**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**

**MASTER
PRELIMINARY REPORT**

October 2, 1984

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Report of a Workshop at SAIC, La Jolla
August 7-8, 1984

Prepared for:

U.S. Department of Energy
Nevada Waste Management Project Office

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ABSTRACT

A workshop was convened on August 7-8, 1984 at the direction of DOE to discuss effects of natural and artificial earthquakes and associated ground motion as related to siting of a high-level radioactive waste (HLW) repository 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 workshop participants were representatives from the DOE/NV Waste Management Project Office, Science Applications, Inc., U.S. Geological Survey, Sandia National Laboratories, and John Blum and Associates. The panel of experts consisted of Dr. W. F. Brace (MIT), G. A. Frazier (Center for Seismic Studies), H. R. Pratt (Science Applications, Inc.), R. B. Smith (University of Utah), B. P. Wernicke (Harvard University), and C. B. Raleigh (Lamont Doherty Geological Observatory). All workshop participants are listed in Appendix 1.

The objective of the meeting was to advise the Nevada Nuclear Waste Storage Investigations (NNWSI) Project about how to present a technically balanced and scientifically credible evaluation of Yucca Mountain for the NNWSI Project 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 Drs. Brace, Frazier and Pratt and are compiled in this report. A more complete document with detailed recommendations will be published at a future date.

EXECUTIVE SUMMARY

- o 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.
- o Crustal extension rates inferred from contemporary seismicity and Quaternary geologic slip rates in the Basin and Range province can not yet provide detailed recurrence intervals for earthquakes at Yucca Mountain. Limitations preclude an accurate assessment using this method to the limited area of Yucca Mountain primarily because of a short historical seismic record and a lack of detailed slip rate data in the immediate site vicinity.
- o There is a high probability that scarps associated with faults capable of producing large earthquakes ($M_s \geq 7$) have been located and mapped.
- o The Death Valley region, about 50 kilometers west of Yucca Mountain, has heretofore not been considered a major source 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 its earthquake capability.
- o 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.
- o 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.

- o 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.
- o 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.
- o 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.
- o Ground motion in compressional regimes such as 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, Harmsen, and Carr (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 (USGS) has recently completed in situ stress measurements in several boreholes at Yucca Mountain. What does the stress state at and near Yucca Mountain imply about future earthquakes near the site?
2. Rogers, Harmsen, and Carr (1983) cite an argument in favor of large magnitude earthquakes, based on the size of Great Basin scarps. What is the evidence for this as it applies to Yucca Mountain?
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. Are these observations relevant in the present context?
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. What would this rate be for Yucca Mountain?
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. In the present context, have the block boundaries been correctly located? In more concrete terms, are currently active fault zones well located in Yucca Mountain?

6. From an overall geologic standpoint, tectonic stability may be assessed from diverse observations of geomorphology, Holocene movement along faults, and the geologic settings of recent great earthquakes, etc. From such a point of view, which area in the Southern Great Basin has the greatest potential for a major earthquake?

1. In Situ Stres

Stress measurements in boreholes at 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 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 of these values, it would have to be concluded that frictional failure on faults properly 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 deeper stress measurements, in the future.

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 and Range Province 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 known only to 1.5 km. It is not known if shallow stress measurements can readily be extrapolated 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 to greater depth are evident.

Accepting the above conclusions that failure on properly oriented faults could occur 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. Current knowledge of tectonics of the Basin and Range is insufficient to choose among alternative interpretations of the on site stress data.

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) could also lead to a conclusion that frictional failure on properly oriented faults is imminent. However, current seismic activity in these regions is negligible.

In summary, in situ stress measurements suggest that frictional failure on properly 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 numerous small earthquakes.

2. Large Scarps

Association of large scarps with large earthquakes in the Great Basin has been suggested by Rogers, Harmsen, and Carr (1983), Bonilla and Buchanan (1970). 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, Schwartz, and Cluff, 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. 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) energy released by underground nuclear explosions may not be a good "trigger" for a tectonic earthquake, (2) it is difficult to differentiate a 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, Helmberger, and Engen, 1983; Dicky, 1968; McKeown and Dickey, 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 and Burchfiel, 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 and Burchfiel, 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, Kintzer, and Somerville, 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, Gans, and Garing (1983)). A key geological observation is that the extension at any given time is localized confined to narrow belts rather than being uniformly distributed across the province as this appears to be the case today in the Death Valley region. In

addition to this, it is clear that some large blocks have remained strain-free during Basin and 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) consisting of measurements made over a block about 40 km in a N-S direction and 20 km E-W direction 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 -0.07×10^{-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 is that the strains accumulate entirely as elastic distortions and 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 measured 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, Kinster, and Somerville (1980), also suggests relatively low strain rates of 2×10^{-8} per year for the Yucca Mountain region, increasing by an order of magnitude southward toward the Garlock fault to 10⁻⁷ per year.

5. Location of Potential Fault Zones

The NTS vicinity is 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 seismic network 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, e.g., Madison, Wasatch, Borah Peak faults, have failed during large earthquakes, evidence to date suggests that they break along segments rather than along their entire length (Swan, Schwartz, and Cluff, 1980). The working group noted that analyses associated with the NNWSI Project 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 termination), 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 Mountain 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, et al 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 and 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. This is due to the extremely low population density, which limits the number of observations in the case of pre-instrument intensity reports, and to the short length of time that regional networks have been in operation. It is imperative that the historical earthquake record is examined for completeness in order to ascertain the level of confidence for the assignment of statistical parameters such as the "a" and "b" values, which reflect the number of earthquakes of a given magnitude occurring through time.

The site-specific seismicity records for 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 term seismicity assessments.

Focal depth distribution of earthquakes can provide information regarding correlations between surface geology and faulting at depth. In general, to estimate focal depth requires that the distance from the epicenter to be no more than the station focal depth in order to obtain 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.

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; Ryall and Vanwormer, 1980; Rogers, Harmsen, and Carr 1981). While Quaternary faulting shows significant oblique lateral slip, large earthquake solutions show major components of E-W extension on normal faults. 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 produced surface faulting show primary displacement in the down-dip direction. The significance of the strike slip solutions is not currently understood; they simply may be the accommodation of strain release along pre-existing fault planes that are not now favorably oriented for strike-slip faulting, or they may represent the potential of large lateral slip along such fault systems as the Death Valley-Furnace Creek zone.

Much of the intraplate deformation of the western United States has been attributed to "block" tectonics where coherent and stable volumes of the upper crust 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 identifying seismicity patterns. Even small earthquakes, although not related to large strain release, may provide estimates of boundary zones. Given that maximum focal depths can be estimated for a region, the thickness of brittle seismogenic volumes can also be estimated.

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 m 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 Furnace Creek Fault is considered to be relatively aseismic in the historical record, there is abundant evidence for major Quaternary displacements (Hunt and Mabey, 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 proven otherwise.

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.

On the assumption that the largest credible earthquake for Yucca Mountain will follow procedures and definitions set forth in 10CFR100, Appendix A, the determination will provide the following:

- o a map of tectonic provinces contained within a 200-mile radius around the site
- o a catalog of historical seismicity within each tectonic province, any part of which is located within the 200-mile radius of the site

- o an evaluation of the association of historical seismic events with capable faults, any part of which is situated within the 200-mile radius of the site.

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

- o What are the largest unassociated earthquakes to be expected within 15 km?
- o What is the largest earthquake of any sort within 50 km?
- o What are the recurrence intervals for large earthquakes?
- o What is the attenuation of ground motion appropriate for Yucca Mountain?
- o 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 there has been movement along any of the faults within 10 km in the last 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:

- o The Basin Range structure was assumed to be undergoing spatially uniform extension at the rate of 0.2 mm/yr per 10 x 10 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 10 x 10 area along the active central Nevada seismic zone.
- o 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 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

$$I = 25,000 \text{ years}$$

for unassociated magnitude 6 earthquakes within about 15 km of the site. Note that these recurrence intervals for unassociated earthquakes differ from those calculated on page 6-7 for associated earthquakes.

Several relevant factors are not included in this estimate for recurrence 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) regards 0.5g as the maximum surface acceleration likely in an extensional regime such as Yucca Mountain.

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 the largest credible magnitude earthquake (Bonilla and Buchanan, 1970; and Mark and Bonilla, 1977) result from data with a great variability in the earthquake fault length that is associated with a given magnitude, even when normal-slip, normal oblique-slip, and strike-slip faults are treated separately. For example, a predicted earthquake magnitude for a 17 km fault is 6.8 ± 0.8 based on 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 earthquake 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 at 17 km. 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:

- o A concerted effort should be made to identify the fault-length relation most applicable for estimating the largest credible magnitude on local seismogenic faults and this relationship should be applied to re-evaluate current estimates.
- o 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 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 more-distant faults (e.g., Furnace Creek) associated with larger magnitude events constitute 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 scenario. 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 to predict seismicity in a region the size of Yucca Mountain. The historical record of the entire Basin and Range province 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 and 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.

1. Develop Quaternary Holocene return rates based on "a" and "b" values derived from historical magnitude and intensity data. Rogers, Perkins, and McKeown (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.

2. Develop slip rates by dating fault offsets within the Basin and 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.
3. Estimate the regional deformations using geodetic control and provide estimates of the uncertainties.
4. Compare the activity rates from historical seismicity, fault offsets, and geodetic surveys to test consistency. Also, compare the results with estimates of the Basin and Range activity developed in other studies. Use these results to develop a range for the return period of local earthquakes of varying magnitudes and site-specific levels of ground motion.

4. Attenuation of Ground Motion

The expected peak acceleration specified in the draft Environmental Assessment for the Yucca Mountain site (1985) was based on the seismic hazard analysis developed by Rogers, Perkins, and McKeown (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, the analysis does not include 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), along with a new reference for magnitude/fault relationships (Bonilla, Mark, and Lienkoemper, 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 (1984) has recently shown that peak acceleration is strongly dependent on stress state. In particular, peak acceleration in the compressional regime such as Southern California is nearly three times greater than in 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 (UNEs) are important in the assessment of the repository facilities located at a depth of 350 m. 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 et al. (1951, 1953, 1954, 1966), and Iwasaki, Wakabayashi, and Tatsuoka (1977) indicated 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 predicted by using the Schnabel and Seed (1973) curves for surface rock velocities at the same focal distance (Pratt, Hustrulid, and Stephenson, 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 sparsity 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.

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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.

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