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SEISMIC HAZARD ANALYSIS FOR THE NTS SPENT REACTOR FUEL TEST SITE

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I.0 INTRODUCTION

The Lawrence Livermore Laboratory (LLL), as a participant in the Nevada Nuclear Waste Storage Investigations of the U.S. Department of Energy (DOE), is technically directing an experiment at the Nevada Test Site (NTS) designed to test the feasibility for storage of spent fuel from nuclear reactors in geologic media (Rainspott, et al., 1979). The LLL experiment is focusing on the response of the geologic media to the decaying thermal load issued from the spent fuel canister since this, more than any other parameter, will determine the viability of the storage technique. The experiment entails, therefore, placement of actual spent fuel into a facility that has been mined into the Climax Stock Granite at a depth of 420 meters below the surface.

As is customary with any large project of this type, LLL is preparing an extensive analysis of the safety associated with this experiment. One component of the safety assessment was the earthquake hazard. While it was intuitively accepted that the hazard was quite low due to the relative aseismicity of the Nevada area, LLL contracted with TERA Corporation to undertake a more quantitative seismic hazard assessment due to the site's proximity to the Yucca and Boundary Faults. This report represents the results of this seismic hazard assessment. The study was directed from LLL by Mr. Richard Carlson. At TERA, the study was under the technical direction of Dr. Kenneth Campbell.

For completeness, it was decided to address two distinct components of the seismic hazard: vibratory ground motion and surface rupture displacement. It was further decided, for several reasons, to assess the seismic hazard probabilistically. First of all, such analyses provide a rational basis for decision-making such as balancing between design criteria and cost. Secondly, probabilistic analysis can properly and rigorously account for the hazard from events of all sizes (not just the largest). Thirdly, the technique accounts for the important uncertainties in each parameter.

The specific tasks that were undertaken by TERA Corporation in support of this effort were as follows:

- A review of pertinent, local historical seismicity
- The identification of faults which could affect the seismic hazard at the spent fuel test-site
- The development of seismicity models for those faults considered a hazard to the site
- The development of a near-source peak acceleration attenuation relationship for the region
- The development and application of a ground motion hazard model for estimating the probabilities and return periods of various levels of peak acceleration at the site
- The development and application of a fault rupture hazard model for estimating the probabilities and return periods of various levels of surface rupture displacement on those faults considered a hazard to the site

The results of this effort are briefly summarized below.

1.1 SUMMARY OF RESULTS

For large peak accelerations (0.5-0.7 g), the seismicity associated with the major faults within the immediate vicinity of the spent fuel test-site will have the greatest impact on the assessment of ground motion hazard. However, the historical seismicity is neither complete enough nor accurate enough to represent a true picture of the long-term seismicity on or near these faults. Therefore, a seismotectonic model, based on geologic slip-rate data, was used to estimate the seismicity associated with nearby faults.

Within the vicinity of the test-site, the faults considered to be active were the Yucca, Carpetbag, Boundary, and Butte faults. The selection of these was based upon evidence of Quaternary movement. Using slip rates estimated from post-tuff deformations in the Yucca Valley, and assuming a b-value of 0.83 and maximum magnitude of 6.8, the seismotectonic model predicts that an earthquake of magnitude ≥ 3.5 will occur once roughly every six years on these faults.

A probabilistic seismic hazard model was used in estimating the hazard due to ground-shaking. A similar model was developed to assess the hazard associated with fault rupture near the test-site. In the analysis, each fault system was divided into a series of segments of equal seismicity. Within each segment, earthquakes were assumed to occur at random in accordance with a Poisson process. The distribution of these events, with respect to magnitude, was constrained to be consistent with a truncated exponential distribution. Fault rupture was taken into account through an empirical relationship between magnitude and fault length. The random occurrence of all events from all fault segments was combined with an attenuation model and used to develop a probability distribution of peak acceleration at the site. Similarly, the distribution for the maximum fault rupture displacement at any point on the fault was developed by combining the random occurrence of events with relationships among magnitude, rupture displacement, and fault dimensions.

The analysis suggests that the occurrence at the spent fuel test-site of peak accelerations exceeding 0.7 g may be associated with a return period of 12,700 years, which corresponds to a probability of occurrence of 3.9×10^{-4} during the five-year life of the experiment. Similarly, a rupture displacement exceeding 5 cm, at a point on the Boundary fault closest to the site, may be associated with a return period of about 1,000 years, which corresponds to a probability of occurrence of 10^{-3} to 10^{-2} during the five-year period of the test. Since these probabilities are for rupture on the faults, the probability of rupture through the site would, of course, be considerably smaller and would depend on the detailed pattern of existing secondary-faulting features.

The estimated annual probabilities of 10^{-4} to 10^{-3} , for accelerations exceeding 0.7 g and rupture displacements exceeding roughly 5 cm, are very low and, in fact, consistent with probability levels used in the design of nuclear reactors.

2.0 GEOLOGY AND SEISMICITY

2.1 GEOLOGY

The Nevada Test Site (NTS) is located in the southcentral section of the Great Basin within the Basin and Range physiographic province. This province is characterized by a series of north-to-northeast trending mountain ranges which rise to heights of between 2,100 and 3,000 m and which are separated by intermountain basins at elevations of 900 m to 1,500 m. The crust of the Great Basin is relatively thin, averaging about 35 km (Hunt, 1967). In general, the rocks of the Great Basin can be characterized as metamorphic rocks of the early Precambrian Age, sedimentary rocks of the late Precambrian, Paleozoic, and Mesozoic Ages; plutonic rocks of the Mesozoic and Tertiary Ages; and volcanic and sedimentary rocks of the Cenozoic Age.

Beginning late in the Paleozoic, the rocks in the basin were subjected to successive periods of compressive deformation which resulted in folding and thrust faulting. This orogenic process climaxed, in the late Mesozoic and early Tertiary, with intrusions of granitic plutons and volcanic activity. The Tertiary volcanic rocks, forming a sequence over 12,190 m thick (Marvin, et al., 1970), are irregularly distributed as a result of preexisting topographic features and structural deformation. Later in the Tertiary (14-17 m.y. ago), the basin area began to undergo a period of general extension. During this period, a series of northwest-striking lineaments formed, creating a zone of disrupted topography called the Walker Lane. The Las Vegas Shear Zone (to the southeast of NTS) and the Furnace Creek-Death Valley Fault Zone (to the southwest) developed within the Walker Lane complex. Although the activity on these faults appears to have died-out about 11 m.y. ago, they have influenced the trend of the block faulting that has followed up until the present (Carr, 1974). An extensive period of volcanism started about 40 m.y. ago and may have continued until the present. The oldest volcanic rocks occur most commonly in east-central Nevada and become progressively younger the farther away they are from the older center. Volcanic activity in the area of the NTS occurred within the last 16 m.y.

Block faulting began with the onset of the general extension of the area. The position of the faults, as mentioned, is the result both of the prevailing tectonic structure and the direction of the prevailing stress due to extension. Basins were formed and filled over the last 17 m.y. (Ekren, et al., 1968) with alluvium and colluvium.

Local Geology (NTS)

Due to the process already described, the geology of the NTS can be broadly divided into 1) a basement of compressively deformed upper Precambrian and Paleozoic sedimentary rocks, 2) an overlying section of Tertiary and Quaternary volcanic rocks broken by normal faulting, and 3) late Tertiary and Quaternary alluvium and colluvium cut by normal faulting.

The period of compression during the Mesozoic produced two major thrust faults parallel to and located to the west of the present-day Yucca Flat; the Mine Mountain Thrust and the CP Thrust. These thrust faults, subsequently cut by normal faulting, have not been active since the Mesozoic.

A new phase of faulting was precipitated by the period of regional extension beginning in the Tertiary and continuing to the present. According to Carr's (1974) tentative model for stress orientation, the NTS is undergoing extension in a N50°W-S50°E direction. Carr suggests that the structural style that has been developing in the Yucca Flat area since the Pliocene is still continuing today. Thus, the present general stress configuration has probably existed for several million years. Carr also notes that there is no great difference in explosion-induced fracture-trends from one part of Yucca Flat to another, which provides additional support to the theory that the uniformity of stress is continuing at present. In our area of concern, the two major fault systems which have formed as a result of this extension are the Carpetbag and Yucca faults. These young faults, striking generally north-south, form the orientation of the present-day basin and ranges of the NTS.

The Climax Granitic Stock

The Climax stock is composed of quartz monzonite and granodiorite (Figure 2-1) intruding rocks of the Paleozoic and Precambrian Ages. It has an average K-Ar age of 93 ± 5 m.y. (Marvin, et al., 1970). The stock and the intruded sedimentary rocks are unconformably overlain by Tertiary pyroclastic rocks consisting of tuff, welded tuff and breccia. Erosion has removed much of the pyroclastic and sedimentary rocks, exposing the underlying stock.

The stock is exposed over an area approximately $2 \frac{1}{4}$ km long in a north-south direction and 1.6 km across at the widest eastward dimension. The topography rises northward from an elevation of about 4,900 ft (1,495 m) on the south, to about 5,800 ft (1,770 m) at the northern boundary. Two major tunnel complexes, the Tiny Tot and the Pile Driver-Hard Hat tunnel complexes, have been driven into the stock. Two underground nuclear tests have been conducted in the Pile Driver-Hard Hat tunnel complex.

Quaternary Faults

The deep troughs and associated faults of the Yucca Flat are of special interest to our understanding of the seismicity of the area. These troughs, although probably controlled in trend by older structures, are relatively young features. Evidence of their youthfulness is supported by a general lack of thickening of the Pliocene Timber Mountain tuff accompanied by an abrupt thickening of the alluvium (Figure 2-2). Carr suggests that these medial troughs seem to represent a relatively young episode of faulting which involved a change in stress orientation and mechanism. Stewart (1971) suggests that this type of narrow-trough feature may be due to localized plastic extension in the lower crust. It is also suggested that the crystallization of large post-volcanic plutons in the central Walker Lane may have increased the capability of the crust to transmit stress. By "spot-welding" the upper crust to the infrastructure, these recent plutons could transfer the deeper lateral stresses to the surface rocks (Carr, 1974), thus contributing to the major faulting in the Yucca Flat. Carr also notes that there is substantial evidence indicating northwest to southeast extension

GEOLOGY

- GAL - ALLUVIUM (QUATERNARY)
- KQM - QUARTZ MONZONITE, CLIMAX STOCK (CRETACEOUS)
- KGD - GRANODIORITE, CLIMAX STOCK (CRETACEOUS)
- Pz - LIMESTONE, DOLOMITE, SHALE, AND QUARTZITE, UNDIVIDED (PALEOZOIC)

LEGEND

- MAJOR FAULT TREND
BAR AND BALL ON DOWNTHROWN SIDE
ARROWS INDICATE RELATIVE MOVEMENT
DOTTED WHERE APPROXIMATELY LOCATED
- CONTACT
SMALL DASH WHERE APPROXIMATELY LOCATED

FIGURE 2-1

GEOLOGY OF THE SPENT FUEL TEST SITE -
CLIMAX STOCK

TERA CORPORATION

FIGURE 2-2

SCHEMATIC CROSS-SECTION OF YUCCA FLAT
 ALONG LATITUDE 37.015° (After Carr, 1974)

(along and adjacent to the Walker Lane) and the formation of deep basins within the last 4-10 m.y.

The major Quaternary faulting in the spent fuel test-site area is confined to the Carpetbag, Boundary, Butte and Yucca faults (Carr, 1974). This is indicated by the large extent of faulting along these zones as compared to the faulting in the tuffs on the edge of the Yucca basin (Figure 2-2). The release of stress occurs largely in existing crustal weaknesses, such as established faults. The Carpetbag fault (Figure 2-3) is the older fault in the basin and also the most difficult to trace. It runs approximately north-south up the basin. Its position in the area of the climax stock is unclear; however, the faulting does bend around the granitic pluton (as the Boundary fault) and extends northward (as the Butte fault).

The Yucca fault runs the length of the flat for about 24 to 32 km (Figure 2-3). The age of the surface scarp of the last movement on this fault is difficult to determine, but it is estimated at between 1,000 and 10,000 years old. The fault runs approximately parallel to the Carpetbag fault and becomes concealed upon approaching the Boundary fault.

These faults are normal faults, active as a result of the general extension of the area. The Carpetbag and Yucca faults exhibit vertical post-tuff cumulative displacements of 600 m and 200 m, respectively (Carr, 1974). However, since the faults do not parallel the existing stress field, they exhibit a component of right-lateral slip as well. Carr estimates that this could easily equal or exceed the average post-tuff vertical component.

According to Carr (1974), the average dip of the faults at the surface is about 60° , with a shallower dip developing with depth. The Paleozoic bedrocks generally exhibit a 40° dip, although dips up to 60° have been observed. The Yucca fault which generally dips about $75-80^{\circ}$ at the surface, flattens to between $55-65^{\circ}$ at depth. The Carpetbag fault, however, appears to have a shallow dip in the southwestern Yucca Flat approaching the 40° dip of the Paleozoic bedding.

FIGURE 2-3
GEOTECTONIC MAP OF THE YUCCA FLAT AREA

We have, then, a picture of the Carpetbag and Yucca faults accommodating the stress in the area of the Yucca Flat, while the Boundary and Butte faults appear to be an extension of this system, relieving the stresses to the north. It is these major Quaternary faults that pose the immediate seismic hazard to the spent fuel test-site. For the purposes of this study, these faults are assumed to form two continuous systems: one represented by the Carpetbag-Boundary-Butte system, and the other by the Yucca-Butte system. Under this hypothesis, the Butte fault is considered to be relieving the stresses associated with both the Carpetbag and Yucca faults to the south, even though there is possible evidence for less extension in the northern area of Yucca Flat.

The closest major Quaternary faults existing outside of the Yucca Flat area are the Mine Mountain fault, located 25-30 km to the south, and the Kawich Valley fault, located some 20 km to the north of the test facility. Since the main bodies of both faults lie at least 50 km from the site, they do not significantly affect the site hazard associated with the 0.5-0.7 g peak accelerations of interest in this study. The faults of the Walker Lane, including the Funeral Mountains and Death Valley faults, are the closest faults that may be expected to produce great earthquakes ($M \geq 8$); but since they are located at a minimum of 100 km southwest of the test-site, they pose no threat to the facility at the acceleration levels of interest.

2.2 SEISMICITY

The historical seismicity of the Yucca Flat region has been complicated by nuclear testing within the area, masking the natural seismicity of the region. The NEIS worldwide catalogue of seismic events lists 19 events of magnitude 3.5 or greater that have occurred from 1932 to 1974 within the Yucca Flat region (Table 2-1). This area, located from 36.95° to 37.3° north latitude and 116.0° to 116.1° west longitude, is approximately 40 km long and 10 km wide, centered on the Yucca Flat. It should be noted that the specified depths are usually poorly constrained and therefore often contain large errors. Furthermore, a depth of 33 km indicates that a depth could not be determined from the data and, therefore, was assumed to be 33 km in computing the epicenter.

TABLE 2-1
LIST OF SEISMIC EVENTS WITHIN THE YUCCA FLAT AREA
1932 - 1974

[36.95°N - 37.30°N]
[116.0°W - 116.1°W]

<u>Year</u>	<u>Month</u>	<u>Day</u>	<u>Time</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Magnitude</u>	<u>Depth</u>
1947	9	23	06:20:40	37.15	116.0	3.5	16
1959	3	13	22:24:18	37.1	116.1	3.5	16
1968	4	26	15:14:52	37.1	116.2	5.1	33
1968	4	26	18:47:32	37.1	116.1	3.6	33
1969	1	22	15:00:03	36.958	116.028	4.6	20
1969	3	18	14:40:02.7	37.16	116.006	4.4	33
1969	6	26	16:00:03	37.101	116.049	4.4	28
1969	9	20	14:30:03	37.149	116.034	4.3	33
1969	11	13	15:15:02	37.15	116.083	3.5	10
1970	5	28	12:00:03	37.174	116.030	4.2	33
1971	8	5	17:58:17	36.91	115.99	4.6	4.6
1971	10	14	14:30:03	37.221	116.071	4.4	33
1971	11	30	15:45:03	37.080	116.070	4.7	39
1972	2	17	19:02:04	37.085	116.076	4.6	33
1972	3	30	21:00:01	36.955	116.033	4.6	10
1973	4	26	15:15:00	37.006	116.018	4.1	5
1974	5	23	13:38:30	37.064	116.072	4.8	5
1974	6	6	14:40:00	37.002	116.042	4.4	2
1974	7	18	14:00:01	37.067	116.066	4.2	5
1974	9	25	14:00:00	36.973	116.002	4.4	5

Of the 19 events mentioned above, the M 4.8 event that occurred on May 23, 1974, was an announced test. The two events that occurred on April 26, 1968 (of M 5.1 and M 3.6) are possible aftershocks of an announced test that was detonated just minutes before the first aftershock (from Carlson, personal communication). Of the remaining 16 events, all 14 that occurred since 1968 have origin times that suggest they were possible unannounced tests conducted within the area. Under this interpretation, the 1947 and 1959 events, both of magnitude 3.5, remain as the only two tectonically-related earthquakes in the original list.

Due to incomplete recording of seismicity in the period before testing and the contamination of the record with unannounced tests, the historical estimate of one event every 21 years of $M > 3.5$ must be considered a lower limit of the true natural seismicity.

It is clear from these data that data-based estimates of the seismicity would be subject to very large errors and large uncertainty. In consideration of this, we have developed the necessary seismicity models for this study using the geologic slip rate rather than the seismic record. (Further justification for this may be found in Allen, 1975.) Approaches such as this, which have been developed in the last few years (Campbell, 1977; Molnar, 1979), have been shown to yield accurate and stable estimates of the seismic activity rate. In particular, the model, as developed below, yields a seismicity model that is in close agreement with the historical seismic record.

Based on the acceleration levels of interest for this study (0.5-0.7 g), we restrict our analysis to the very nearby fault systems, as shown in Figure 2-3. The development of a seismotectonically derived seismicity needed for these two faults is developed in the section below.

Seismicity Model

Brune (1968) has proposed an expression that can be used to estimate the total average slip $\langle u \rangle$ on a fault from the sum of seismic moments of earthquakes on the fault. This expression is given by

$$\langle u \rangle = \frac{1}{\mu A_0} \sum M_0 \quad (2-1)$$

where μ is the shear rigidity of the medium, A_0 is the total area of the fault zone given by its length L_0 times its width W_0 , and M_0 is seismic moment defined as $\mu A \bar{D}$, (where A is the area of fault rupture for the event and $\bar{D}$ is the mean displacement).

Equation 2-1 can be generalized to establish a relationship between number of events having magnitudes m and greater, $N(m)$, and the slip rate S_R . The total slip per year that can be expected to result from the occurrence of earthquakes on the fault can be given by

$$S_R = \frac{1}{\mu A_0} \int_{-\infty}^{M_U} M_0(m) |dN(m)| \quad (2-2)$$

where M_U is the upperbound magnitude on the fault, and $|dN(m)|$ is the number of events per year having magnitudes equal to m . The absolute value is required because the number of events decrease with increasing m , giving a negative slope for the $N(m)$ versus m relation. In Equation 2-2 only the absolute number of events is required.

In order to analyze Equation 2-2, relationships among $M_0(m)$, $|dN(m)|$ and m are required. Let it be assumed that, for the fault, the number of earthquake occurrences per year of a given magnitude or greater can be given by the magnitude-frequency law,

$$N(m) = 10^{a-bm}; \quad m \leq M_U \quad (2-3)$$

Taking the derivative of this expression gives,

$$|dN(m)| = b \log_{10} 10^{a-bm} dm \quad (2-4)$$

Let it also be assumed that the seismic moment of an event can be related to its magnitude by a relationship of the form,

$$M_o(m) = 10^{C_1 + C_2 m} \quad (2-5)$$

which has been suggested from both empirical and theoretical considerations.

An expression for slip rate is obtained by substituting Equations 2-4 and 2-5 into Equation 2-2 and integrating, thus obtaining,

$$S_R = \frac{b}{(C_2 - b) \mu A_o} 10^a \left[M_o(M_U) 10^{-b M_U} \right] \quad (2-6)$$

An expression for the number of events per year of magnitude greater than or equal to m may be obtained by solving this equation for 10^a and multiplying each side by 10^{-bm} ,

$$N(m) = \frac{S_R \mu A_o (C_2 - b)}{M_o(M_U) b} \left[10^{b(M_U - m)} \right] \quad (2-7)$$

Similar models have been recently proposed and applied by Anderson (1979) and Molnar (1979).

Seismicity Estimates

Geologic slip-rate estimates for the Yucca and Carpetbag faults were obtained from post-Tuff vertical displacements on these two faults. Carr (1974) suggested that 200 m of vertical offset could be associated with the Yucca fault and 600 m of vertical offset could be associated with the Carpetbag zone. He also suggested that right-lateral displacements could easily be as great as the vertical offsets.

The youngest tuff that has been displaced by the faults is the Timber Mountain tuff of early Pliocene Age, some 11.3-9.7 m.y. old. The formation of deep basins in the area, which may be interpreted as the onset of normal/right lateral

faulting in the Yucca Flat, is believed to have begun some 4 to 10 m.y. ago. From this we assumed a conservative estimate of 5 m.y. over which the post-Tuff displacements may have taken place.

Assuming horizontal and vertical displacements to be equal, the total slip vectors would be equal to 1.41 times the vertical offset. This corresponds to total offsets of 280 m for the Yucca fault and 850 m for the Carpetbag fault. Resulting slip rates were computed as follows:

$$\text{Yucca fault: } S_R = \frac{2.8 \times 10^4 \text{ cm}}{5 \times 10^6 \text{ yr}} = 0.0056 \text{ cm/yr}$$

$$\text{Carpetbag fault: } S_R = \frac{8.5 \times 10^4 \text{ cm}}{5 \times 10^6 \text{ yr}} = 0.017 \text{ cm/yr}$$

An upper bound magnitude of 6.8 was adopted for both fault systems, based on Rogers, et al. (1977) estimate for the Yucca fault. It is not clear whether this value was meant to represent local magnitude (M_L) or surface wave magnitude (M_S). The M_L assumption used in the analysis is the more conservative, since an M_L of 6.8 is consistent with an M_S of approximately 7 1/4 (Nuttli, personal communication, 1979). A recent survey of practicing geologists and seismologists (Eguchi, et al., 1979) has suggested that an M_S of 7 1/4 is the maximum credible event on the Yucca fault, which is supportive of an M_L 6.3 upper limit on magnitude.

A relationship between seismic moment and magnitude was developed from 167 recorded seismograms from earthquakes of $2.0 \leq M_L \leq 6.8$ occurring in Southern California. Seismic moments were estimated by several investigators (e.g., Thatcher and Hanks, 1973) who matched observed source displacement spectra with spectra determined from dislocation theory. A least-squares analysis of these data resulted in the following log-linear relationship:

$$\log_{10} M_0 (\text{m}) = 16.30 + 1.41 m \quad (2-8)$$

where $M_0(m)$ is seismic moment in dyne-cm, with a standard error of 0.42 and a correlation coefficient of 0.95. Based on this equation, the seismic moment of the M_L 6.8 upper bound earthquake is estimated to be 7.0×10^{25} dyne-cm.

The fault width (W_0) is the distance from the surface to the maximum depth of the faulting as measured along the dip of the fault plane. The average dip of the Carpetbag and Yucca faults, is approximately 50° from horizontal (Carr, 1974). The depth of rock at which earthquakes might be generated in the NTS area is probably around 10-15 km, based on observations of earthquakes to the south of the study area and a recent survey of experts (Eguchi, et al., 1979). Using these ranges for the dip and depth of faulting, a fault width of 15 km was estimated.

The upper extent of the Butte fault (Figure 2-3) was determined as the terminus of Quaternary faulting (Carr, 1974). The southern extent of faulting, at $37^\circ N$ latitude (as used in the hazard analyses), was arbitrarily chosen to reflect a distance beyond which no significant contribution to either the ground motion or fault rupture hazard would be expected. The total lengths of the fault systems shown in Figure 2-3 are listed in Table 2-2.

The remaining data required to estimate the seismicity of the two fault zones is listed in Table 2-2. Although much of the seismotectonic data was based on the Carpetbag and Yucca faults specifically, these estimates have been generalized to include both the Boundary and Butte faults for which little information is available. Based on Equation 2-7 and Table 2-2 as input, the seismotectonic estimate of seismicity was determined as follows:

Yucca-Butte Fault System

$$\log_{10} N(m) = 1.58 - 0.83 m \quad (2-9)$$

corresponding to 0.043 events/yr of magnitude greater than or equal to 3.55;

Carpetbag-Boundary-Butte Fault System

$$\text{Log}_{10} N(m) = 2.10 - 0.83 m \quad (2-10)$$

corresponding to 0.14 events/yr of magnitude greater than or equal to 3.55.

The total seismicity on these two systems at the $M \ 3 \frac{1}{2}$ threshold is 0.18 events/yr, corresponding to the occurrence of one event every five to six years. This may be contrasted with a rate of two events in the past 43 years for the Yucca Flat area, based upon our interpretation of the historic record.

The higher seismicity on the Carpetbag fault system, based on the geologic record in the past several million years, is interpreted in this study as inferring that it is currently more active than the Yucca fault. The lack of surface expression of the Carpetbag fault, however, might suggest that it is less active. This apparent contradiction could be interpreted as suggesting either that the geologic data are in error or that under the current tectonic regime the activity has shifted to the younger Yucca fault.

The issue is complicated further by the increased depth of alluvial deposits overlying the Carpetbag system (Figure 2-2), possibly hindering the development of surface expression. The use of the higher activity rate of the Carpetbag fault is conservative, however, since this system, including the Boundary fault, comes the closest to the test-facility.

TABLE 2-2
SUMMARY OF SEISMOTECTONIC DATA USED IN THE ESTIMATE OF SEISMICITY

<u>Parameter</u>	<u>Symbol</u>	<u>Yucca-Butte Fault</u>	<u>Carpetbag- Boundary- Butte Fault</u>	<u>Reference</u>
Slip-Rate (cm/yr)	S_R	0.0056	0.017	Section 4-2
Upper Bound Magnitude	M_U	6.8	6.8	Rogers et al. (1977)
Seismic Moment of M_U (dyne-cm)	$M_o(M_U)$	7.0×10^{25}	7.0×10^{25}	Equation 2-8
Lower Bound Magnitude	M_L	3.55	3.55	Section 5-3
Fault Length (km)	L_o	34	37	Figure 2-3
Fault Width (km)	W_o	15	15	Section 4-2
Fault Area (km ²)	A_o	510	555	$L_o \times W_o$
Shear Rigidity (dyne/cm ²)	μ	3×10^{11}	3×10^{11}	Campbell (1977)
Seismic Moment Coefficient	C_2	1.41	1.41	Equation 2-8
Richter b-value	b	0.83	0.83	Rogers et al. (1977)
Seismicity (events/yr $\geq M_L$)	$N(M_L)$	0.043	0.14	Equations 2-9 and 2-10

3.0 VIBRATORY GROUND MOTION HAZARD

The probability that the peak acceleration (A) is greater than some specified value (a) can be fundamentally represented by the total probability theorem

$$P[A > a] = \iint P[A > a/m \text{ and } r] f_M(m) f_R(r) dm dr$$

where P indicates probability, $A > a$ is the event whose probability is sought, and m and R are the continuous, independent random variables of magnitude and distance which influence A. The probability that $A > a$ will occur can be calculated by multiplying the conditional probability of $A > a$ (given m and r) times the probabilities of m and r , and integrating over all the possible values of m and r .

In describing the seismicity of the sources, we are hindered by incomplete and inaccurate historical data that are limited to a short time span. Reliance on frequency data alone can result in erroneous conclusions. For this reason, we base our analysis on geological and seismological data in order to increase the reliability and predictability of the seismicity.

In the overall approach, each fault system is divided into a series of segments of equal seismicity. Within each segment, earthquakes are assumed to occur at random as a Poisson process. The distribution of these events, with respect to magnitude, is consistent with a truncated exponential distribution. Fault rupture is taken into account through an empirical relationship between magnitude and fault length. The random occurrence of all events from all fault segments, when combined with an attenuation model, is used to develop a probability distribution of peak acceleration at the site. The next section presents a theoretical development of the earthquake occurrence model used in the analysis. The following section describes how the contributions to the seismic hazard from several distinct source regions are combined. Finally, the last section presents the application of these models to the experiment site.

3.1 EARTHQUAKE OCCURRENCE MODEL

The basic input parameters of the earthquake occurrence model are the magnitude range (upper and lower bound magnitudes) and earthquake recurrence. With respect to earthquake data, the magnitudes are discretized every 1/4 of a magnitude unit as is commonly done in data recording. This representation permits the use of discrete models.

The development of the model involves three steps:

- (1) Assuming that earthquake occurrences form a Poisson process with mean rate of occurrence independent of magnitude, a distribution is obtained on the number of occurrences for the time period considered.
- (2) Given that an event has occurred, a distribution on the magnitude of events is determined. The process generating model can be assumed to be Bernoulli. The probability of success, p_{M_i} , corresponding to each trial, is defined as the probability that the event that has occurred is of magnitude M_i . Thus, the probability of failure, $q_{M_i} = 1 - p_{M_i}$, at each trial is the probability that the event is not of magnitude M_i . The probability of having r events of magnitude M_i , given that a total of n events have occurred, can therefore be obtained using the binomial distribution.
- (3) The distribution of the number of events of each magnitude, independent of the number of trials, is obtained by combining steps one and two.

Earthquake Occurrence (Poisson Model)

It is assumed, once the seismic sources have been located, that earthquake occurrences on each source form a Poisson process with mean rate of occurrence independent of magnitude. For earthquake events to follow the Poisson model, the following assumptions must be valid:

1. Earthquakes are spatially independent
2. Earthquakes are temporally independent
3. The probability that two seismic events will take place at the same time and at the same location approaches zero.

The first assumption implies that the occurrence or absence of a seismic event at one site does not affect the occurrence or absence of another seismic event at some other site or the same site. The second assumption implies that seismic events do not have memory. The assumptions of spatial and temporal independence have been verified by data when aftershock sequences are removed, and are commonly accepted. The degree of dependence between events, due to the dual mechanism of stress accumulation and release, has not yet been determined with any amount of precision, but the earth's "memory" appears to fade quite rapidly with time (Gardner and Knopoff, 1974). The third assumption implies that, for a small time-interval, more than one seismic event cannot occur on one source.

Thus, considering all the events of magnitude greater than an arbitrary lower bound, a distribution is obtained for the number of occurrences in a given period of time, t . The lower bound is chosen so that earthquakes of magnitude smaller than the one specified, which have a negligible damage potential, can thus be disregarded. This distribution is obtained for each seismic source.

In its general form, the Poisson law can be written as

$$P_N(n/\lambda) = \frac{e^{-\lambda t} (\lambda t)^n}{n!}, \quad t > 0; n \text{ integer} \geq 0, \quad (3-1)$$

where

$P_N(n/\lambda)$ = probability of having n events in time period t , given λ

n = number of events

λ = mean rate of occurrence per unit of time

Thus, if the mean rate of occurrence λ is known, the probability distribution function can be defined completely.

The parameter λ is obtained from the data and can be modified subjectively. In the present case, it is expressed as the mean rate of occurrence, per year, of earthquakes larger than magnitude 3.5. Using Equation 3-1, the probability of any number of events within a source region during the future time period can be obtained. As an example:

$$P(0) = \frac{e^{-\lambda t} (\lambda t)^0}{0!} = e^{-\lambda t} \quad (3-2)$$

$$P(1) = e^{-\lambda t} \lambda t, \text{ etc.}$$

Since these outcomes are exhaustive and mutually exclusive, the condition $\sum_n P(n) = 1.0$ is satisfied. Two typical plots of these discrete distributions are given in Figure 3-1.

Estimate of λ

If one assumes that the number of seismic events for a future time t follows a Poisson probability law, there is still uncertainty about the parameter λ , the mean rate of occurrence (Equation 3-1). Therefore, λ is treated as a random variable. The probabilistic information on λ can be obtained through historical data or from the subjective knowledge of the analyst. The subjective probability distribution on λ is called the "prior distribution."

FIGURE 3-1
TYPICAL DISTRIBUTIONS FOR POISSON AND BERNOULLI MODEL

The concept of conjugate prior is used for analytical simplicity (Raiffa and Schlaifer, 1961). Therefore, the prior distribution for the random variable λ is chosen as the gamma distribution with parameters λ' and ν' . Since the gamma distribution can fit a large variety of shapes, this choice does not introduce any major limitations in the model.

Using the historical information, one can obtain the sample likelihood function for λ . The posterior distribution for λ can be obtained by combining the prior distribution and the sample likelihood function by means of Bayes' theorem.

Let $f_{\lambda}'(\lambda)$ be the prior probability distribution function for λ , and $L(\lambda)$ be the sample likelihood function for λ (given by the Poisson law for n observations), then the posterior distribution $f_{\lambda}''(\lambda)$ is obtained as

$$f_{\lambda}''(\lambda) = N_1 L(\lambda) f_{\lambda}'(\lambda), \quad (3-3)$$

where N_1 is a normalizing constant. The posterior distribution of λ is also gamma type with parameters λ'' and ν'' .

In Equation 3-1, the conditional probability on the number of events n is based on λ . The unconditional or the marginal distribution on n can be obtained by using Equation 3-1 together with Equation 3-3 and integrating over all λ 's. Thus,

$$P_N(n) = \int_0^{\infty} P_N(n/\lambda) f_{\lambda}''(\lambda) d\lambda$$

which leads to

$$P_N(n) = \frac{\Gamma(n + \nu'')}{n! (\nu'')^n} \cdot \frac{t^n \lambda''^{\nu''}}{(t + \lambda'')^{n + \nu''}} \quad (3-4)$$

for n integer ≥ 0 , $\nu'' > 0$, $\lambda'' > 0$, $t > 0$.

Equation 3-4 is called the "marginal Bayesian distribution of n ." This distribution, after the uncertainties on the mean rate of occurrence are considered, gives the probability of the number of events above a predetermined lower bound M_0 , in time period t .

Distribution of Magnitudes (Bernoulli Model)

A Bernoulli trial is used to model information on magnitudes. Given that an event has occurred, the probability that it is of any given Richter magnitude can be represented in terms of a Bernoulli trial. If the seismic event that has occurred is of the M_i under consideration, then the outcome of the Bernoulli trial is a success. Conversely, failure at each trial implies that the seismic event that has occurred is of some other magnitude.

If p_{M_i} = probability of success at each trial corresponding to M_i

and $q_{M_i} = 1 - p_{M_i}$

= probability of failure at each trial,

then using the binomial law,

$$P_R(r_{M_i}/n, p_{M_i}) = C_n^{r_{M_i}} p_{M_i}^{r_{M_i}} (1-p_{M_i})^{n-r_{M_i}} \quad (3-5)$$

for n integer > 0 , r_{M_i} integer; $0 \leq r_{M_i} \leq n$, and $0 \leq p_{M_i} \leq 1$,

where $P_R(r_{M_i}/n, p_{M_i})$ is read as the probability that r_{M_i} events of magnitude M_i will occur out of a total of n events, given that the probability of occurrence of M_i is p_{M_i} at each trial, and

$$C_n^{r_{M_i}} = \frac{n!}{r_{M_i}!(n-r_{M_i})!}$$

A different probability p_{M_i} is obtained for each M_i considered in the model. A similar equation is thus obtained for each of the other magnitudes. The probabilities p_{M_i} are mutually exclusive within the range of selected magnitudes, hence,

$$\sum_{\text{all } M_i} p_{M_i} = 1.0.$$

As an example, for $M_i = 6$ and $n = 5$,

$$P(0 \text{ events of } M = 6 \text{ given } 5 \text{ earthquakes}) = (1 - p_6)^5$$

$$P(1 \text{ events of } M = 6 \text{ given } 5 \text{ earthquakes}) = 5 \times p_6 \times (1 - p)^4$$

$$P(5 \text{ events of } M = 6 \text{ given } 5 \text{ earthquakes}) = p_6^5.$$

It should be noted that

$$\sum_{r=0}^n p(r/n) = 1.0.$$

Typical plots of the above distribution are shown in Figure 3-1.

To be consistent with the Gutenberg-Richter earthquake recurrence relationship, the probability p_{M_i} should be consistent with an exponential distribution of magnitudes. Cornell (1971) has proposed such a distribution which incorporates both lower and upper bound limits on magnitude:

$$P(M \leq m) = K \left\{ 1 - \text{Exp} \left[-\beta (m - M_L) \right] \right\} \quad (3-6)$$

where,

$$\begin{aligned} P(M \leq m) &= \text{probability of } M \leq m \\ K &= \left\{ 1 - \text{Exp} \left[-\beta (M_U - M_L) \right] \right\}^{-1} \\ \beta &= 2.3b \\ M_U &= \text{upper bound magnitude} \\ M_L &= \text{lower bound magnitude} \end{aligned}$$

The probability that an earthquake has a magnitude within the range $m_i \pm \Delta m/2$, equivalent to the Bernoulli parameter p_{M_i} , then becomes

$$p_{M_i} = P(M \leq m_i + \Delta m/2) - P(M \leq m_i - \Delta m/2) \quad (3-7)$$

Equation 3-5 represents the generating process for the number of events M_i . However, this information is conditional on the knowledge about p_{M_i} , the probability of success corresponding to M_i .

Estimate of p_{M_i}

The conjugate prior distribution on p_{M_i} , $f'_p(p_{M_i})$, is assumed to be beta type with parameters η' and ξ' . Since the normalized beta distribution is bounded between 0 and 1, and fits a large variety of shapes, this choice does not introduce any major limitations in the model. A prior distribution of a similar form has to be assumed for each of the magnitudes considered.

The usual format of the available data indicates that, among the n earthquakes observed for a given source, r_{M_i} were of M_i . This information is used in the construction of the sample likelihood function. The sample likelihood function on p_{M_i} , $L(p_{M_i}/n, r_{M_i})$, may be obtained from the generating process (Equation 3-5).

The posterior distribution $f''_p(p_{M_i})$ is given by

$$f''_p(p_{M_i}) = N_i L(p_{M_i}/n, r_{M_i}) f'_p(p_{M_i}) \quad (3-8)$$

where N_i is a normalizing constant. The posterior distribution on p_{M_i} is also beta type with parameters η'' and ξ'' .

In Equation 3-5, the conditional probability on the number of successes, r_{M_i} , is based on p_{M_i} and n . The condition on p_{M_i} can be removed using Equation 3-8 and integrating over all the values of p_{M_i} as follows:

$$P_R(r_{M_i}/n) = \int_0^1 P_R(r_{M_i}/p_{M_i}, n) f_P^n(p_{M_i}) dp_{M_i} \quad (3-9)$$

$$= C_n^{r_{M_i}} \left[\frac{\Gamma(\eta_{M_i}'')}{\Gamma(\xi_{M_i}'') \Gamma(\eta_{M_i}'' - \xi_{M_i}'')} \cdot \frac{(a_{M_i})^{(\beta_{M_i} - a_{M_i})}}{\Gamma(\beta_{M_i})} \right]$$

for n integer > 0 , r_{M_i} integer; $0 \leq r_{M_i} \leq n$,

$$\text{and } \xi_{M_i}'' = \xi_{M_i}' + r_{M_i}$$

$$\eta_{M_i}'' = \eta_{M_i}' + n$$

$$r_{M_i} + \xi_{M_i}'' = a_{M_i}$$

$$n + \eta_{M_i}'' = \beta_{M_i}$$

The above expression is the distribution on the number of earthquakes of magnitude M_i given that n earthquakes have occurred. There is a similar distribution for each M_i considered.

Marginal Distribution on the Number of Magnitudes

The distribution of the number of events of each magnitude, independent of the number of trials, is obtained from Equations 3-4 and 3-9, thus

$$P_R(r_{M_i}) = \sum_{n=0}^{\infty} P_R(r_{M_i}/n) P_N(n) \quad (3-10)$$

$$\begin{aligned}
 &= \sum_{n=0}^{\infty} C_n \frac{r_{M_i} \Gamma(\eta''_{M_i})}{\Gamma(\xi''_{M_i}) \Gamma(\eta''_{M_i} - \xi''_{M_i})} \\
 &\quad \cdot \frac{\Gamma(r_{M_i} + \xi''_{M_i}) \Gamma(n + \eta''_{M_i} - r_{M_i} - \xi''_{M_i})}{(n + \eta''_{M_i})} \\
 &\quad \cdot \frac{\Gamma(n + \nu'') t^n \lambda'' \nu''}{n! \Gamma(\nu'') (t + \lambda'')^n + \nu''}
 \end{aligned}$$

This distribution describes totally the seismicity of the source cons terms of the two parameters magnitude (M_i) and number of occurrences (n).

The Bernoulli model has the advantage that the probability of occurrence of an earthquake of any given magnitude (p_{M_i}) can be established and updated independently of other magnitudes. It also offers greater flexibility in the use of historical seismicity data and in combining it with subjective information through a Bayesian approach.

3.2 SEISMIC EXPOSURE EVALUATION

A typical seismic region contains a number of earthquake sources. The seismic exposure evaluation aims at combining the effect of all sources to provide an estimate of the probability of occurrence of at least one event of a given ground motion within the time period of interest. By repeating the process for a number of ground motion levels, a probability distribution function or cumulative distribution function for the ground motion is developed at the site.

One of the important elements of a seismic exposure evaluation is the attenuation relation, or transfer function, that specifies the ground motion parameter at the site, given the occurrence of an earthquake. As is conventional in most

seismic hazard analyses, we chose to characterize the vibratory motion at the site in terms of peak horizontal acceleration (PHA). Because of the proximity of the experiment site to the Yucca and Boundary faults, an attenuation relation that focused on the near-source environment was used. Furthermore, since the site is at a depth of 420 meters in a large crystalline rock mass, the attenuation relation emphasized the response of embedded structures.

The model, which has been previously derived and reported upon (Campbell, 1979), is based on 439 earthquake accelerations from 86 earthquakes recorded within 25 kilometers of the source. A significant fraction of the data was recorded in the basements of small buildings, thereby permitting a statistical representation of embedment effects. Besides addressing embedment, the statistical analysis of these data also addressed obvious biases contained in the data set, such as multiple recordings from single earthquakes, and the abundance of data from smaller earthquakes. This was dealt with through a weighting scheme in the regression analysis that resulted in each earthquake having the same weight and in each magnitude interval having the same weight. The weighted regression analysis on these data resulted in the following estimate of PHA:

$$\ln \text{PHA} = -5.06 + 0.69 M_L - 0.40 \ln (R + 1) + (0.016 M_L - 0.13) \ln^2 (R + 1)$$

for PHA in g's and R in kilometers, with a standard error of estimate of 0.61 and a correlation coefficient of 0.75. This expression is plotted in Figure 3-2.

As discussed above, maximum peak horizontal acceleration (PHA) is the ground motion parameter of interest in this study. In this model the magnitude and PHA are discretized to equal step-increments so that all the integration signs can be replaced by summations. Since the distance is a parameter in the attenuation relationships, the process of dividing a source of length L_0 into smaller segments enables one to take into consideration the distance variation to the site from different parts of a long source. The size of the segments is chosen small enough that the approximation from a continuous to discrete computation is acceptable.

FIGURE 3-2
NEAR SOURCE ATTENUATION OF PEAK HORIZONTAL
ACCELERATION FOR EMBEDDED STRUCTURES

The seismicity within a source remains the same from segment to segment. From the Gamma distribution, the average mean rate of occurrence of earthquakes for a source is ν''/λ'' . The rate for a segment ΔL then becomes

$$\left(\frac{\nu''}{\lambda''}\right)_{\Delta} = \frac{\nu''}{\lambda''} \frac{\Delta L}{L_0} \quad (3-11)$$

The distribution on the number of events for each segment may then be obtained from Equation 3-4, where ν'' is replaced by ν''_{Δ} . The conditional distribution on magnitudes, given n events, remains unchanged by the segmentation of the sources. The distribution of the number of occurrences of each magnitude is given by Equation 3-9. The same distribution applies for any segment of the source. The distribution of the number of occurrences of each M increment can be presented under a matrix form that describes the total seismicity of the segment.

Only a finite number of different magnitude events can occur on the segment (from the largest to the smallest magnitude considered). The number of occurrences of any of these events is limited by the associated probability of their occurrence. Events are disregarded when this probability becomes negligible, for example, 10^{-8} . Hence, the total number of events is finite and can easily be handled under the summation signs.

Consistent with distances used in the development of the attenuation relationship, distances associated with $M < 5$ events were taken as epicentral distance, where the epicenter is assumed to occur at the midpoint of the segment. For those earthquakes with $M \geq 5$, where significant fault rupture can be expected, distances were computed from the location of the closest expected rupture. This was determined by assuming that the epicenter occurring at the midpoint of a segment will rupture adjacent segments bilaterally, where the length is computed from a relationship between fault length L and magnitude,

$$L(M) = A_L + B_L M. \quad (3-12)$$

A description of the fault-length relationship used in the analyses appears in Section 4.0.

Once the distance from the segment to the site is known, all the parameters of the attenuation relationships are determined. For a given event M_j occurring on a segment of distance R_j from the site, the probability of obtaining a maximum acceleration a_i at the site is given by $f(a_i/M_j, R_j)$, which is the distribution of accelerations for a given magnitude and distance. This distribution is chosen to be lognormal, and reflects the uncertainty in the peak acceleration attenuation relationship.

Contribution of One Segment

The contribution to acceleration greater than or equal to a_i of all events M_j occurring on the same segment is computed as:

$$P(A > a_i) = pP(M_j) + [1 - (1 - p)^2] P(2M_j) + \dots \\ + [1 - (1 - p)^n] P(nM_j) \quad (3-13)$$

where

$P(A > a_i)$ = probability of obtaining acceleration greater than or equal to a_i at least once

$P(kM_j)$ = probability of k occurrences of event M_j with $k = 1, 2, \dots, n$

p = $P(A \geq a_i/M_j)$, probability of obtaining an acceleration greater or equal to a_i given an event M_j .

Setting $q = 1 - p$, the above expression can be rewritten:

$$P(A \leq a_i) = P(\text{no } M_j) + \sum_{k=1}^n q^k P(kM_j) \quad (3-14)$$

with n chosen so that $q^k P(kM_j)$ can be neglected.

The above discussion assumes independence among events. Hence, the contribution of all possible events can be combined as follows:

$$P(A > a_i) \Big|_{\text{one segment}} = 1 - \prod_{\substack{\text{all} \\ M_j}} \left[1 - P(A > a_i)_{M_j} \right] \quad (3-15)$$

The whole range of magnitudes is included, from the largest one down to the smallest one that generates a noticeable effect at the site ($M_j \geq M_{\min}$ as a function of distance). This eliminates the consideration of a large number of events.

Contribution of One or Several Sources

Because the events are assumed to be independent from segment to segment, the contribution of each segment of a source is combined as in Equation 3-15.

$$P(A > a_i)_{\text{one source}} = 1 - \prod_{\text{all segments}} \left[1 - P(A > a_i)_{\text{one segment}} \right] \quad (3-16)$$

When several sources are considered, the same principle is applied for each source. Thus,

$$P(A > a_i) = 1 - \prod_{\text{all sources}} \left[1 - P(A > a_i) \right]_{\text{one source}} \quad (3-17)$$

This expression gives the probability that, at least once during the period of interest, a_i will be exceeded.

Once a cumulative distribution function is established for a site, the seismic exposure can be determined for any desired probability of nonexceedence. Before discussing this process, the following definitions are presented:

PROBABILITY OF NONEXCEEDENCE	The probability that a given level of ground motion will not be exceeded within the period of interest
PERIOD OF INTEREST	The assumed design life or useful life of a structure or project
RETURN PERIOD (RP)	The mean waiting time for an event of interest (assuming a Poisson law of occurrence of earthquakes).

Once a period of interest is selected, the acceleration corresponding to a given probability of nonexceedence or a given return period can be estimated by applying Bernoulli's binomial probability law, which states (for independent trials) that if p is the probability of success at each trial, the probability of r successes in n trials is given by:

$$P_R(r/n) = C_r^n p^r (1-p)^{n-r} \quad (3-18)$$

where n integer > 0 ; $0 < r < n$; and

$$C_r^n = \frac{n!}{r! (n-r)!}$$

Thus, if the period of interest is 50 years and an acceleration corresponding to a 200-year return period is desired for a site, we proceed as follows:

$$p = \frac{1}{RP} = 0.005 \text{ per year.}$$

Hence, the probability of at least one success in 50 years (trials) is

1 - probability (no success in 50 years)

$$1 - P_R(0/50).$$

Here, $n = 50$ years and $r = 0$. Using Equation 3-18,

$$P_R(0/50) = C_0^{50} (p)^0 (1-p)^{50} = (1-0.005)^{50} = 0.778.$$

Hence, probability of exceedence in 50 years = $1 - 0.778 \approx 0.22$. The desired acceleration may be found from the CDF corresponding to a probability of exceedence = 22%.

Figure 3-3 gives a relationship between return period, period of interest, and probability of nonexceedence. Note that this shows that accelerations associated with a 200-year return period have a 22% probability of being exceeded in 50 years. The relationship is general and can be applied to any situation based on the Poisson's law for mean rate of occurrence and the Bernoulli binomial law.

The following observations are useful with regard to the return period concept.

- (1) A return period (RP) is the mean (or average) waiting time for an event of interest (assuming Poisson occurrence of events).
- (2) The probability that an event corresponding to a return period RP will occur in any given year is given by $p = 1/RP$. Hence, for a return period of 500 years, $p = 0.002$.

FIGURE 3-3
RELATIONSHIPS BETWEEN RETURN PERIOD,
PERIOD OF INTEREST AND PROBABILITY
OF NONEXCEEDENCE

- (3) The probability that no event of the RP type will occur in RP years can be approximated by $1/e$ for large RP ($RP \geq 15$), where $e = 2.718$. Thus, if the return period is 100 years, the probability that in 100 years there will not be a single event producing the 100-year peak ground acceleration is given by $1/e \approx 0.36$, or there is a 64% chance that in 100 years there will be at least one event producing a 100-year peak acceleration or more.

3.3 SITE HAZARD RESULTS

The ground motion hazard model presented in the previous sections (in Equations 3-10 through 3-17), was used to establish a distribution for the probability of exceedence of given levels of peak acceleration for the spent fuel test site. Only the two fault systems in the immediate vicinity of the site were considered in the analysis (see Figure 2-3). Due to their close proximity to the site, they represent the major contribution to the hazard for the acceleration levels of interest in this study (i.e., 0.5 to 0.7 g's). It should be cautioned, however, that, for accelerations less than this range, the influence of more distant, major active fault systems could become significant.

A lower bound magnitude of 3.5 was selected to represent a threshold below which earthquake occurrences could be neglected. This threshold was chosen so that computed peak accelerations from the closest segment of the fault to the site, would fall below the 0.5 - 0.7 g range of interest at the upper 2 to 3 standard deviation limit. An upper bound magnitude of 6.8 was adopted for both fault systems, based on Rogers, et al (1977) estimate for the Yucca fault (see Section 2.2).

Since the two fault systems in Figure 2-3 dip to the east approximately 50° , it was considered inappropriate to use their surface expressions as the source of hypothesized events. Epicenters would be systematically located towards the east, away from the site, depending on the depth of the event.

Historically, earthquakes of $M \geq 3.5$ have rarely occurred at depths of less than about 2 to 5 kilometers (e.g., Hileman et al., 1973). The crust above these

depths is not considered competent enough to build up stresses associated with these larger events. Similarly, earthquakes that rupture the surface are not believed to release significant amounts of energy within the upper several kilometers of the crust, based partially on the depth distribution of aftershocks (Boore et al., 1978).

If we assume that earthquakes of $M \geq 3.5$ occur at depths no shallower than 2 km, then, based on a fault dip of about 50° , hypothesized epicenters would be displaced a minimum of 2 km towards the east, away from the site. Similarly, if we assume that no significant energy release from the larger events can occur above a depth of 2 km, then the closest zone of significant energy release, for a fault dipping 50° to the east, would be $2\frac{1}{2}$ km from the surface expression of the fault in a direction below and away from the site. It is important to emphasize that this is the closest distance to significant energy release, not the closest distance to the fault. Such a distance definition is conventionally applied in earthquake engineering. We feel that this geometry is reasonable due to the weathering and therefore increased scattering and absorption of the seismic energy near the surface. In the analysis, all events were assumed to occur along the surface expression of the faults at a depth of 2 km, thereby conservatively accounting for both the epicenter bias of the smaller events and the significant distance to the zone of energy release for the larger events. This is schematically shown in Figure 3-4.

The results of the analysis, which are presented in Figures 3-5 and 3-6 for peak horizontal accelerations of 0.1 to 0.8 g, suggest that the occurrence of peak accelerations exceeding 0.5 g and 0.7 g may be associated with return periods of 4,150 and 12,700 years, respectively. This corresponds to exceedence probabilities of 1.2×10^{-3} for 0.5 g and 3.9×10^{-4} for 0.7 g during the five-year life of the experiment. We note that our approach and objective is significantly different than that used in Rodgers, et al (1977), and therefore the results cannot be quantitatively compared. First of all, we have focused on the near source derived hazard at a site with a very different tectonic setting. Second, we have explicitly considered the fact that our site is embedded 420 meters, and have incorporated this into our attenuation relation.

FIGURE 3-4
 DIAGRAM SHOWING RELATIONSHIP BETWEEN HYPOTHESIZED
 EARTHQUAKE SOURCES AND FAULT GEOMETRY

FIGURE 3-5
RETURN PERIOD OF PEAK HORIZONTAL ACCELERATION
FOR THE SPENT FUEL TEST SITE

TERA CORPORATION

FIGURE 3-6
FIVE YEAR EXCEEDENCE PROBABILITY OF PEAK
HORIZONTAL ACCELERATION FOR THE SPENT FUEL TEST SITE

4.0 FAULT RUPTURE HAZARD

The proximity of two major faults to the spent fuel test-site suggests a possible hazard due to fault rupture. A rigorous analysis of this hazard would require a detailed knowledge of the fault and fracture pattern in the immediate vicinity of the facility, which is beyond the scope of this study. A general assessment of the fault rupture hazard may be made, however, through a study of the nearby Boundary and Yucca faults.

Fault rupture hazard is defined as the probability that the maximum surface displacement at a point on the fault exceeds a given value over the time period of interest. The general approach is similar to that used in assessing ground motion hazard (Section 3.0). Each fault system is divided into a series of segments of equal seismicity. Earthquake occurrences within each segment are treated as Poisson-Bernoulli processes, as before. The random occurrence of all events from each fault is combined with a fault rupture model to develop a probability distribution of surface displacement for any point on the fault.

4.1 FAULT RUPTURE PARAMETERS

The three fault rupture parameters required in the development of the hazard model are fault rupture length (L), fault rupture displacement (D), and fault rupture radius (R). Models used to estimate these parameters from earthquake magnitude (M) were developed from regression analyses using the method of least squares. A statistical summary of these analyses is presented in Table 4-1, and tabulated values of the parameters are provided in Table 4-2.

Fault Length (L)

Stiemmons (1977) has recently tabulated fault length and displacement data for 87 worldwide earthquakes occurring since 1819. He used these data to develop relationships between magnitude and fault length, where fault length was the independent variable. His equations are thus valid for estimating magnitude from fault length.

TABLE 4-1

SUMMARY OF REGRESSION ANALYSES FOR FAULT LENGTH,
FAULT DISPLACEMENT AND SOURCE RADIUS

$$\ln Y = A_Y + B_Y M$$

<u>Parameter</u>	<u>Coefficients</u>		<u>Standard Error</u>	<u>Correlation Coefficient</u>	<u>N</u>
	<u>A_Y</u>	<u>B_Y</u>			
Fault Length, L(km)	-4.670	1.185	0.83	0.76	73
Fault Displacement, D(cm)	-3.797	1.273	0.84	0.76	73
Source Radius, R(km)	-3.391	0.843	0.63	0.73	163

TABLE 4-2
TABULATED VALUES OF FAULT LENGTH,
FAULT DISPLACEMENT, AND SOURCE RADIUS

Magnitude (M_L)	Fault Length L(km)	Source Radius R(km)	Fault Displacement D(cm)
3.5	0.6	0.6	1.9
4.0	1.1	1.0	3.7
4.5	2.0	1.5	6.9
5.0	3.6	2.3	13.0
5.5	6.3	3.5	25.0
6.0	12.0	5.3	47.0
6.5	21.0	8.0	88.0
7.0	38.0	12.0	166.0

In our model, what is required is an estimate of length when magnitude is known. Therefore, the regression analyses were repeated using M as the independent variable. The limited amount of data available on normal-oblique slip faults precluded their exclusive use in the analysis. Therefore, it was decided to use data from all fault types in the regression.

Based on the 73 observations for $4.0 \leq M \leq 8.7$ in Slemmons (1977), the log-linear relationship between L and M was found to be

$$\ln L(M) = -4.67 + 1.19 M \quad (4-1)$$

for fault length in kilometers.

Fault Displacement (D)

A similar analysis was run for maximum fault displacement. Again using the Slemmons (1977) data for all fault types, the log-linear relationship between D and M was determined as

$$\ln D(M) = -3.80 + 1.27 M \quad (4-2)$$

for displacement in centimeters.

Source Radius (R)

Source radius is a measure of the true rupture dimensions, not just those observed on the surface after the earthquake. It requires that theoretical source spectrum shapes be fitted to observed spectra, and that the source parameters be estimated from theoretical dislocation models. Source radius thus represents the radius of a circular rupture surface whose area is equivalent to that of the actual rupture surface.

From Brune's (1970) dislocation model, source radius may be computed from the relationship

$$R = \frac{2.34 \beta}{2 \pi f_0} \quad (4-3)$$

where β is the shear-wave velocity of the medium, and f_0 is corner frequency (the point where the high frequency decay begins on the source displacement spectrum).

Using this model, Thatcher and Hanks (1973) estimated the source radius of many Southern California earthquakes. Campbell (1977) expanded this set to include 163 earthquakes of $3.0 \leq M_L \leq 6.8$. Using these data, the following log-linear relationship between R (in kilometers) and M was established:

$$\ln R(M) = -3.39 + 0.84 M \quad (4-4)$$

4.2 FAULT RUPTURE HAZARD MODEL

For an earthquake of given magnitude and location, the probability of observing a displacement greater than a particular level at a point on the fault located at a distance, x_i , is comprised of a joint probability of three events. The first is the probability that surface rupture occurs, which we will designate as "event E_s ." The second is the probability that surface rupture extends at least as far as the point of interest (designated as "event E_d "). The last is the probability that the displacement exceeds the specified value (designated as "event E_d ").

Mathematically, this joint probability may be expressed as

$$P(D > d | M_j, x_i) = P(E_d \cap E_d \cap E_s)$$

where M_j is the magnitude under consideration and x_i is the distance along the fault from segment i (the location of the earthquake) to the point in question (Figure 4-1).

Simplifying, by means of conditional probability theory,

FIGURE 4-1
SCHEMATIC OF THE FAULT RUPTURE
HAZARD MODEL

$$\begin{aligned}
 P(D > d | M_j, x_i) &= P(E_d | E_f \cap E_s) \cdot P(E_f \cap E_s) \\
 &= P(E_d | E_f \cap E_s) \cdot P(E_f | E_s) \cdot P(E_s) \quad (4-5)
 \end{aligned}$$

with all events being contingent upon the occurrence of a given earthquake. After developing models for the above probabilities and unconditionalizing with respect to M_j and x_i , Equation 4-5 may then represent the hazard from all possible earthquakes on the fault.

P(E_s)

Surface rupture during a given earthquake is assumed to occur if the source radius (R) is greater than the distance along the fault plane from the center of the rupture to the ground surface, designated as " w_i " (Figure 4-1). Since, for a given earthquake, the horizontal extent of faulting tends to be greater than the vertical extent, this definition of surface rupture is considered conservative.

For a given magnitude M_j , we may compute source radius from Equation (4-4),

$$\ln R_j = A_R + B_R M_j \quad (4-6)$$

Because of uncertainty in this expression, R_j may be considered a random variable. Let us assume R_j to be lognormally distributed with a median of $\ln R_j$ and a standard deviation σ_R (on $\ln R$) equal to the standard error of estimate, Table 4-1. Then, the probability that R_j is greater than w_i (the event E_s) is given by

$$\begin{aligned}
 P(E_s) &= P(R_j > w_i) \\
 &= 1 - P(R_j \leq w_i)
 \end{aligned}$$

$$\begin{aligned}
 &= 1 - \frac{1}{\sigma_R \sqrt{2\pi}} \int_{-\infty}^{\ln w_i} \left[\exp -1/2 \left(\frac{y - \ln R_j}{R} \right)^2 \right] dy \\
 &= 1 - \Phi \left(\frac{\ln w_i - \ln R_j}{\sigma_R} \right) \quad (4-7)
 \end{aligned}$$

where $\Phi(*)$ represents the standard-normal cumulative distribution function.

$$P(E_f | E_r)$$

Given that a surface rupture occurs, let it be assumed that its length is equally distributed in both directions along the fault trace (i.e., bilateral rupture). The midpoint of this rupture is directly above the assumed point of initiation (Figure 4-1). For rupture to occur at the site of interest, it must proceed at least as far as that distance from the midpoint of the surface expression to the site, x_i . Therefore, rupture occurs at the site if $L_j/2 > x_i$, where L_j is the surface rupture length associated with a magnitude M_j event.

L_j is computed from Equation 4-1, thus

$$\ln L_j = A_L + B_L M_j \quad (4-8)$$

To account for uncertainty in the regression, L_j may be considered lognormally distributed, with median $\ln L_j$ and standard deviation (on $\ln L$) of σ_L .

The probability of the event E_f occurring (given E_r), becomes

$$\begin{aligned}
 P(E_f | E_r) &= P(L_j/2 > x_i) \\
 &= P(L_j > 2x_i)
 \end{aligned}$$

$$\begin{aligned}
 &= 1 - P(L_j \leq 2x_i) \\
 &= 1 - \Phi\left(\frac{\ln L_j - 2x_i}{\sigma_L}\right)
 \end{aligned}
 \tag{4-9}$$

$$P(E_d | E_f \cap E_s)$$

Given that surface rupture occurs and that it proceeds at least as far as the site, the surface displacement associated with the earthquake M_j may be estimated from Equation 4-2 as follows:

$$\ln D_j = A_D + B_D M_j \tag{4-10}$$

Accounting for uncertainty in this estimate, D_j is considered lognormally distributed, with median $\ln D_j$ and standard deviation (on $\ln D$) of σ_D . The probability that the displacement exceeds some specified value d then becomes

$$\begin{aligned}
 P(E_d | E_f \cap E_s) &= P(D_j > d) \\
 &= 1 - P(D_j \leq d) \\
 &= 1 - \Phi\left(\frac{\ln D_j - \ln d}{\sigma_D}\right)
 \end{aligned}
 \tag{4-11}$$

Displacement Hazard

The surface displacement hazard for a point on a fault associated with an earthquake on segment i of magnitude M_j is obtained by substituting Equations 4-7, 4-9 and 4-11 into Equation 4-5.

$$P(D \leq d \mid k=1, M_j, x_i) = \left[1 - \Phi \left(\frac{\ln D_j - \ln d}{\sigma_D} \right) \right] \cdot \left[1 - \Phi \left(\frac{\ln L_j - \ln x_i}{\sigma_L} \right) \right] \cdot \left[1 - \Phi \left(\frac{\ln R_j - \ln w_i}{\sigma_R} \right) \right] \quad (4-12)$$

The total hazard at the point in question requires combining the hazards associated with all possible earthquakes hypothesized to occur on the fault. For this purpose, the two-dimensional fault plane of area A_0 is divided into an equal number of segments of equal seismicity.

The development of the surface rupture displacement hazard from this point on is equivalent to the development of the ground motion hazard described in Section 3.2, Equations 3-13 through 3-18. Letting $q = 1 - P(D > d \mid k=1, M_j, x_i)$, then, by Equation 3-14, the probability associated with all events of magnitude M_j on segment i becomes,

$$P(D \leq d \mid M_j, x_i) = P(\text{no } M_j) + \sum_{k=1}^n q^{k/c} P(kM_j) \quad (4-13)$$

The contribution of all possible magnitudes on segment i becomes

$$P(D > d \mid x_i) = 1 - \pi_{\text{all}} \left[1 - P(D > d \mid M_j, x_i) \right] \quad (4-14)$$

M_j

and the contribution of all segments becomes

$$P(D > d) = 1 - \pi_{\text{all}} \left[1 - P(D > d \mid x_i) \right] \quad (4-15)$$

x_i

This expression gives the probability of a displacement exceeding d at least once during the exposure period of interest. The associated return period becomes

$$RP = \left\{ 1 - \left[1 - P(D > d) \right]^{1/t} \right\} \quad (4-16)$$

where t is the exposure period of interest in years.

4.3 SITE HAZARD RESULTS

The fault rupture hazard associated with the Yucca-Butte and Carpetbag-Boundary-Butte fault systems (shown in Figure 2-3) was investigated using the model developed in the previous sections. Distributions for the exceedence probabilities of maximum surface displacement were developed for points on the two fault systems adjacent to the spent fuel test-site.

Earthquake occurrence models for both faults were the same as were used in the estimation of ground motion hazard. Fault widths, measured along the dip of the fault planes, were taken as 15 km.

The results of the analysis may be found in Figures 4-2 and 4-3 for an experiment duration of five years. The return period associated with a maximum displacement exceeding 5 cm is 1,060 years for the Boundary fault and 3,200 years for the Yucca fault. Corresponding exceedence probabilities for the five-year duration of the experiment are 4.8×10^{-3} for the Boundary fault and 1.6×10^{-3} for the Yucca fault.

The risk associated with ground rupture through the test-site is considerably less than these calculations would imply. Displacements across the test facility could result if, for instance:

- Rupture on the Yucca or Boundary faults broke along a fresh surface through the facility, rather than breaking along their existing fault planes

FIGURE 4-2
RETURN PERIOD OF FAULT DISPLACEMENT
FOR A POINT ON THE BOUNDARY AND YUCCA FAULTS
ADJACENT TO THE SPENT FUEL TEST SITE

FIGURE 4-3

FIVE YEAR EXCEEDENCE PROBABILITY OF FAULT
DISPLACEMENT FOR A POINT ON THE BOUNDARY AND
YUCCA FAULTS ADJACENT TO THE SPENT FUEL TEST SITE

TERA CORPORATION

- There exists a fault through the facility that could independently displace or rupture in conjunction with the other faults (no such fault is visible at the surface)
- Movement occurs along the joints and fractures of the rock comprising the Climax stock

These events may be considered rarer and would be associated with displacements of lesser magnitude than corresponding displacement on the two known major fault zones (Bonilla, 1979). A detailed analysis of the immediate vicinity of the test facility would be required to qualitatively assess the hazard associated with these events.

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