (I) for magnitude 6 earthquakes within 15 km is approximately,

$$I = \frac{(150\ \text{mm/earthquake}) \times (3\ \text{earthquakes for release within 15 km})}{.02\ \text{mm/yr within 15 km}}$$

$$= 2500\ \text{years}$$

If 90 percent of the magnitude 6 earthquakes were associated with identifiable faults, the recurrence interval for unassociated earthquakes would increase by a factor of ten, or

I = 25,000 years

for unassociated magnitude 6 earthquakes within about 15 km of the site. Note that these recurrence intervals for unassociated earthquakes are different from those calculated on page 8 for associated earthquakes.

Several relevant factors are not included in this estimate for recurrance interval. Nevertheless, the potential for earthquakes unassociated with identified seismogenic faults appears to be substantial and should be considered in the development of ground-motion criteria for the site. The working group recommended three approaches for dealing with the issue of unassociated earthquakes.

1. The historic seismicity within the Basin Range should be carefully reviewed for unassociated earthquakes of magnitude greater than 5.5. The numbers and magnitudes of earthquakes not associated with faults within the Basin Range could then be used to estimate the potential for unassociated earthquakes in the near-site region by scaling the results to the site area. Completeness of this seismic record is critical for these studies.

2. Extensive field investigations should be conducted within about 10 km of the site to further assess the potential for significant local earthquakes. The investigations should identify any throughgoing fault-related features and characterize the local earthquake history from geologic imprints using a combination of gravity and magnetic surveys, radar soundings, fault trenching and age dating.

3. Ground motion criteria should be developed over a range that accommodates reasonably plausible earthquakes, including local earthquakes not associated with any identified seismogenic fault. Although, the seismogenic characteristics indicate that ground accelerations in excess of 0.4g are not likely during preclosure, more severe levels of ground motion cannot be ruled out. However, McGarr (1984, in press) regards 0.5g as the maximum surface acceleration likely in an extensional regime, like Yucca Mt.

2. Largest Credible Earthquake Within 50 km

Knowledge of existing faults is based primarily on surface expression. Large scarps have been associated with both large earthquakes and as cumulative displacements. Unless there is a clear surface manifestation of a fault terminus, the precise subsurface length will remain uncertain.

Relations between fault length and largest credible magnitude (Bonilla and Buchanan, 1970, and Mark and Bonilla, 1977) result from data with a great spread in the earthquake fault length associated with a given magnitude, even when normal-slip, normal oblique-slip, and strike-slip faults are treated separately. For example, a predicted magnitude for a 17 km fault is 6.8 ± 0.8 based on their standard errors of the estimates. Much of this spread is due to differences in the true earthquake fault length and surface expression. (The Working Group did not have access to a recent report by Bonilla or recent tabulations of earthquake fault length for varying magnitudes by Slemmons). The relation between earthquake fault length and magnitude appears to be one of the most tenuous links in hazard assessment.

What is needed is a tabulation of the largest historical magnitude for faults of various types and lengths with focus on normal, oblique and strike-slip events that occur in intraplate extensional regimes. An earthquake of magnitude 6.8 is hardly credible on a local fault that is only 17 km long, provided the fault does indeed terminate. Because of uncertainties in the actual extent of the seismogenic faults at depth, magnitudes from 6.6 to 6.8 have been estimated for faults within about 30 km of the site.

The working group has identified two courses of action. First, a concerted effort should be made to identify the fault-length relation most applicable for estimating the largest credible magnitude on the local seismogenic faults, and this relation should be applied to re-evaluate current estimates. Second, field work should be initiated to establish constraints on the fault length that could plausibly fracture in a single earthquake. Trenching and age-dating of faults especially close to Yucca Mountain (Bow Ridge, Paintbrush Canyon, Solitario Canyon, etc.) associated with radar sounding should be accomplished by a team of independent observers. This effort should be extended to several locations along each capable fault longer than a few thousand feet.

Information currently available does not permit a determination of whether the close faults or the farther faults (e.g., Furnace Creek) associated with larger magnitudes constitutes the more likely hazard. Empirical relationships between peak ground acceleration and earthquake magnitude for varying distances indicate that a magnitude 6.5 earthquake at a distance of 15 km will generate higher accelerations than a magnitude 7.5 at 50 km or greater. Similarly, a magnitude 6 earthquake at distances less than 15 km could produce even higher accelerations. A moderate to large earthquake at distances in excess of 30 km probably represents the most likely scenerio; whereas, the largest credible accelerations would likely result from a moderate earthquake at a distance less than 20 km.

3. Future Seismicity

Average estimates for the rate and magnitude distribution of future earthquakes in the Basin Range can be extrapolated from the historic and geologic record. The historic record is too brief to represent the potential for earthquakes on individual faults or in a region the size of Yucca Mountain. The historical record of the entire Basin Range is needed to approach valid sampling statistics, and the corollary follows that extrapolations of future earthquakes during preclosure (about 90 years) can only be applied with confidence over a large region the size of the Basin Range.

To demonstrate a reliable basis for extrapolating the rate and magnitude distribution of future earthquakes, alternate procedures for characterizing previous earthquake activity should be examined, and consistency should be established. Specifically, the working group recommends the following studies to assess future seismicity.

(a) Develop Quaternary Holocene return rates based on "a" and "b" values derived from historical magnitude and intensity data. Rogers (1977) developed numbers for earthquakes within 400 km, which included large earthquakes on the San Andreas fault. This work should be revised to include only earthquakes from the Basin and Range, not including San Andreas earthquakes. Seismic activity based on historical data should include a measure of the uncertainty.

(b) Develop slip rates by dating fault offsets within the Basin Range. Spatial variations for the rate of deformation should be estimated to identify the relative stability or instability of Yucca Mountain. Estimates of the uncertainty should also be developed. Analyses of the above techniques should be made to determine both sensitivity and resolution of the above proposed solutions using the extreme ranges of significant parameters.

(c) Estimate the regional deformations using geodetic control and provide estimates of the uncertainties.

(d) Compare the activity rates from historical seismicity, fault offsets and geodetic surveys to test consistency. Also, compare the results with estimates of the Basin Range activity developed in other studies. Use these results to develop a range for the return period of local earthquakes of varying magnitude and site-specific levels of ground motion.

4. Attenuation of Ground Motion

The expected peak acceleration specified in the draft SCR (1983) for Yucca Mountain was based on the seismic hazard analysis developed by Rogers, et al (1977). This analysis utilized a ground-motion attenuation relationship developed by Schnabel and Seed (1973). Although this relationship was a reasonable one to use prior to 1980, other attenuation curves have been developed as a result of more recent data. Furthermore, it does not have a specified standard error, preventing estimates of uncertainty.

It is recommended that the expected peak acceleration at Yucca Mountain be recalculated using one of the more recent attenuation relationships, e.g., Campbell (1981), Joyner and Boore (1981) or Bonilla et al., (1984). It should be noted that published attenuation functions are dominated by data from Southern California. Thus, the use of these empirical functions could contain biases resulting from differences in the properties of the earthquake sources and wave paths between Southern California and the tectonic subprovince containing Yucca Mountain. The possibility of biases should be investigated using ground motion recordings of earthquakes in normal fault environments, incorporating where possible measurements from extensional zones of the western United States and others. Also, site-specific conditions (rock, alluvium, etc) should be considered in the development of site-specific ground motion criteria.

McGarr (in press, 1984) has recently shown that peak acceleration is strongly dependent on stress state. In particular, peak acceleration in a compressional regime such as southern California is nearly three times greater that is an extensional regime such as Nevada, for earthquakes of comparable size and focal depth. Use of acceleration relationships from events in California may be very misleading for hazard assessment at Yucca Mountain.

Finally, it is further recommended that the design peak ground acceleration include a provision for the uncertainties in the estimate of peak ground accelerations from a specified earthquake magnitude at a specified distance. Mean estimates plus one standard deviation would be appropriate for characterizing these uncertainties.

5. Attenuation of Ground Motion with Depth

Ground motions resulting from both earthquakes and underground nuclear explosions (UNE's) are important in the assessment of the reposity facilities located at a depth of 350m. While motions at depth have been and continue to be recorded at NTS for UNE motions, few subsurface recordings of earthquakes have been made.

Japanese data on earthquakes, reported by Okamoto (1973), Kanai and others (1951, 1953, 1954, 1966), and Iwasaki et al. (1977) indicate that motions in general decrease with depth, although little or no reduction was observed at isolated sites for some earthquakes. A velocity attenuation curve developed by Kanai for a depth of 100 m in rock, predicts velocities less than Seed's curves for surface rock velocities at the same focal distance (Pratt et al., 1978). Owen and Scholl (1980) have observed that the amount of depth reduction is dependent upon site geology, wave form and motion duration. The latter two parameters are, in turn, dependent upon earthquake magnitude, source type, epicentral distances, and wave path geology.

Given the uncertainties in modeling depth dependence and the sparcity of ground motion measurements at depth for earthquakes, it is not feasible at this time to provide precise predictions of the motions at depth from values at the surface. Current evidence indicates that acceleration at the repository depth will be significantly less than at the surface and that velocity will also attenuate with depth, but less significantly than for acceleration. Below the free surface of the earth displacement will probably not be significantly reduced but the data base is extremely sparse.

Without better predictors, it is reasonably conservative to ignore potential reduction with depth for the purpose of design of tunnel and underground chambers. Data summarized by Dowding (1978) indicate that in general underground structures are less likely to be damaged than surface structures at the same epicentral distance. Dowding found that tunnels sustained no damage for surface accelerations below 0.2g, minor damage between 0.2-0.5g, and major damage only above 0.5g. Major damage, when it has occurred, has been almost always associated with the portal regions and shallow-cover. Also, observations demonstrate that tunnel systems are susceptible to damage at frequencies higher than those which typically damage surface structures and generally require higher levels of acceleration to initiate damage. Thus, the underground repository can be designed to accommodate ground motions as severe as those used to design surface structures.

The working group reviewed results of ground motion from UNE's and observed the trend of decrease in peak vector acceleration, velocity, and displacement with depth. On average the peak vector acceleration at 350 meters is reduced by a factor of 2 relative to that at the surface. Reduction of peak vector velocity and displacement is less. All three parameters show strong effects of the geology at the point of measurement. Frequency content of the waves at the surface and at depth are different and vary significantly with the site conditions.

Because the depths of UNE's are ordinarily shallow compared to earthquake hypocenters and because the wave characteristics are significantly different, caution should be exercised in any effort to apply depth effects from UNE's to earthquakes. At intermediate and large distances, some comparisons could be made provided differences in the wave types and the frequency content are taken into account.

The working group noted that currently no earthquake measurements are being made at the repository horizon in Yucca Mountain. Site-specific measurements are needed to utilize reductions in ground motion with depth in the design criteria.

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Appendix 1

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A brief background description of the members of the group of experts is given below.

William F. Brace - Professor and Chairman, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology at Cambridge, MA; member of the National Academy of Sciences; Fellow of American Academy of Arts and Sciences; President of Tectonophysics Section of the American Geophysical Union (1963-1969). Dr. Brace is an internationally known expert in the area of tectonophysics and the physical and mechanical properties of earth materials. He is Associate Editor of the Rock Mechanics Journal; Associate Editor Tectonophysics, Geological Society of American, and International Journal of Rock Mechanics and Mining Science. Dr. Brace is a leading member of the academic community in the role of in situ stresses as they relate to seismicity and tectonics. Ph.D., geology, Massachusetts Institute of Technology, 1953.

Gerald A. Frazier - Senior Scientist, Science Applications International Corporation, La Jolla, California. Dr. Frazier is an expert in the assessment of earthquake and explosion induced ground motions. He has led several studies for evaluating potential earthquake hazards to nuclear power plants and has provided a lead role in the licensing pursuits for utility companies. He has developed technology for numerically simulating explosion induced ground motions for both near and far-field response. He is the lead research seismologist at the DARPA Center for Seismic Studies, Washington, D.C. Ph.D., civil engineering, Montana State University, 1969.

Howard R. Pratt - Corporate Vice President, Science Applications International Corporation, La Jolla, California. Dr. Pratt manages the Earth Sciences Operation which has six divisions specializing in (1) geology and geophysics, (2) instrumentation engineering and data processing, (3) civil engineering, (4) geotechnical engineering, geomechanics and solid mechanics. Programs cover a wide range of calculational and experimental support efforts in areas such as nuclear weapons effects, nuclear waste isolation, nuclear power plant design, civil works projects, and energy resource exploration. He is a recognized expert in rock mechanics and engineering geology and has conducted active research in (1) large-scale field experiments to evaluate material properties in situ stress, (2) ground motions associated with earthquakes and explosive sources. Adjunct Professor University of Utah (1969 to present). Ph.D., geology, University of Rochester, 1966.

C. Barry Raleigh - Director Lamont-Doherty Geological Observatory of Columbia University and Professor, Department of Geological Sciences, Columbia University, New York, New York. Dr. Raleigh is an internationally known expert in the area of tectonophysics, earthquake prediction, and experimental rock mechanics. Author of over eighty papers in these technical areas, including many on in situ stress measurements. Fellow, American Geophysical Union and Geological Society of America, President, Tectonics section, American Geophysical Union. Former Coordinator of the Earthquake Prediction Program, U.S. Geological Survey and Chief of the branch of Earthquake Tectonics, Office of

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Robert B. Smith - Professor Geophysics, Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah and Director, University of Utah, Seismograph Stations. Dr. Smith's primary research areas are in theory and method in seismic reflection and refraction; earthquake seismology, and tectonophysics. His research interests are earthquake investigations of intraplate earthquakes with emphasis on intermountain seismic belt; seismological investigations of crustal structure of the Western United States; and mechanical properties of mountain building uplift and magma placement from seismological data. Associate editor of the Journal of Geophysical Research, Member of the National Academy of Science Committee on Seismology, Ph.D., Geophysics, University of Utah, 1967.

Brian P. Wernicke - Assistant Professor, Department of Geological Sciences, Harvard University, Cambridge, Massachusetts. Dr. Wernicke is an expert in the structural geology of the Basin and Range Province in the United States. He is nationally known for his work in extension tectonics of the Basin and Range Province of Nevada, Utah and California and the author of many papers on that subject. Consulting geologist to oil companies on the structure and tectonics of Western United States. Ph.D., Geology, Massachusetts Institute of Technology, 1982.

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December 10, 1984

Carl A. Johnson
Chief - Technical Programs
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Office of the Governor
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Dear Carl:

This is a tardy response to your letter of November 21st, but I have been very busy as an aftermath of the GSA Meeting.

I read the report of the workshop on Tectonic Stability and Expected Ground Motion at Yucca Mountain from the Science Applications International (SAI) on August 7-8, 1984. I have not given this document a close review, but I believe that some of the bullet items in the Executive Summary are misleading. Although the tectonic activity is lower than the average of most of the Basin and Range Province, this meeting did not recognize many aspects of the neotectonic setting.

The panel was composed of many illustrious researchers, however it did not include someone with strength in the general field of neotectonics, active faulting, and evaluations of associated earthquake magnitudes. It would have been helpful for them to have someone with backgrounds similar to that of Lloyd Cluff, Bob Wallace, George Brogan, or Clarence Allen.

Briefly, my comments on the topics given in the Executive Summary, E-1 and E-2, follow below. You may wish to contact me by telephone for more detailed comments.

Bullet 1: I agree.

Bullet 2: I agree.

Bullet 3: I disagree, at least in part. The backup statements on pp. 10-12 have many errors in analysis. The NTS and its surroundings may be one of the most scrutinized areas of the BAR province, but current stateoftheart methods of fault detection and analysis have not been undertaken. Half-length methods, or other fractional length methods need to be evaluated for this area. I agree with the statement "that it is recommended that significant surface faults with Quaternary-Holocene scarps within about 30 km of the site be trenched to determine slip rate".

Degradation of scarps, and particularly the degradation of strike-slip scarps in a topography of moderate relief, indicates that faults without scarps should also be trenched. The comment "There is a high probability that fault scarps associated with faults capable of producing large earthquaes (Ms 7) have been located and mapped", may misrepresent the the neotectonic setting and tectonic stability. A comparison is made with the Wasatch Fault, a narrow zone of much higher than normal rate of activity and geomorphic expression. Other areas have subtle geomorphic expression, for example the Cedar Mountain earthquake zone of Ms = 7.3 in a possibly similar part of the Walker Lane. Here the main mechanism was strike- slip faulting, which may be similar to the structures along the northern end of Yucca Mountain. The recent studies of Livaccari and Ernie Anderson suggest that this may be in a domain in which strike-slip faulting may be important. This indicates the possibility of earthquakes of above 7 with unevaluated combinations of listric or detachment faulting (e.g. Hardyman, Hudson, Profitt, Molinari and others in the northern Walker Lane. The strike-slip faulting of the nearby active fault zone in Rock Valley is not recognized, nor the field evidence of many late Quaternary faults near the site.

There is no low-sun angle aerial photography that has been systematically evaluated for tectonic activity; this is one of the best methods for recognizing and assessing active faults.

Bullet 4. This item has been partly answered by studies of George Brogan supported by the U. S. Geological Survey, to help in evaluating the NTS area. He also worked under me on this area as part of an incomplete Ph. D. thesis.

Bullet 5. I agree, but for partly different reasons. The possibility that the siting area has listric or detachment faults indicates the possibility that magnitude 6.0 (6 would be better) is not necessarily a conservative figure and that higher magnitude earthquakes could occur and have little or no surface expression (e.g. Cedar Mountain).

Bullet 6. I strongly disagree. I believe that recent reductions in standard errors of estimate and reevaluations of worldwide data make the relationship of earthquake size and faulting parameters a valid method of study for many fault zones that affect the site. The comment was made in the text on p. 17, that the Working Group did not have access to a recent report by Bonilla, or for recent tabulations that I had prepared. If these had been available to the Working Group, I believe that their comments would have been changed. Never-the-less, I believe that the reader of this bullet would be given a false impression.

Bullet 7. I agree.

Bullet 8. I agree.

Bullet 9. I agree that attenuation appears to increase with depth. I also agree that to ignore this potential change is probabily conservative. I disagree that this may be the best approach to apply at this time. I believe that strong ground motion will decrease rapidly with increasing depth. I feel that this factor should be evaluated for all waste repository sites.

Bullet 10. I strongly agree, but believe that there have been few studies to demonstrate this point.

I hope that these comments will help in your assessment of the workshop report.

Best wishes,

Burt Slemmons

cc. Dae Chung

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7 January 1985

Telephone (702) 784-4975

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Dear Carl:

Following your 10 December 1984 request, Bill Peppin and I have reviewed the Science Applications International Corporation (SAIC) report titled Tectonic Stability and Expected Ground Motion at Yucca Mountain. Our reviews are of necessity preliminary because we have not yet received the Draft Environmental Assessment and some of the key references cited in the SAIC report are not available through the University. However, some preliminary comments may be in order at this time, with a detailed review of the EA and other materials to follow in February.

Makeup of the Panel. The group convened by SAIC included recognized experts in rock mechanics (Pratt, Raleigh, Brace), theoretical modeling of signals from earthquakes and explosions (Frazier), structural geology (Wernicke) and earthquake/exploration seismology (Smith). There was no one on the panel with expertise in neotectonics, the group was probably over-represented in rock mechanics, and it was underrepresented in earthquake seismology. While several members of the group have had experience in the eastern Great Basin or California, none have worked extensively in the western Nevada region where Yucca Mountain is located. There are gaps in the report, including the omission of a great deal of work that has been done in the western Great Basin and is relevant to the Yucca Mountain site assessment.

In-Situ Stress Measurements. On pages 3 and 4 the SAIC panel presents observations based on in-situ stress measurements. These observations suggest that such measurements are of little use in evaluating the potential for faulting at the site, yet the panel concludes from the measurements that failure on normal faults at Yucca Mountain might be induced by small changes in regional stress or pore pressure.

Evidence from Fault Scarps. On page 5 the group points out that large scarps may in some cases be associated with recurrent displacements rather than single large events and, on the other hand, that major earthquakes may in some cases be associated with small scarps. An example of the latter would be the M = 7.3 Cedar Mountains earthquake in 1932, which involved primarily strike-slip displacement and produced small scarps that will probably be obliterated by erosion after a few centuries. Yet on page 10 the panel concludes that "there is a high probability that all Quaternary-Holocene scarps associated with faults capable of producing large earthquakes are known." I question the validity of this statement.

In the same context, the panel suggests on pages 5 and 10 that large scarps may form by successive breaks along separate fault segments, and that an attempt should be made to "see if faults of concern can be segmented on the basis of end points." In the western Great Basin this might not be appropriate: historic faulting in this part of the province includes 100 km of scarps formed in the 1872 Owens Valley earthquake (M 8.3), 65 km in the 1915 Pleasant Valley earthquake (M 7.6), 61 km in the 1932 Cedar Mountains shock (M 7.3), and 18, 30, 59 and 62 km in the 1954 Rainbow Mountain, Stillwater, Fairview Peak and Dixie Valley events (M 6.6, 6.8, 7.1 and 6.9, respectively). Based on the large magnitudes, determined either instrumentally or from the extent of the felt area, it is not likely that any of these faults formed by a succession of small-magnitude shocks. These earthquakes should have been considered by the panel since they are in the same region as the Yucca Mountain site.

Fault Length. The panel observes on page 17 that published relationships predict that a 17 km-long fault break will be associated with an earthquake of magnitude 6.8, and that this relationship may be inappropriate for the Great Basin. In a paper cited by the panel we derived a magnitude-fault length relationship based on nine events in the western Great Basin with magnitudes in the range 5.6-7.6. This relationship predicts a much lower magnitude, 6.0, for the 17-km fault break. The panel's speculations on page 18 agree with a probabilistic study we did ten years ago, which showed that in terms simply of maximum acceleration moderate earthquakes near a typical site in the western Great Basin are of more concern than larger events that may occur some distance from the site. However, depending on the importance of the duration of strong shaking, the larger events could be of more concern.

Depth of Nucleation of Strong Earthquakes. On page 3 the panel cites a conclusion of Smith and Bruhn, that large (M 7+) earthquakes in the Basin and Range province nucleate at a depth of about 15 km. In general this conclusion would agree with our observations in the western Great Basin, which showed that focal depth of earthquake sequences correlated with the magnitude of the main shock. On the other hand recent work by the Nevada seismology group indicates that the depth of nucleation for ML 6.0-6.5 earthquakes is 8-11 km — considerably closer to the depth (4-6 km) at which induced seismicity at NTS has occurred. It is worth noting that ML 6+ earthquakes at Mammoth Lakes had focal depth as shallow as 5 km.

Explosion-Induced Faulting. The situation with regard to explosion-induced faulting and tectonic stress release may not be as gloomy as the SAIC group concludes on page 6. While observations in this area show a complex pattern, they do sample tectonic processes in the crust to depths of 5-6 km — close to the depth where strong earthquakes appear to nucleate in the western Great Basin. A thorough review of the various lines of evidence (explosion-induced ground breakage, teleseismic and near-field observations of tectonic release, aftershocks of explosions, strain measurements) should be carried out before such studies are written off as inappropriate to the Yucca Mountain question. A large body of literature in this area is not considered by the panel.

Strike-Slip Faulting. On page 12 the panel admits to some confusion regarding the significance of strike-slip fault-plane solutions in an area characterized by lithospheric extension. A good deal of effort in our program has been directed toward this problem, and published papers show that in a number of areas in the western Great Basin earthquake mechanisms change systematically from strike-slip at shallow depth to oblique- or normal-slip at mid-crustal depths. Our explanation for this is in terms of the rate of increase of the overburden pressure compared with maximum and minimum horizontal tectonic stress in the region. While NTS was not included in our analysis the observations there appear to be consistent with this model.

Extension Rates. On page 8 the panel concludes from trilateration measurements that the Yucca Flat area is being strained at a rate appropriate for one meter of displacement every 400-1,000 years, but they note on page 15 that there is no clear evidence to indicate that any of the faults within 10 km of the Yucca Mountain site have moved in the last 35,000 years. This is not a contradiction since the two areas are more than 10 km apart, but the implied difference in rate of earthquake occurrence is curious and suggests that more work needs to be done on this problem. With regard to the trilateration measurements, geodetic surveys before and after the 1980 Mammoth Lakes earthquakes (in an area about the size of NTS) show that slow E-W extensional strain rates (about the same as those observed at Yucca Valley) during the 1970's were punctuated by much larger E-W extensional strains at the time of the earthquakes.

Mammoth Lakes Earthquakes. Throughout the report the panel uses as examples primarily earthquakes and fault scarps in the eastern part of the Basin and Range province, in Utah, Idaho and Montana. In the vicinity of Mammoth Lakes, California, a major earthquake swarm has been in progress since 1978 and has been associated with magmatic resurgence in Long Valley caldera. The Mammoth Lakes sequence has been studied in more detail than perhaps any earthquake sequence of comparable size, and dozens of papers have been written covering all aspects — geologic, geophysical, seismological — of this sequence. In view of the close connection between tectonic and volcanic activity in the development of the western Great Basin in general and the NTS area in particular, it is strange that the wealth of material on this sequence has been overlooked by the panel.

As mentioned above, these comments are only preliminary and are based primarily on the SAIC report itself rather than the materials reviewed by the working group. We look forward to receiving the draft EA and supporting materials for a more detailed review in February.

Sincerely,

Alan Ryall

Alan S. Ryall, Jr.
Director

COMMENTS ON THE DOCUMENT TITLED "TECTONIC STABILITY AND EXPECTED GROUND MOTION AT YUCCA MOUNTAIN"

W. A. Peppin 31 Dec 84

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The subject document is a summary of the relevant information needed to assess the ground motion to be expected at a proposed waste respository site at Yucca Mountain on NTS. It is put together by a panel of experts who have considerable knowledge of the relevant issues. The following is intended to suggest ways in which the recommendations made might be modified or expanded upon.

1. Some Missing Subtopics. The executive summary, presented as pages E-1 and E-2 of the document, is intended to summarize all of the issues relevant to ground motion and tectonic stability. This is good, but could be expanded to include the following subtopics:

(1) Instrumentation. At page 24 it was noted that no earthquake measurements are being made at the repository horizon in Yucca Mountain. The need to develop site-specific ground motion parameters was also stressed. Therefore, it is clear that, at any site proposed to be a critical facility and also within a tectonic region, on-site seismic monitoring should be initiated at the earliest possible time. Therefore, recommendations should include a section about placing instrumentation which will be capable of providing information at the earliest possible time. For example, it would now be very useful to have surface and underground recordings of nuclear tests, which provide a basis for quite complete assessment of strong ground motions at the repository site. With present technology, this monitoring effort could be implemented quite cheaply. Also, high-gain instrumentation could be used to monitor microseismicity at the Yucca Mountain site, which evidently has not been done to date. Recurrence rates elsewhere in the Basin and Range, obtained from microseismicity, have been shown to agree reasonably well with recurrence rates obtained from long-term geologic recurrence rates, and could thus provide another set of key information about the proposed site.

(2) Volcanism. The report has ignored the possibility of disruption of the repository by volcanism. As recent volcanism is known quite close to the site, this should have at least been mentioned in the report.

(3) Mammoth Lakes/Borah Peak data bases. Recent intense sequences at Mammoth Lakes and Borah Peak have provided a lot of excellent information pertinent to the siting issue, particularly on strong ground motion parameters in an extensional environment. It appears that the report has not properly made use of relevant information from, particularly, the Mammoth Lakes sequence (see also below.)

2. Specifics.

(1) Section on tectonic stability (pp 1-13)

It seems premature to rely on in-situ stress measurements as an indicator that earthquakes will occur, as there is no published demonstration that such measurements have anything to do at all with the stresses associated with earthquakes. Therefore, results obtained at Yucca Mountain might be misleading (indeed, it is noted at page 4 that stress levels measured in aseismic areas of the Gulf Coast and elsewhere compare to those measured at Yucca Mountain, suggesting that seismic activity there is not imminent).

I have not read the work done in the Wasatch, which, by implication, shows that certain large scarps there result not from large earthquakes, but rather from a lot of smaller (?) ones. At this point (page 5) the report appears to be needlessly misleading. Elsewhere in the report it is noted that M6 events are not necessarily associated with surface faulting, so that, if a scarp is moved by an earthquake, it probably is large (M6+). From the standpoint of seismic risk, it is undoubtedly just such an earthquake that poses the greatest problem for the repository site. In other words, it adds little to argue that a scarp found near the site may have been caused by a sequence of little earthquakes ("little" here must mean magnitude 6+).

The program of weapon testing provides a significant data base to do some assessment of present-day stresses. Aki (early 70s) and more recently Wallace and Helmberger (1984) have discussed the decrease in excitation of Love waves or SH generation in tests done on the test site. Therefore, the potential exists to estimate the stress available to cause earthquakes to a depth of about 5 km on the test site. The method would be to use the fact documented by Aki and Wallace that, when tests are fired repeatedly in a part of the test site, the amount of Love wave and SH excitation drops essentially to zero. Thus, by looking at the combined release by the explosions and their aftershock sequences, one could determine the stresses available to produce seismic radiation. I would say that this is every bit as fruitful an avenue as in-situ stress measurements by which to assess the present day capability of faults in the region. Also, it should be emphasized that there is no clear evidence that any nuclear explosion has caused seismic energy release of amount comparable to the energy of the explosion except very close to the shotpoint (possible M 5.9 earthquake associated with BENHAM, Aki et al., 1969,) so it should be clearly stated that the history of weapons testing probably has nothing to do with the possibility of earthquakes at Yucca Mountain.

At page 7 we find the statement that "...the extension [of the Basin and Range] at any given time is confined to narrow belts as appears to be the case today in the Death Valley region, rather than being uniformly distributed across the province." What about Slemmon's map of quaternary faults, and what about Wallace's work? Do these imply that we expect to find seismicity only along belts, or can we really say nothing about the possibility of seismicity continuing to follow the W. Nevada zone of recent activity, for example? At pages 7 and 8 I don't agree that it is unreasonable to place bounds on the extension rates at Yucca Mountain by use of province-wide rates. It seems to me that a defensible approach would be to use the recurrence rates for the whole Basin and Range, then prorate the Yucca Mountain rates down by the known smaller amount of strain accumulating (Greensfelder et al).

The suggestion to do trenching on significant faults with Quaternary-Holocene scarps (p10) is an invitation to a large amount of work. The language might be tightened to make this a bit less open-ended.

(2) Section on ground motion (pp14-24) The section on unassociated earthquakes is good in that it brings out what I believe to be the biggest problem area, namely, the nearby occurrence of an earthquake of magnitude about 6. This is the area that should receive the closest scrutiny in my opinion. I don't see much hope of associating most of the earthquakes with known faults, as, for earthquakes near m 6 this is almost never done in practice.

The data taken in the recent Mammoth Lakes sequence must be considered in view of the statements on p16 of the report, which state that "...0.5 g is the maximum surface acceleration likely in an extensional regime". However, in the recent sequence at Mammoth Lakes quite a few accelerations in excess of this value were observed, up to 0.7 g. Therefore, it may be that the recent McGarr work cited does not apply to the Basin and Range for some reason (Mammoth Lakes tectonics are dominated by NE extension.)

On page 17 is a discussion of the largest credible earthquake within 50 km of the site. It doesn't seem to me that we need to worry so much about the relation between fault length and magnitude, because a postulated large earthquake at distance is not going to produce high accelerations, but will have long duration. The high accelerations are almost certainly going to be produced by the smaller but closer design earthquake, and seismic hazard analysis with almost any reasonable model parameters will undoubtedly confirm this.

I would not agree with the conclusion from McGarr (1984) that PGA values are expected to be three times higher in compressional regimes than extensional ones, given the high accelerations observed at Mammoth Lakes.

I think that the report is too pessimistic at page 23 where it states that "it is not feasible at this time to provide precise predictions of the motions at depth from values at the surface". Some recent work I did at Blume pertains. Our basic result was that downhole versus surface values of peak ground motion parameters could be expected to diminish by about a factor of 2 at depth for all wave types (based on hundreds of observations.) For NRC purposes, we have established a precedent that allows some reduction of the design acceleration from peak surface values, and this may be applicable at repository depths.

On the whole, I believe this report has been fairly good in summarizing the problems and possible or potential solutions. The authors have clearly acted responsibly to the needs of DOE in this matter.