SEISMIC RISK ANALYSIS FOR THE ATOMICS INTERNATIONAL NUCLEAR MATERIALS DEVELOPMENT FACILITY SANTA SUSANA, CALIFORNIA

Submitted to

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1.0 INTRODUCTION AND SUMMARY

In this report, TERA Corporation presents the results of a detailed seismic risk analysis of the Nuclear Materials Development Facility (NMDF) operated by Atomics International at Santa Susana, California.

This report is one part of a larger effort being directed by the U.S. Nuclear Regulatory Commission. The NRC's objective in commissioning the overall report is to assess and improve, to the extent practicable, the ability of this facility to withstand adverse natural phenomena without loss of capacity. This report focuses on earthquakes; the other natural hazards, being addressed in separate reports, are severe weather (strong winds and tornados) and floods. The overall analysis will provide a mean-centered assessment of the consequences of an accident resulting from any of these natural phenomena. The assessment will express a quantitative probabilistic measure of the potential structural damage and the release function. It will also provide a probabilistic estimate of the resulting dose of radioactivity to the public.

To ensure credible results, very sophisticated but well-accepted techniques were employed in this component of the project, an analysis of the seismic hazard. The calculational method we used, which is based on Cornell's work (1968), has been previously applied to safety evaluations of major projects.

The historical seismic record was established after a review of available literature, consultation with operators of local seismic arrays and examination of appropriate seismic data bases including the USGS, California Institute of Technology and NEIS data bases.

The resulting seismic record, covering the period 1769-1977, was used to identify all possible sources of seismicity that could affect the site. Inadequacies and incompleteness in this record were explicitly considered in this definition of source regions and their activity rates. Where there were uncertainties, we assigned subjective probabilities to the span of uncertainty.

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The acceleration attenuation relation used in the analysis was developed based on a complete re-evaluation of all relevant strong motion data, with particular attention directed to the near-field environment.

To guarantee use of the best available calculational methods and input, the entire project was reviewed by two seismologists with particular expertise in the local and regional seismology and tectonic setting:

Dr. John G. Anderson
University of Southern California

Professor Stewart W. Smith,
University of Washington

The results of our analysis, which include estimates of the uncertainty, are presented in Figure 1-1. Our best estimate curve indicates that the Atomics International Facility will experience 30 percent g with a return period of 55 years and 60 perce t g with a return period of 750 years. The curves on either side of our best estimates represent roughly the one standard deviation confidence limits about this best estimate.

These curves provide the seismic design basis for the NMDF in terms of peak ground acceleration. For those structures and equipment that could experience structural amplification, we recommend application of the mean rock response spectrum contained in WASH 1255.

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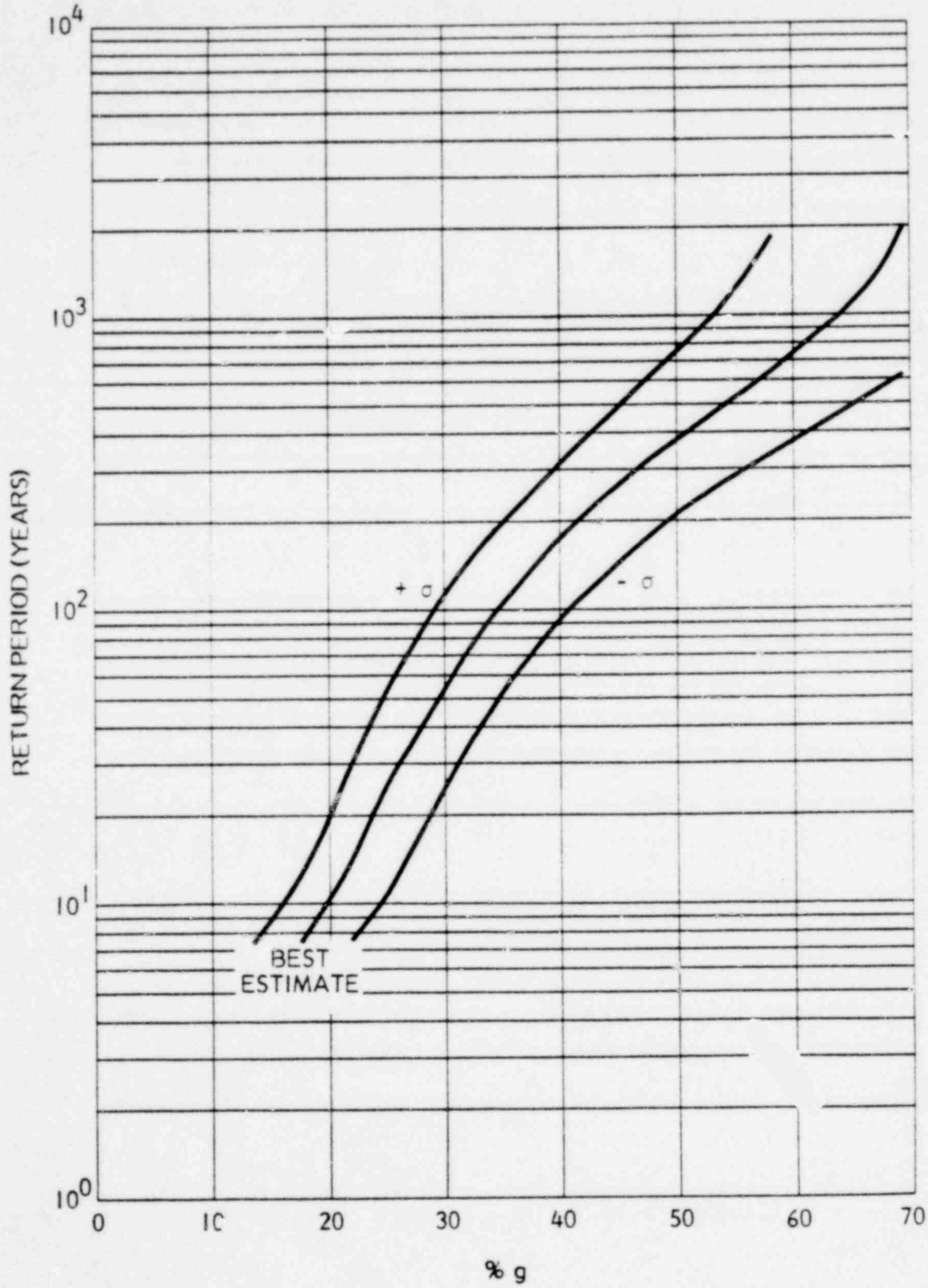

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FIGURE I-1

RETURN PERIOD - ACCELERATION FOR THE NMDF

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2.0 SEISMIC RISK METHODOLOGY

A seismic risk analysis is only as credible as the risk analysis methodology and the input to it. This section presents the basis for our selection of a probabilistic Poisson model for the risk assessment at the Nuclear Materials Development Facility.

There are generally two distinctly different approaches to seismic risk analysis: probabilistic and deterministic.

Using the deterministic approach, the analyst judgmentally decides that an earthquake of a given magnitude or intensity occurs at a specific location. He then attenuates the ground motion from the earthquake source to the site and determines the effects of that quake. The problem in using this approach is that it is difficult to define the margin of safety or the degree of conservatism in the resulting design parameters. Analysts are often asked to provide information on the "maximum possible" or "most probable" earthquakes for design purposes, but the deterministic approach does not easily provide those answers.

A probabilistic approach, on the other hand, quantifies the uncertainty in the number, size, and location of possible future earthquakes and allows an analyst to present the trade-off between more costly designs or retrofits and the economic or social impact of a failure. Because the product of a probabilistic approach is a measure of the seismic risk expressed in terms of return period, this trade-off can easily be quantified.

Although the probabilistic approach requires significantly more effort than the deterministic approach, it has the following advantages:

- It quantifies the risk in terms of return period;
- It rigorously incorporates the complete historical seismic record;
- It can incorporate the judgment and experience of the analyst; 844 032

- It accounts for incomplete knowledge regarding the location of faults;
- It has the flexibility to assess the risk at the site in terms of spectral acceleration, velocity, displacement, or earthquake intensity.

The credibility of the probabilistic approach has been established through detailed technical review of its application to several important projects and areas. Recent applications include assessments of the seismic risk in Boston (Cornell and Merz, 1974), in the San Francisco Bay Area (Vagliente, 1973), in the Puget Sound Area (Stepp, 1974) and continental United States (Algermissen and Perkins, 1976). Results of these studies have been applied to, among other areas:

- Development of long-range earthquake engineering research goals;
- Planning decisions for urban development;
- Environmental hazards associated with the milling of uranium; and
- Design considerations for radioactive waste repositories.

This diversity of application demonstrates the inherent flexibility of the risk assessment approach.

2.1 THEORY

The risk calculations can be fundamentally represented by the total probability theorem

$$P\left[A\right] = \iint P\left[A/m \text{ and } r\right] f_M(m)\, f_R(r)\, dmdr$$

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

In our assessment of the NMDF, A will be taken as maximum acceleration and therefore

$$P\,[A/m \text{ and } r]$$

will be derived from data relating peak acceleration to epicentral distance and earthquake magnitude. Often known as attenuation data, these data are usually lognormally distributed around a mean relationship of the form (McGuire,1977a).

$$A = C_1\, e^{C_2 M} (R+r_o)^{C_3}\,.$$

The distribution on earthquake magnitude, $f_M(m)$, can readily be derived from an actual or postulated frequency relationship of the form

$$\log N = a\text{-}bM$$

where N is the number of earthquakes having magnitude greater than M, and a and b are constants characteristic of the particular source region under consideration. It follows (Cornell, 1968) that f_M can be derived from the cumulative distribution function, F_M, which has the form,

$$F_M = k\,(1\text{-}e^{-\beta M})$$

where k is a normalizing constant and β = bln10.

The distribution on distance, $f_R(r)$, depends on the geometry of the problem under consideration. For simple geometries, the distributions can often be integrated analytically. Realistic geometries however, require numerical evaluation of the integral. A very versatile computer program has been developed by Anderson and Trifunac (1978) that incorporates the theory presented above with a numerical integration scheme that allows for evaluation of very complex source-site geometries.

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The overall approach to performing seismic risk assessment by this theory is summarized below. First, the historical earthquake record and local attenuation data are combined with the experience of the analyst to produce the functional relationships applicable to the area under consideration. The source regions are divided into circular sectors and proportional seismicity is allocated to each sector. The total expected number of events causing maximum accelerations at the site greater than a particular test acceleration is obtained by summing the events from each sector within each source region. The risk associated with this test acceleration is then calculated using the conventional assumption that earthquakes have a Poisson distribution in time. It then follows that the return period is simply the reciprocal of the risk.

In recognition of the uncertainties in any seismological analysis, we test the sensitivity of results to variations, corresponding to the uncertainty, in key parameters. The results are then combined by assigning subjective probabilities to the range of variations and weighting the results accordingly. The final synthesized estimate of the seismic risk can be considered a Bayesian estimate (Cornell and Merz, 1974).

3.0 GEOLOGY

3.1 REGIONAL GEOLOGY

3.1.1 SUMMARY

The Atomics International Nuclear Materials Development Facility is located in the Los Angeles area of the Transverse Range Geomorphic Province of California. The area is within the Simi Hills, approximately 10 miles west of Canoga Park, California.

The geology of the southern Ventura County part of the province is dominated by the Ventura basin, which extends westerly under the present Pacific Ocean. This is an east-trending region that has been down-warped and in which has been deposited a great thickness of sediments during the last 60 to 75 million years. The sedimentary rocks have been tectonically deformed and partly uplifted to form hills and mountains.

3.1.2 REGIONAL PHYSIOGRAPHY

Regionally, the study area is situated on a plateau named Burro Flats within the Simi Hills, isolated by distance and rugged terrain from densely populated areas. A semi-arid region, the low altitude and ocean influence results in a relatively mild climate throughout the year.

The Ventura basin is an elongate sedimentary trough which, together with its deformed structures, trends approximately east-west. Most of the southeastern part of the Ventura basin is in the Santa Clara watershed. Old high-level erosion surfaces, some more than 3,000 feet in altitude, and younger, topographically lower river-terrace surfaces and deposits are conspicuous (Winterer and Durham, 1962).

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3.1.3 GEOLOGY

A great thickness of sediments has been deposited in the Ventura basin, mostly by the sea which has since receded from the eastern part of the basin. The resultant sedimentary rocks have been tectonically deformed and partly uplifted to form hills and mountains. Sediment is still being deposited along intervening valleys and canyons and into the sea, principally from the Santa Clara and Ventura Rivers. The Santa Clara River is a remnant of what was probably a much greater river system, whose earlier delta is preserved as the sediments of early to late Quaternary age underlying large areas in the eastern and central parts of the county, and beneath the Oxnard Plain (Weber, et al., 1973).

The Ventura basin is a narrow trough, filled with sedimentary rocks, whose axis coincides approximately with the Santa Clara River valley and the Santa Barbara Channel. This narrow troughlike form did not begin to develop until near the beginning of the Miocene epoch (Winterer and Durham, 1962). Near the south margin of the Ventura basin the thick section of upper Cenozoic rocks has been thrust southward along the Santa Susana fault toward the older rocks of the Simi Hills. The southeastward-trending San Gabriel fault transects the northeastern part of the basin. Dissimilar facies in the pre-Pliocene rocks on opposite sides of this fault indicate a long period of continued movement. The major folds and faults between the San Gabriel and Santa Susana faults trend northwestward; most of the faults are southward dipping reverse faults.

Much of the folding and faulting has been due to compression from north to south during the last five to one million years (Weber, et al., 1973). This folding and faulting has resulted in the San Cayetano, Oak Ridge, Santa Susana and other fault zones.

3.1.4 REGIONAL STRATIGRAPHY

The sedimentary rocks in the area range from the Cretaceous "Chico Formation" to Recent. Maximum thickness of the Chico Formation ranges to 5,500 feet in the Simi Hills-Santa Susana Mountains regions. The overlying Tertiary and Quaternary deposits include those of landslide, steam, and lacustrine origin.

3.1.5 REGIONAL STR ICTU. E

Major folding and fault... the area took place during the last one to five million year, and was due to north to south compression. Fault zones developed include the San Andreas, the Santa Ynez, the Newport-Inglewood, the San Gabriel, and the Malibu Coast faults. Each of these faults is briefly reviewed below.

San Andreas Fault. This active master fault traverses 800 miles of western California, and passes within 34 miles of the Burro Flats site. It has been the locus of at least one great earthquake during historic time, and present evaluations suggest that the most likely place for the next earthquake is the fault segment that generated the Fort Tejon earthquake of 1857, which lies opposite the Burro Flats site. Surface rupture has accompanied the larger and some of the smaller historic earthquakes on the fault. Marked topographic evidence of fault disruption of the ground surface testifies to persistence of this activity back at least into the recent past, and geologic evidence indicates persistence of right slip for many tens of millions of years. Geodetic measurements reveal that deformation across the fault system is continuing today, indicating that future earthquakes can be expected.

Santa Ynez Fault. This is a major active fault in California that trends eastward for about 82 miles along the north margin of the Transverse Ranges, and approaches within 30 miles of the Burro Flats site at its eastern end. It has a total displacement measurable in miles, and bears evidence of quite youthful movement.

The fault is the site of fairly consistent left-lateral stream offsets, and there are reports of furrowing of the ground surface, ponding of slope wash, and vague indications that in one place terrace deposits may be faulted. Thus it must be concluded that the Santa Ynez fault has been active in late Quaternary time, and probably in Holocene time as well.

Like the San Andreas fault, the Santa Ynez fault is a steep fault with a relatively straight trace and is marked by a zone of shearing as wide as 1,500 feet and

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numerous elongate fault slivers. Displacement across the fault is probably at least several miles, with significant components of both dip-slip and leftlateral strike-slip.

Newport-Inglewood Zone. This active structural zone, probably a part of the San An -as fault system, has undergone major right slip and seems to separate continental from Franciscan basement at depth. From a point about 20 miles southeast of the Burro Flats site it extends southeastward for 45 miles across the Los Angeles Basin, and continues on for an unknown distance beneath the Pacific Ocean. Abundant evidence of late Quaternary displacement exists along the zone and it is considered the source of the 1933 Long Beach earthquake.

The zone consists of a complex of interrelated faults and folds in a sedimentary section about 12,000 feet thick, which extends down into basement rock as a relatively simple fault zone. The Newport-Inglewood zone does not extend northwestward beyond the Malibu Coast fault, but rather merges with that fault to form a coherent structural system. This system has allowed Franciscan terrain of the continental borderland to move northwestward along the Newport-Inglewood zone and down beneath the leading edge of the Transverse Ranges along the Malibu Coast fault.

San Gabriel Fault. This is a major fault in the San Andreas fault system that has undergone 20 to 30 miles of right slip. The fault is 74 miles long (including its southern branch), and passes within 16 miles of the Burro Flats site. Opinion differs over the present tectonic vitality of the San Gabriel fault. Richter (1958) and others have concluded that this fault is inactive.

Malibu Coast Fault. As a member of the Santa Monica fault system, this north-dipping fault forms part of the south margin of the Transverse Ranges structural province, and in concert with the right-lateral Newport-Inglewood zone, it has undergone thousands of feet of thrust movement. The Malibu Coast fault extends westward for 30 miles from the Newport-Inglewood zone along the south margin of the Santa Monica Mountains, passes within 13 miles of the Burro Flats

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site, and may continue westward beneath the Pacific Ocean for 15 or more miles. Several lines of evidence suggest that the fault has potential as a future generator of large earthquakes.

The Malibu Coast fault is a north-dipping thrust that separates sedimentary sections of different characters, and is inferred to separate continental from Franciscan basement at depth. With the Newport-Inglewood zone it forms a coherent structural system that has allowed Franciscan terrain of the continental borderland to move northwestward along the Newport-Inglewood zone and down beneath the leading edge of the Transverse Ranges along the Malibu Coast fault.

3.2 SITE GEOLOGY

The Atomics International NMD Facility is located near Canoga Park, Ventura County, California. The site comprises approximately 1,500 acres of which the test facility occupies an area of some 82.19 acres. The geographic coordinates are approximately 34°14' N and 118°42' W with elevations ranging from 1,650 to 2,250 feet above sea level.

The site lies entirely within a pocket known as Burro Flats, formed by the higher surrounding Simi Hills and affording relative isolation from the surrounding communities. Its higher elevation, ranging from 800 to 1,000 feet above the populated valley floors, serves to enhance its isolation. This site is situated in rugged terrain typical of mountain areas of recent geologic age. The site may be described as an irregular plateau sprinkled with outcroppings above the more level patches and with peripheral eroded gullies. Elevations of the site vary from 1,650 to 2,250 feet above sea level.

3.2.1 STRATIGRAPHY

The Simi Hills, Santa Monica Mountains, Santa Ana Mountains, and Elsinore localities have very similar stratigraphic sequences and depositional environments (Sage, 1971, 1973). Principal sequences in the study area include the

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Paleocene Simi Conglomerate member which disconformably overlies the Upper Cretaceous "Chico Formation" and is in turn graditional with the Las Virgenes Sandstone and Burro Sandstone members. The Eocene Santa Susana Shale and Paleocene Burro Sandstone contact is disconformable in the Santa Susana Mountains, is gradational in the eastern Simi Hills and is unconformable in the western Simi Hills. Sage (1973) suggests that the Simi Conglomerate member and the overlying Burro Sandstone member represent at least four separate depositional environments.

3.2.2 STRUCTURE

There are two faults in the immediate site area that require discussion.

Santa Rosa Fault. This fault (also known as the Simi fault, and at the northeast end, as Las Llajas fault) lies 5.5 miles northwest of the Burro Flats site, where it extends northeastward fo. '0 miles parallel to structure in the late Cenozoic Ventura basin. Little is known of the fault from the published literature, but it must at least tentatively be considered to have had late Quaternary displacement.

The fault is a northwest-dipping thrust fault, and this sense of displacement is also suggested by the distribution of stratigraphic units on the state map. This geometry seems to associate the fault with Ventura basin structure, so that it probably is a relatively young fault.

Santa Susana Thrust. Along the south margin of the eastern end of the Ventura basin, eight miles north of the Burro Flats site, late Cenozoic rocks have been thrust southward along the 15-mile Santa Susana thrust for at least 1-1/2 and possibly five miles. Saul (1975) concludes that this fault is currently inactive and that motion on the fault has not occurred since the middle Pleistocene. Because of its proximity to the site, this fault is treated in particular detail in Section 5.0.

3.3 GEOLOGIC HAZARDS

Non-tectonic geologic hazards for The Atomic International NMD Facility have been evaluated. This has been done on a preliminary basis with emphasis placed upon a search of the literature and review of maps of the area. In addition, a brief site visit was made and included both the facility proper and the immediate surroundings.

3.3.1 FAULT OFFSET HAZARD

Based on existing geologic information (Sage, 1971 and 1973), there are no known active faults underlying the structures in the study area. Therefore, a potential hazard resulting from surface failure or fault offset at the site is considered to be very remote.

As to local faulting, there is an east-west trending left lateral fault positively identified and located in general across the southern boundary of Burro Flats proper (refer to Plate I of Weber et al., 1973). Other faults include one trending northwesterly, separating the Chico and Martinez formations which can be traced from the Los Angeles - Ventura County line westward to west of Runkle Canyon. Fault planes appear nearly vertical with a steep downward dip; the fault is inactive and has not moved for millions of years (Facilities and Industrial Engineering Group, 1975).

3.3.2 SOIL LIQUEFACTION

Soil liquefaction is a phenomenon in which a saturated cohesionless soil layer located close to the ground surface loses strength during cyclic loading such as imposed by earthquakes. During the loss of strength, the soil acquires a mobility sufficient to permit both horizontal and vertical movements. Soils that are most susceptible to liquefaction are clean, loose, saturated, uniformly graded, fine grained sands that lie within 50 feet of the ground surface.

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A problem in southern Ventura County equally as serious as the identification of active faults is the problem of identifying the geologic units as to their seismic response characteristics. Richter (1959) stated that much of the alluviated area of the Santa Clara Valley and the Ventura basin should expect shaking sufficient to cause considerable damage in specially designed buildings and great damage to normally substantial buildings. In the eastern part of the Ventura basin this was demonstrated during the San Fernando earthquake. The expected damage to areas where ground water is within 15 feet of the surface could be even greater, but would be relatively less in areas underlain by older alluvium and even less on more indurated or cemented Tertiary rocks. Older landslides may be reactivated or new landslides may originate in some areas of Tertiary rocks of the county during an earthquake. A summary showing how various building site materials may respond to shaking that leads to liquefaction is provided in a report by Barosh (1969).

Because the soil cover is so thin to non-existent at the site and because the ground water system is virtually non-existent and at considerable depth, the possibility of soil liquefaction occurring at the site is very remote. Relatively firm bedrock is the surficial material at the site.

3.3.3 LANDSLIDES

Landsliding is widespread in southern Ventura County, especially in rocks of the Pico, Santa Barbara, Monterey/Models, and Rincon formations and also in rocks of other formations. Large slides are prominent along major fault zones, such as along the apparently active San Cayetano and Oak Ridge faults. Existing bedrock landslides range in age from the late Quaternary to the present. Specific mapping of landslides in Ventura County has been done by Neel (1969-1970) and Leighton (1966).

Landslides, slumping and other indications of slope failure are not evident on Burro Flats proper. Exposures of stable bedrock, little soil cover and low relief inhibit the mass movement of rock materials.

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4.0 SEISMOLOGY

While the detailed elements of the seismic risk assessment are discussed in Section 5.0, the historical seismic record is of such significance that it is discussed separately below.

A complete evaluation of the historical record is the keystone to the risk assessment because of the important time and spatial distribution information it contains. With regard to time, the record provides detailed historical earthquake frequency information that can best be represented by the relationship, log N = a-bM. Further, the spatial distribution of earthquakes around the site can often be used to delineate seismic source regions within which earthquakes have common characteristics.

Unfortunately, earthquakes have been reliably reported only since the 1930s when a nationwide earthquake instrumentation program was started. The pre-1930 record is a very valuable supplement to the recent recorded data but due to sparce settlement and scattered intensity reports, much of these data cannot be reliably used in developing earthquake statistics. In addition, the hypocentral locations are sufficiently inaccurate that, except for very large earthquakes, it is virtually impossible to associate either the historical or instrumental seismicity with particular faults. Furthermore, the recurrence interval for those larger earthquakes that can be associated with faults is believed to be several times longer than the historical seismic record.

Since necessary input to a seismic risk calculation includes estimates of the seismic activity rates on the specific faults in the site vicinity, we are faced with two alternatives. The first alternative would be to subjectively allocate the regional seismicity to the specific faults. There is little basis for this approach because of the density of faults in the vicinity of the site. The second alternative is to use available geologic information for each fault to provide an estimate of the "secular" seismicity (Allen, et al., 1965) on each fault. This alternative provides an opportunity to accurately describe the recurrence of large

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earthquakes through examination of up to 10^5 years of earthquakes as contained in the geologic record. This approach, which is appropriate only where there is sufficient geologic information, is the approach selected for this study. The following section, Calculations And Results, develops the seismicity model based on the geologic record and compares this model with the regional seismicity.

In the following sections, we review the historical and instrumental record of seismicity in the vicinity of Santa Susana, discuss the capable faults in the area, conclude that the seismic record is insufficient to characterize the seismicity of the individual faults.

As an overview perspective, we present in Figure 4-1 a seismicity map of California. Note first the structural complexity of the Los Angeles area as opposed to other parts of the state. For example, the significant structural features in the San Francisco Bay Area are three principal faults: the San Andreas, the Hayward, and the Calaveras Faults. On the other hand, significant structural features in the site area consist of more than 12 active faults, only six of which are illustrated in Figure 4-1. A more detailed presentation of the capable faults in the area is given in Figure 4-2. Returning to Figure 4-1, note the relative aseismic character of the site area in the Los Angeles Basin relative to, say, the San Francisco Bay Area. These two points, structural complexity and relative aseismicity, characterize the difficulty in developing seismic activity rates for faults in the site area.

In spite of the relative aseismicity of the site area, there have been several significant earthquakes on nearby faults. These events serve to define the seismic capability of the entire region, and further serve as a benchmark against which any seismicity model must favorably compare. Figure 4-3 presents the detailed seismic history for magnitude 5 and greater events in the site area, and Table 4-1 lists the most significant events that have occurred in the Los Angeles Basin since 1857.

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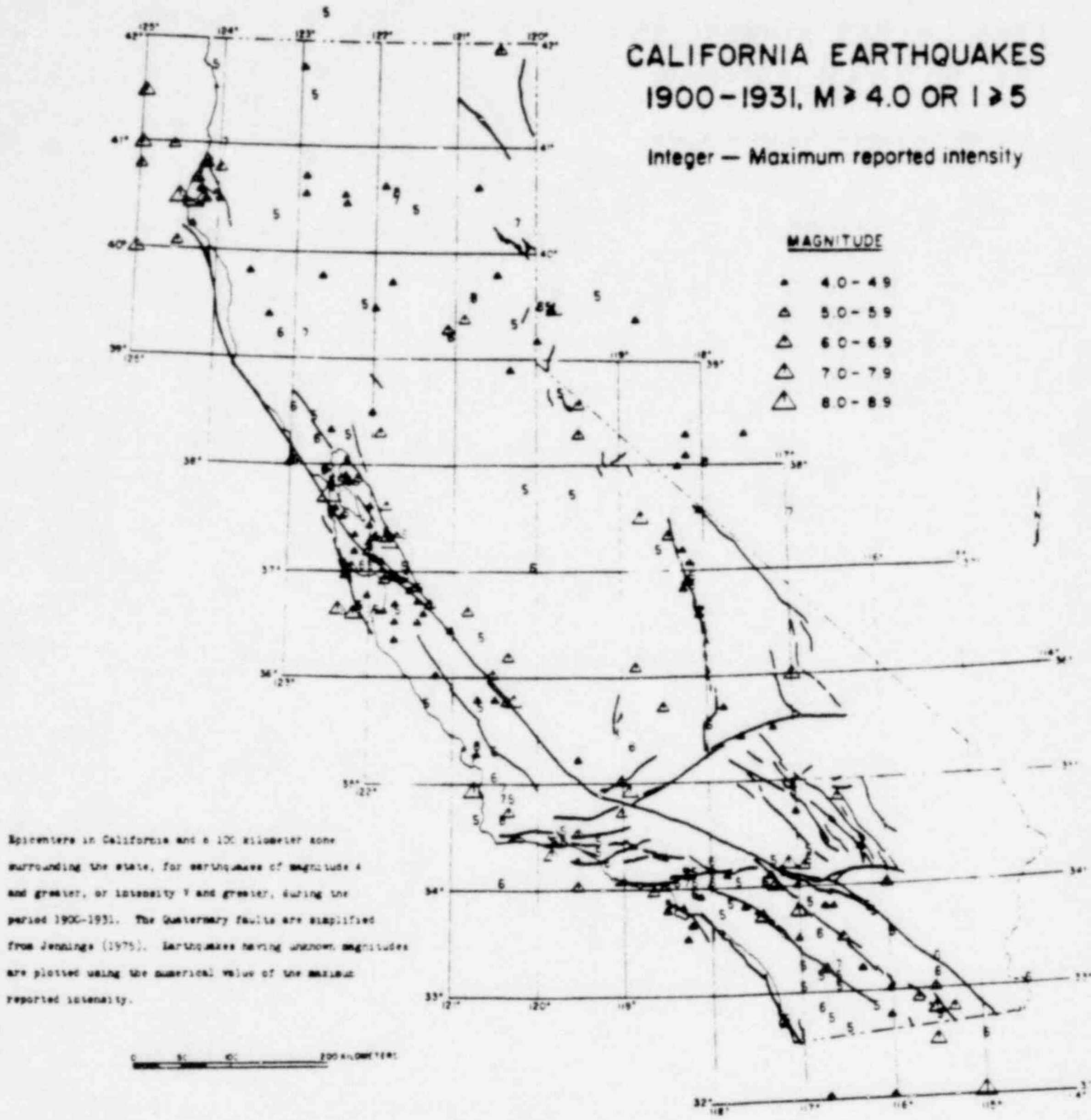

FIGURE 4-1

CALIFORNIA EARTHQUAKES
1900-1931, M ≥ 4.0 OR I ≥ 5
(From Toppozada, 1978)

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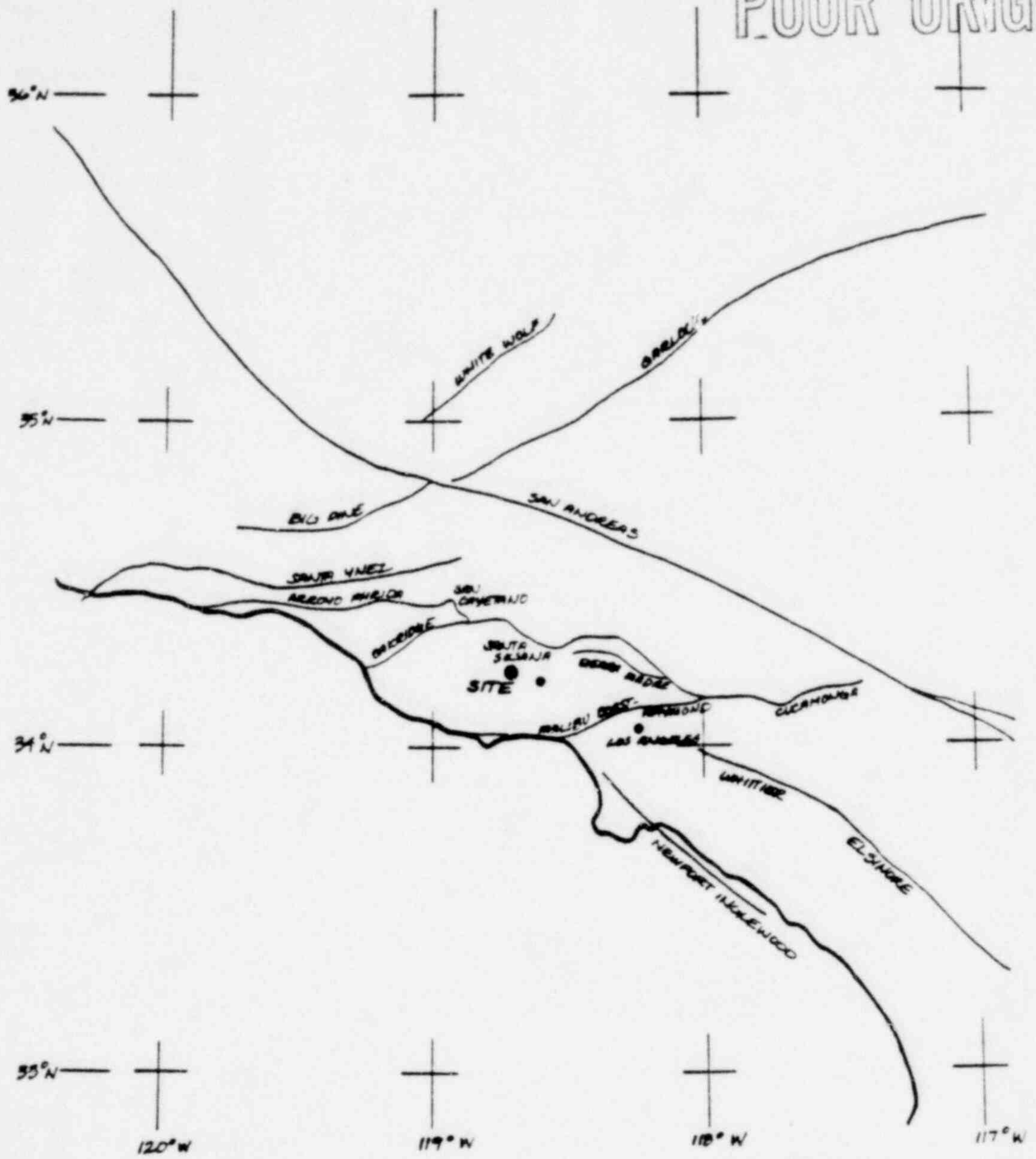

FIGURE 4-2

FAULTS IN SOUTHWEST CALIFORNIA WITH DEMONSTRATED QUATERNARY DISPLACEMENT (From Jennings, 1975)

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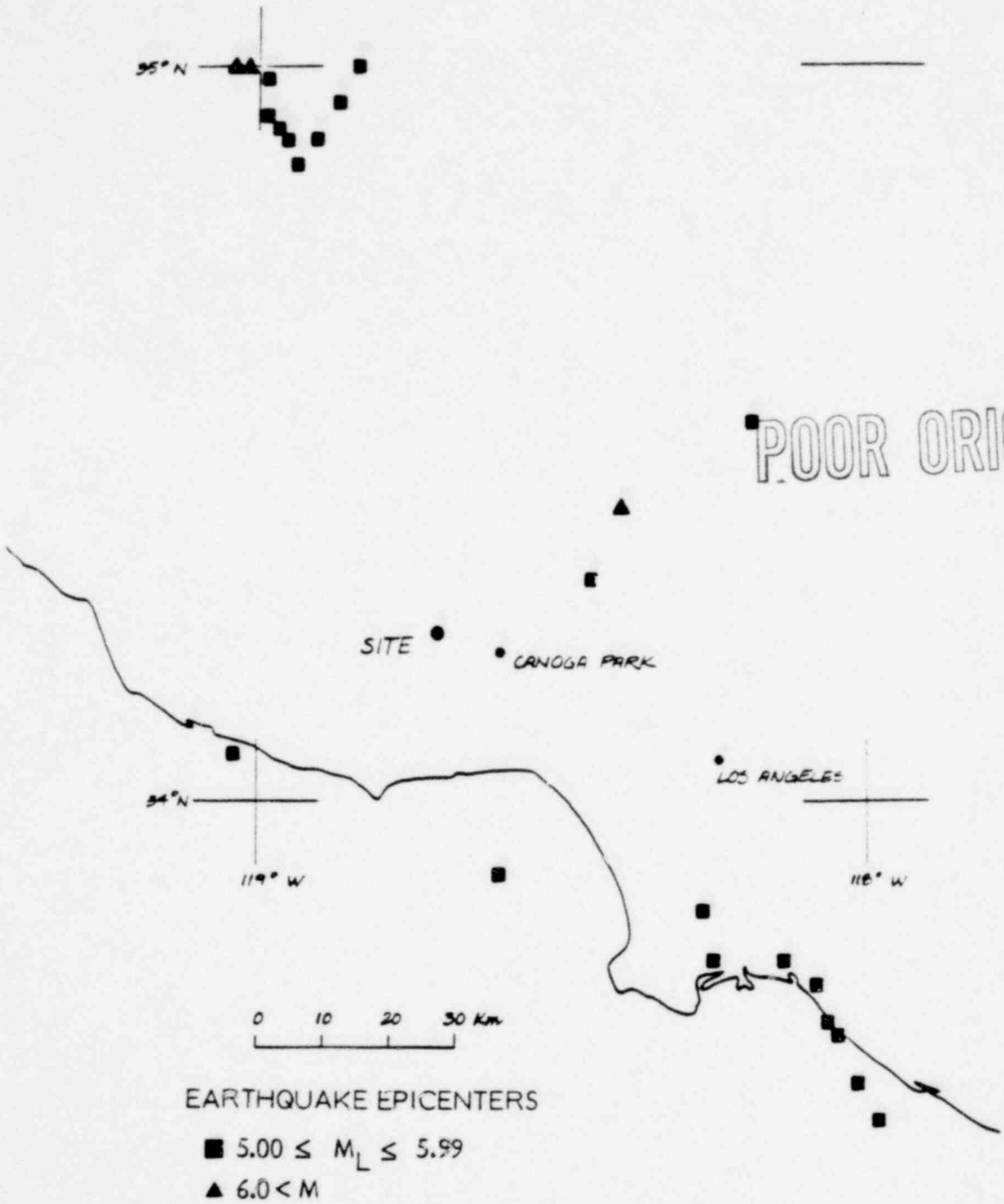

FIGURE 4-3

EARTHQUAKE EPICENTER MAP

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TABLE 4-1

MAGNITUDE 6 AND GREATER EARTHQUAKES
IN SOUTHWEST CALIFORNIA

Year	Description	Magnitude	Lat.	Long.
1857	Fort Tejon	8.0	--	--
1916	White Wolf	6.0	34.9	118.9
1925	Santa Barbara Ch.	6.3	34.3	119.8
1927	Point Arquello	7.5	34.5	121.0
1933	Long Beach	6.3	33.6	118.0
1941	Santa Barbara Ch.	6.0	34.4	119.6
1952	Kern County	7.7	35.0	119.0
1952	Aftershock	6.4	35.0	119.0
1952	Aftershock	6.1	35.4	118.6
1952	Aftershock	6.1	35.4	118.9
1971	San Fernando	6.4	34.4	118.4
1973	Point Mugo	6.0	34.1	119.0

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5.0 CALCULATIONS AND RESULTS

In the previous sections, we have described the regional seismicity around Santa Susana and have discussed the most appropriate method of risk analysis. In this section, we apply these concepts to the NMDF site. The detailed input to the calculational model is described below, followed by a presentation of the results.

5.1 INPUT

As described in Section 2.0, Seismic Risk Methodology, the input to a probabilistic risk assessment comprises earthquake frequency relations, attenuation functions and a specification of local source regions. Because risk assessment calculations are very sensitive to the particular composition of the input, we consulted with several seismologists during the preparation of input for the NMD Facility analysis.

5.1.1 SOURCE REGIONS

The capable earthquake sources are of two broad classes; specific earthquake fault sources and diffuse areal sources.

Our selection of the specific faults for the risk model was guided by the work of Jennings (1975) and was therefore restricted to faults on which there has been Quaternary displacement. Further, based on sensitivity studies with preliminary seismic risk models, we restrict the faults selected for detailed modeling to those within 100 km of the site. The resulting set of specific faults is presented in Figure 5-1.

The region of diffuse seismicity in our seismicity model accounts for the difference in the observed regional seismicity and the accumulated model seismicity for the faults on Figure 5-1. This source region, therefore, accounts for our uncertainty in prescribing activity rates for specific faults, where this uncertainty is first contained within our specification of the activity rate, and

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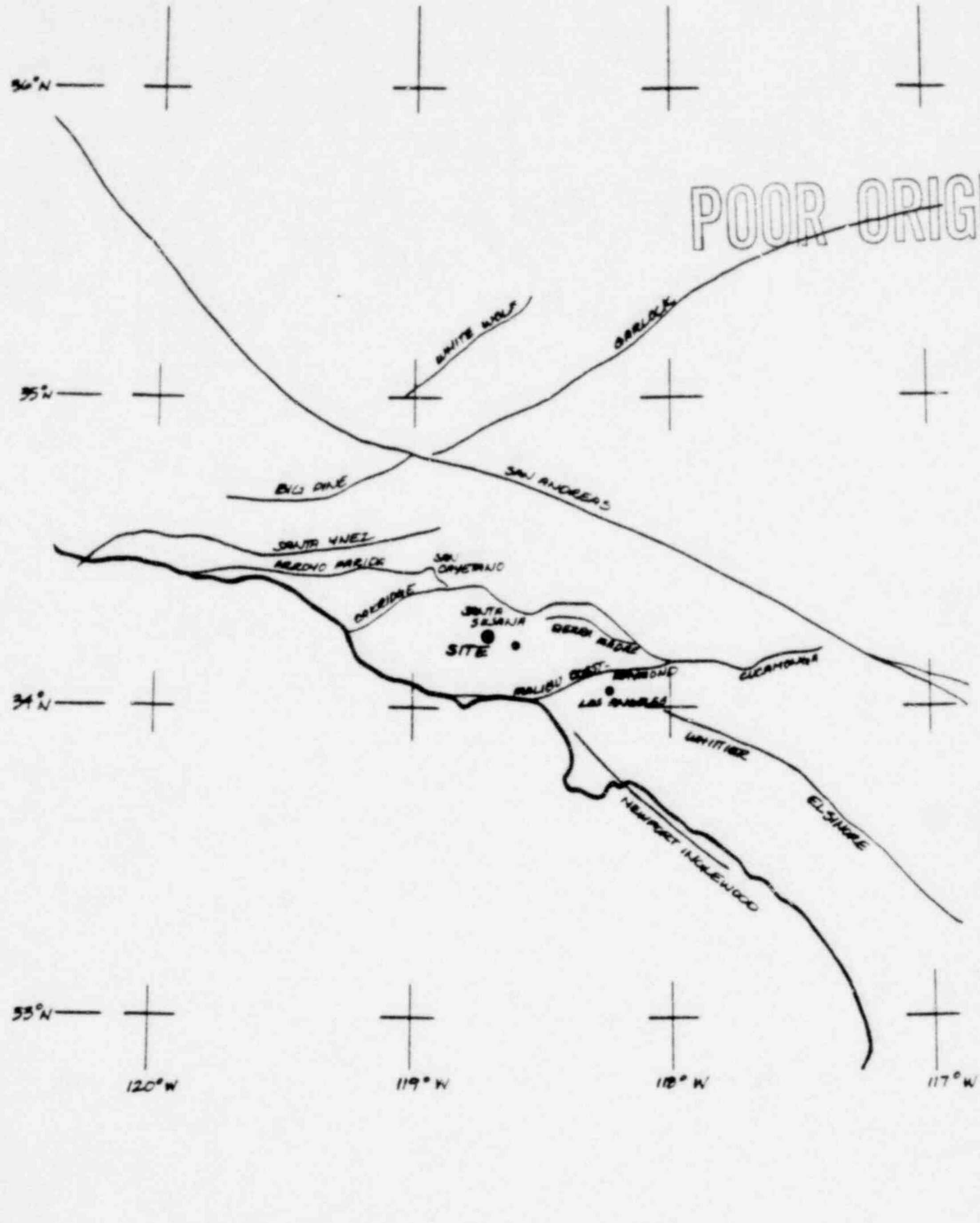

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FIGURE 5-1

FAULTS IN SOUTHWEST CALIFORNIA WITH DEMONSTRATED QUATERNARY DISPLACEMENT (From Jennings, 1975)

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second in our selection of the "active" faults. Including the areal diffuse region allows for possible seismicity on other minor, or poorly understood faults.

5.1.2 MODEL SEISMICITY

As discussed in the previous section, the seismicity and structure of the site area are such that conventional approaches for allocating historical and instrumental seismicity fail because of the uncertainties involved. In this section, we develop an independent assessment of possible seismicity on the site area faults based on available geologic information. The geologic information we require is the average annual slip rate of each fault. We incorporate the best estimates of the slip rate for the specific faults into the slip rate-magnitude relations presented by Campbell (1977) and Anderson (1978) to derive these activity rates. Table 5-1 lists the specific faults considered here, specifies the slip rate and its reference, and indicates the best estimate maximum earthquake for the source.

We use the data in Table 5-1 along with the "b" value of 0.86 determined by Allen, et al., from a statistical analysis of over 10,000 earthquakes to determine the activity rates for each fault. Table 5-2 presents a summary comparison between the seismicity predicted by this model and the actual recorded seismicity for the most active faults in the site area. Note that the seismicity of the diffuse zone is, as described above, designed to model the observed diffuse seismicity. Our best estimate of the activity rate in the diffuse region is plotted in Figure 5-2.

In Figure 5-3, we present a comparison of this seismicity model with the data. The model is seen to overestimate the number of events per year with magnitudes less than 7, and underestimate the historical rate of events with magnitude 7½ to 8. In no case is the rate for events less than magnitude 7 off by more than a factor of 2 from the data.

The magnitude 7½ and 8 data are based on so few earthquakes that the points can not be considered reliable. Sieh (1977) provides geologic data for recurrence rates of major events at two sites on the San Andreas fault: Pallett Creek and

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TABLE 5-1

Fault	Geologic Slip Rate (mm/Year)	Citation	Maximum Earthquake
Rinconada	3.0	11	8.0
Hosgri	10.0	12, 13	8.0
White Wolf	0.4	2	8.0
Santa Ynez	2.0	10	8.0
Big Pine	2.0	2	7.5
Garlock	8.0	2	8.0
San Cayetano	0.05	10	7.5
San Andreas	40.0	1	8.5
Santa Susana	1.2	5, 6, 7, 8, 9	7.0
Sierra Madre	8.0	2	7.5
Malibu Coast	0.15	3	7.5
Oakridge	0.3	16	7.0
Newport-Inglewood	0.3	3, 4, 15	7.5
Palos Verdes	0.7	14	7.5
Chino	0.07	14	7.0
Elsinore	0.8	2	8.0

CITATIONS

1. Ehlert and Ehlig (1977)
2. Lamar, et al. (1973)
3. Hill (1971)
4. Yeates (1973)
5. Barnhart and Slosson (1973)
6. Ehlig (1975)
7. Saul (1975)
8. Hazzard (1944)
9. Ingram (1959)
10. Dibblee(1966)
11. Hart (1976)
12. Weber and Lajoie (1977)
13. Graham and Dickinson (1978)
14. Yerkes, et al. (1965)
15. Wright, et al. (1973)
16. Quick (1973)

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TABLE 5-2

COMPARISON OF THE MODEL SEISMICITY
WITH THE DATA FOR SEVERAL SIGNIFICANT FAULTS

SUBREGION	MAGNITUDE											
	2.5[1]	3.0[1]	3.5[1]	4.0[1]	4.5[2]	5.0[2]	5.5[2]	6.0[2]	6.[illegible]	7.0[3]	7.5[4]	8.0[4]
Events/year (Data)												
Entire region[5]	54.0	66.0	27.0	8.80	4.800	1.200	.3600	.2200	.0540	---	.0170	.0083
San Andreas	---	---	---	---	---	---	---	---	---	---	---	.0083
Hosgri	---	---	---	---	---	---	---	---	---	---	.0083	
Newport-Inglewood	11.0	05.6	01.9	0.66	1.000	0.390	.0970	---	.0140	---	---	
White Wolf	14.0	32.0	08.7	2.40	?.300	0.560	.1700	.1200	.0140	---	.0083	
Sierra Madre	08.7	08.8	07.2	3.20	0.440	0.0[illegible]3	.0240	.0480	.0140	---	---	
Remainder	22.0	16.0	09.6	2.60	0.850	0.170	.0730	.0480	.0140	---	---	
Events/year (Model)												
San Andreas					3.700	1.400	.5000	.19[illegible]	.0700	.0260	.0096	.0022
Hosgri					0.590	0.220	.0810	.0300	.0110	.0041	.0010	---
Newport-Inglewood					0.027	0.010	.0038	.0014	.0005	.0001	---	---
White Wolf					0.016	0.006	.0022	.0008	.0003	.0001	.0001[6]	---
Sierra Madre					0.620	0.230	.0860	.0320	.0120	.0044	.0010	---
Diffuse zone[7]		33.0	09.6	2.6[illegible]	0.840	0.250	.0730	.0220	.0064	---	---	---

1. Data from NOAA earthquake data file 1953.0 - 1974.33
2. Data from NOAA earthquake data file 1933.0 - 1974.33
3. Data from Table II 1903.0 - 1977.0
4. Data from Table II 1857.0 - 1977.0
5. 33.0 - 35.5° N, 117.5 - 121° W
6. Rounded up
7. Seismicity obtained empirically to match "remainder" in data

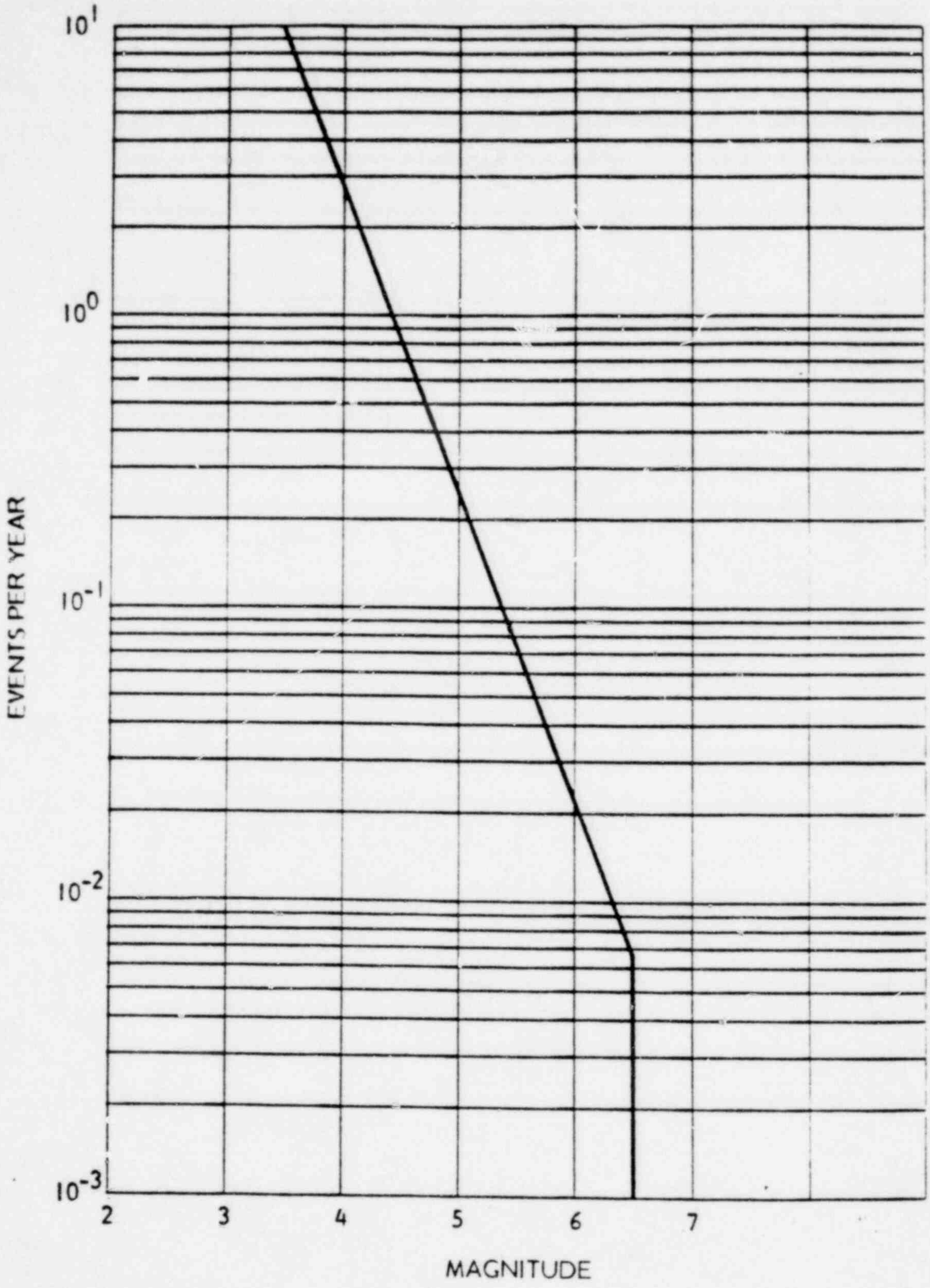

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FIGURE 5-2

RECURRENCE RELATION FOR THE DIFFUSE SOURCE REGION

(33.0 - 35.5° N, 117.5 - 121.0° W)

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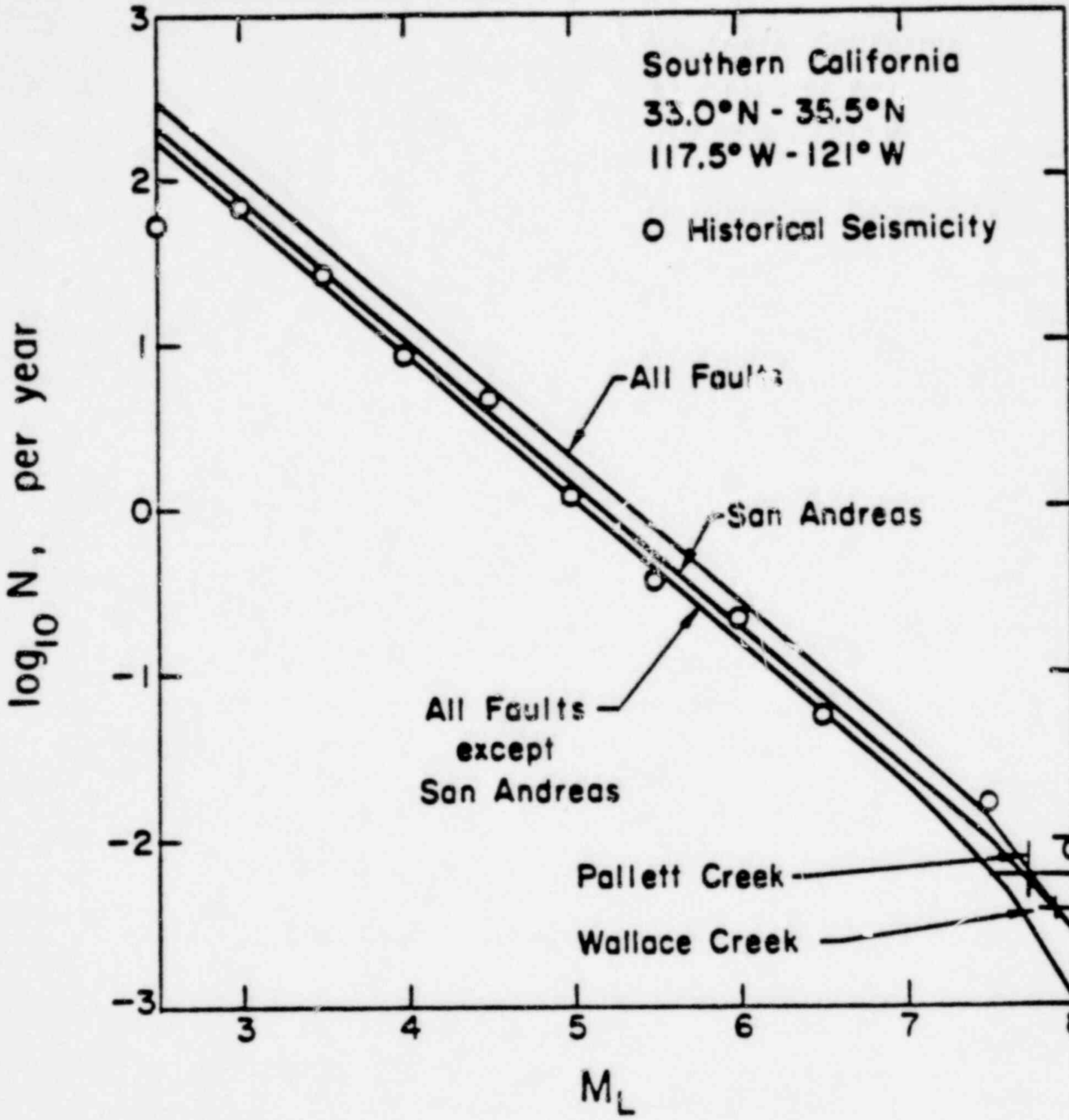

FIGURE 5-3

HISTORICAL SEISMICITY

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Wallace Creek. Rates implied from his data are also plotted on Figure 5-3. Thus, it appears that the seismicity model, based on slip rates, does a reasonable job of estimating the overall seismicity of this region.

However, study of the details in Table 5-2 shows that even though the overall rate for the area is estimated fairly well, the rates for individual faults are almost unrelated. The San Andreas represents the most notable point: although the slip rate implies that it should be the most active fault, it has been completely inactive during the instrumental period. The high seismicity in the total is obtained because the Newport-Inglewood and the White Wolf faults have been considerably more active than the geologic data predicts. The discrepancy appears to arise because the historic interval is so much shorter than the recurrence interval for the faults in the area. Allen et al., (1965) discuss this problem in considerable detail.

From this viewpoint, the more remarkable observation is the apparent coincidence of the total rates for the area. Either these total rates are similar because of a lucky coincidence, or the seismicity of the region as a whole is a more stable parameter than the seismicity of selected faults within the region. Since the cause of the seismicity appears to be relative motion of the Pacific and the North American plates, and since that rate is fairly uniform so far as is known, the uniform rate of strain accumulation which is implied suggests a physical explanation for the second hypothesis.

One particular fault in our model warrents particular discussion. Because of its proximity to the site, the Santa Susana fault is a major contributor to the seismic risk at the Facility. Our best estimate of the activity on this fault is based on a slip rate of 1.2 mm/yr (Table 5-1). We summarize below the basis for this slip rate and indicate its uncertainty.

The published data on the fault is rather extensive considering its short length (40 kilometers). The literature we consulted included the following:

Barnhart and Slosson (1973)
Oakeshott, G.B. (1955)

844 057

Evicon Corporation (1976)
Bishop, R.J. (1950)
Slosson and Barnhart (1967)
Jennings, R.A. (1957)
Proctor, et al. (1972)
Ehlig, P.L. (1975)
Hazzard, J.C. (1944)
Ingram, W.L. (1959)

Of these papers, two are most significant.

Barnhart and Slosson (1973)

Quote Oakeshott (1958) in saying there is "about 2.5 km of horizontal shortening and vertical separation." The fault merges to the east with a series of faults that become the Sierra Madre fault system. "In the Santa Susana Mountains, Tertiary is thrust over Plio-Pleistocene sediments and to the east, basement was thrust up and over Pliocene and Pleistocene sediments. Recent studies strongly suggest post-Pleistocene orogenic activity along the central and western portion of this fault zone."

If there is 2.5 km offset since the beginning of Pleistocene,

$$\frac{2.5 \text{ km}}{2 \text{ my}} = 1.2 \text{ mm/yr}$$

If it occurred since upper Miocene,

$$\frac{2.5 \text{ km}}{10 \text{ my}} = 0.25 \text{ mm/yr}$$

Ehlig (1975)

In the same volume as the article by Saul (1975), Ehlig states that "uplift of the Santa Susana Mountains has occured during the late Pleistocene and Holocene." (p. 18) Therefore, using 1 my rather than 2 my to estimate the slip rate, we get

$$\frac{2.5 \text{ km}}{1 \text{ my}} = 2.5 \text{ mm/yr}$$

Again, we judge a best estimate slip rate of 1.2 mm/yr but the above discussion establishes that the uncertainty is a multiplicative factor of two.

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In summary, for the development of our seismicity model we have extended our information base to include extensive geologic information and in so doing have determined realistic and credible estimates of activity rates that could not otherwise be determined. The validity of the model is established by the comparison in Figure 5-3 between the regional seismicity and our model.

5.1.3 ATTENUATION

One of the keystones to any seismic analysis is the specification of decay of peak acceleration with distance from the earthquake. Credible attenuation relations have in the past been difficult to develop for two reasons: first the large scatter in the data makes a deterministic evaluation very difficult and second, the data are very sparse in the near-field, thus allowing for a variety of interpretations.

Because of its particular significance at this site, a very careful re-evaluation of all the data was performed in order to ensure state-of-the-art interpretation and maximum credibility (Boore, 1977).

The overall approach to development of an attenuation relation for this analysis is as follows:

1) Use appropriate data in the range 20-100 km to estimate the far-field attenuation.

2) Focus on the acceleration data at ≃ 10 km to fix the trend in the near-field.

3) Rely on all available data points at ranges less than 10 km to establish the very near-field accelerations.

Peak acceleration data for development of the attenuation relation were collected from the following sources:

- Brune, et al., 1977
- Galanopoulos and Drakopoulos, 1974

844 059

- Hanks and Johnson, 1976
- Boore, et al. to be published, 1977
- USGS Circulars;

672, 1972	717-D, 1976
713, 1974	736-A, 1976
717-A, 1975	736-B, 1976
717-B, 1975	736-C, 1977
717-C, 1976	736-D, 1977

The magnitude range 5.0-7.0 has been emphasized in the data collection and interpretation in anticipation of the significant magnitude level of earthquakes in the Santa Susana area. As an illustration, Figure 5-4 shows the data in the magnitude ranges 6.0 -7.0. The emphasis in this figure is on the 20-100 km ranges, but the available very near-field data (less than 10 km) are also plotted. In this model, range is usually the distance to the nearest point on the fault or the distance to the zone of principal energy release, if this can be determined. The data are for both rock and soil sites since there appears to be no statistically valid reaon for their discrimination (Boore, et al., 1977). The relations are, therefore, for a typical, average site. Superimposed on the data in this figure are the attenuation relations that result from consideration of all these data. We include two attenuation relations here to capture the uncertainty associated with the extrapolated near-field accelerations. The scatter about these mean relationships is best characterized by a log normal one standard deviation of 0.45. This fits the data reasonably well and is consistent with the dispersion calculated by other investigators (e.g., Donovan, 1974), considering that our analysis is for a specific site in a specific tectonic setting.

The recommended attenuation relations, which are a blend of judgment and regression analysis, are summarized in Figures 5-5 and 5-6 can be characterized by the analytic expressions:

$$A_H = 6.7 \exp(0.277M + .016\,M^2)\,(r + 10)^{-1.75}$$

$$A_H = 0.193 \exp(2.98\,M - 0.58\,M^2 + 0.04\,M^3)\,(r + 12)^{-1.75}$$

where r is in kilometers and A_H is in fraction g.

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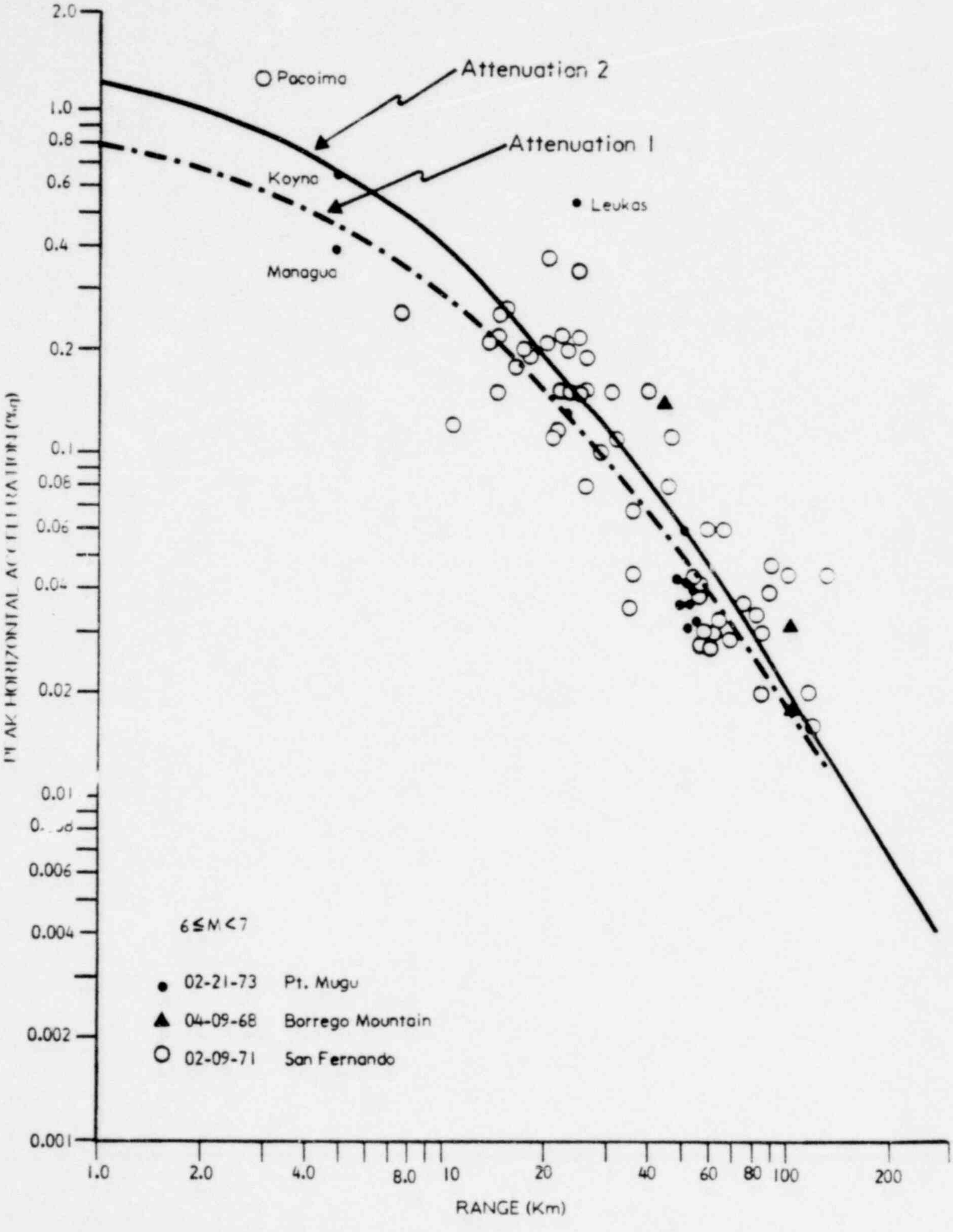

FIGURE 5-4

TWO ATTENUATION RELATIONS USED IN THE TERA ANALYSIS

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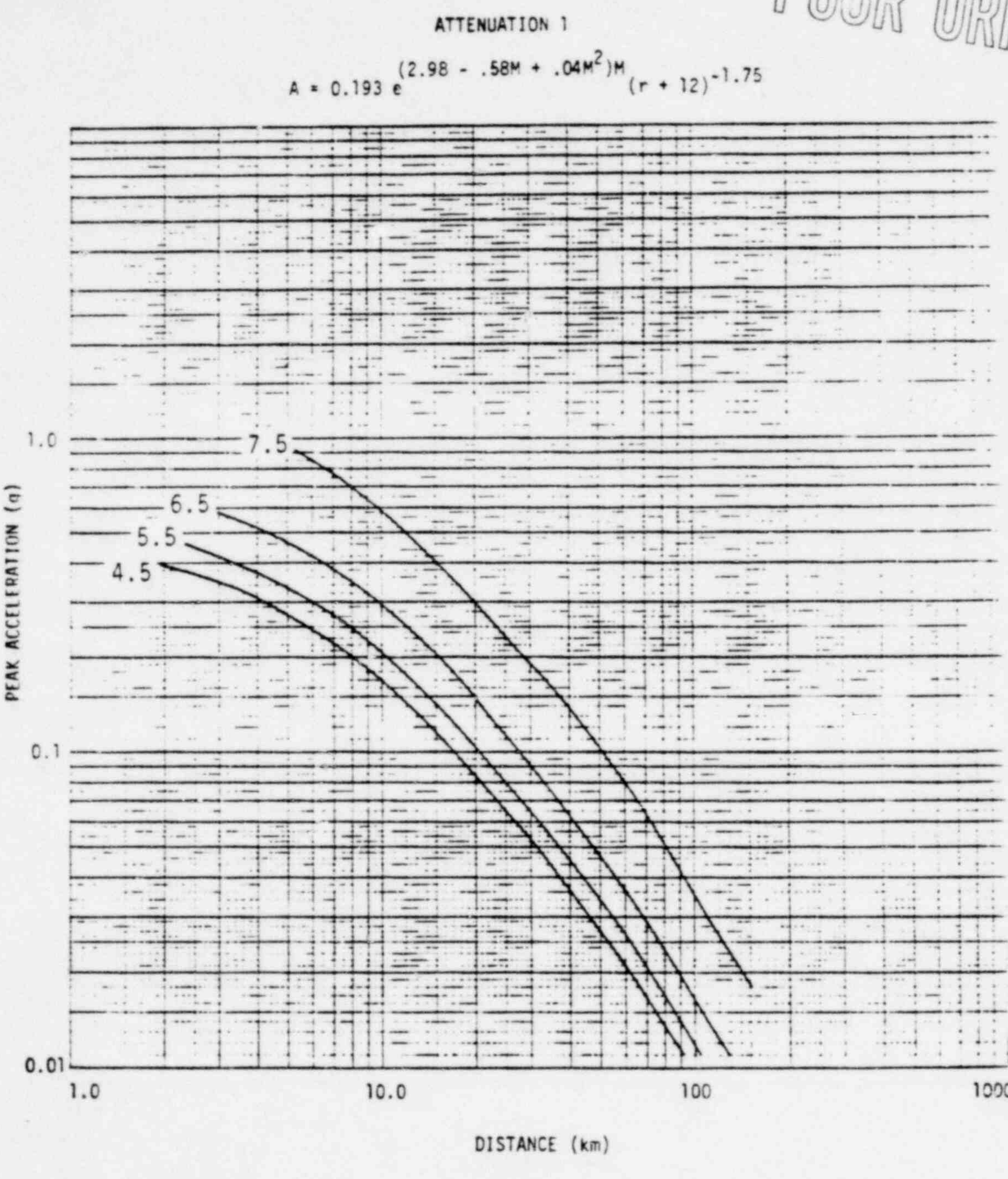

FIGURE 5-5

ATTENUATION RELATIONSHIPS

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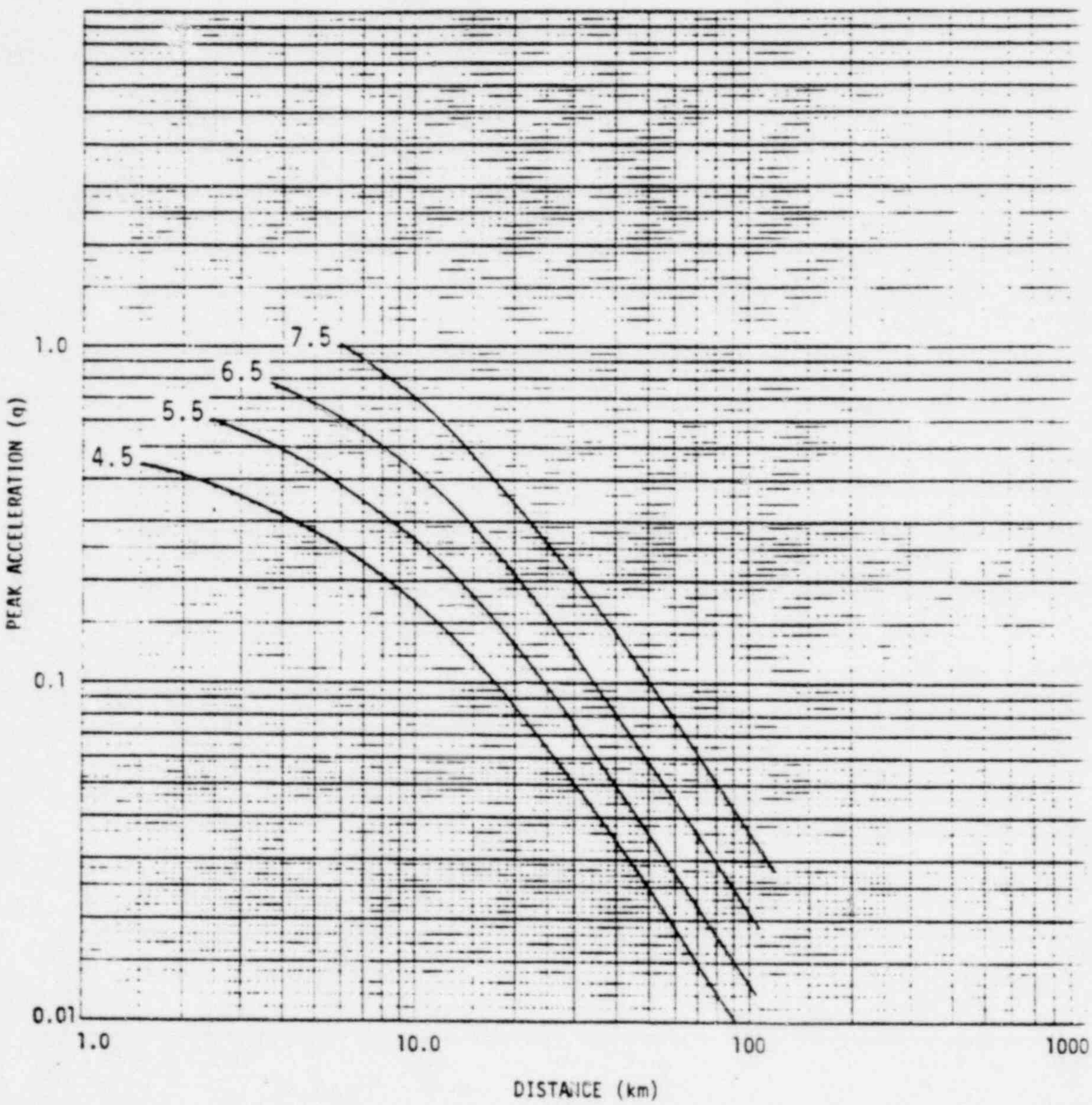
ATTENUATION 2

$$A = 6.7\ e^{(.277\ +\ .016M)M}\ (r + 10)^{-1.75}$$



POOR ORIGINAL

FIGURE 5-6

ATTENUATION RELATIONSHIPS

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5.2 RESULTS

The results were obtained by computer calculations with a risk analysis code (Anderson and Trifunac, 1978) that is based on the work of Cornell (1968). The basis for this approach was summarized in Section 2.0.

As described in Section 2.0, the computer code calculates the expected number of earthquakes causing accelerations greater than a specified acceleration and this is done for each source region and the host region. The expected numbers are summed for each region, and the resulting risk calculated from

$$\text{risk} = 1.0 - \exp(-\text{ total expected number}).$$

The return period associated with the specified acceleration is then the reciprocal of the risk. It follows from the definition of return period that accelerations with a particular return period have a 63 percent probability of being exceeded within the return period.

Our estimate of the seismic risk represents the weighted results from five individual calculations. The five calculations represent a base case and our perturbations of input parameters about this base. The perturbations are weighted by subjective estimates of their probability of occurrence and thus their weighted combination can be considered a Bayesian estimate.

The parameters that are considered uncertain and which are included in our estimate of the risk are the activity rates for the Santa Susana fault and the Diffuse Source region, and the magnitude of the data dispersion about the mean acceleration attenuation relationship. The variations of these parameters represent the overall uncertainties in:

- Our ability to define the strain energy limit of faults around the site

844 064

- The correlation between earthquake magnitude and intensity
- The shape and level of the attenuation relation

The base case is considered to consist of the following input:

- Best estimate activity rates for the Santa Susana fault (1.2 mm/yr slip rate) and the Diffuse Source region (Figure 5-2)
- Acceleration one standard deviation dispersion, $\sigma_{\ln A_H} = 0.45$

We characterize the uncertainty in these data by considering that it is roughly 70 percent probable that the activity rates on the Santa Susana fault and in the Diffuse Source region will be as specified above. We consider it roughly 15 percent probable that the activity rates would be double our best estimate and also 15 percent probable that the rates would be one-half our best estimate. Note that this range covers the uncertainty in the Santa Susana slip rate.

Similarly, we consider that it is 70 percent probable that the acceleration dispersion is as specified above and that it is respectively 15 percent probable that the dispersion will be 0.35 and 0.55.

The results from these five sets of parameters have been combined to produce our Bayesian best estimate in accordance with the probability of the combination. These results are presented in Figure 5-7. Also shown in this figure is our estimate of the plus and minus one standard deviations about our best estimate results. These were derived by assigning equal weights to respectively the two more conservative and less conservative sets of parameters.

5.3 RESPONSE SPECTRUM

These results define the peak horizontal acceleration at the facility for various return periods. We have also determined an appropriate response spectrum for the site since some structures and equipment at the NMD Facility have sufficiently low fundamental frequencies to experience spectral amplification of

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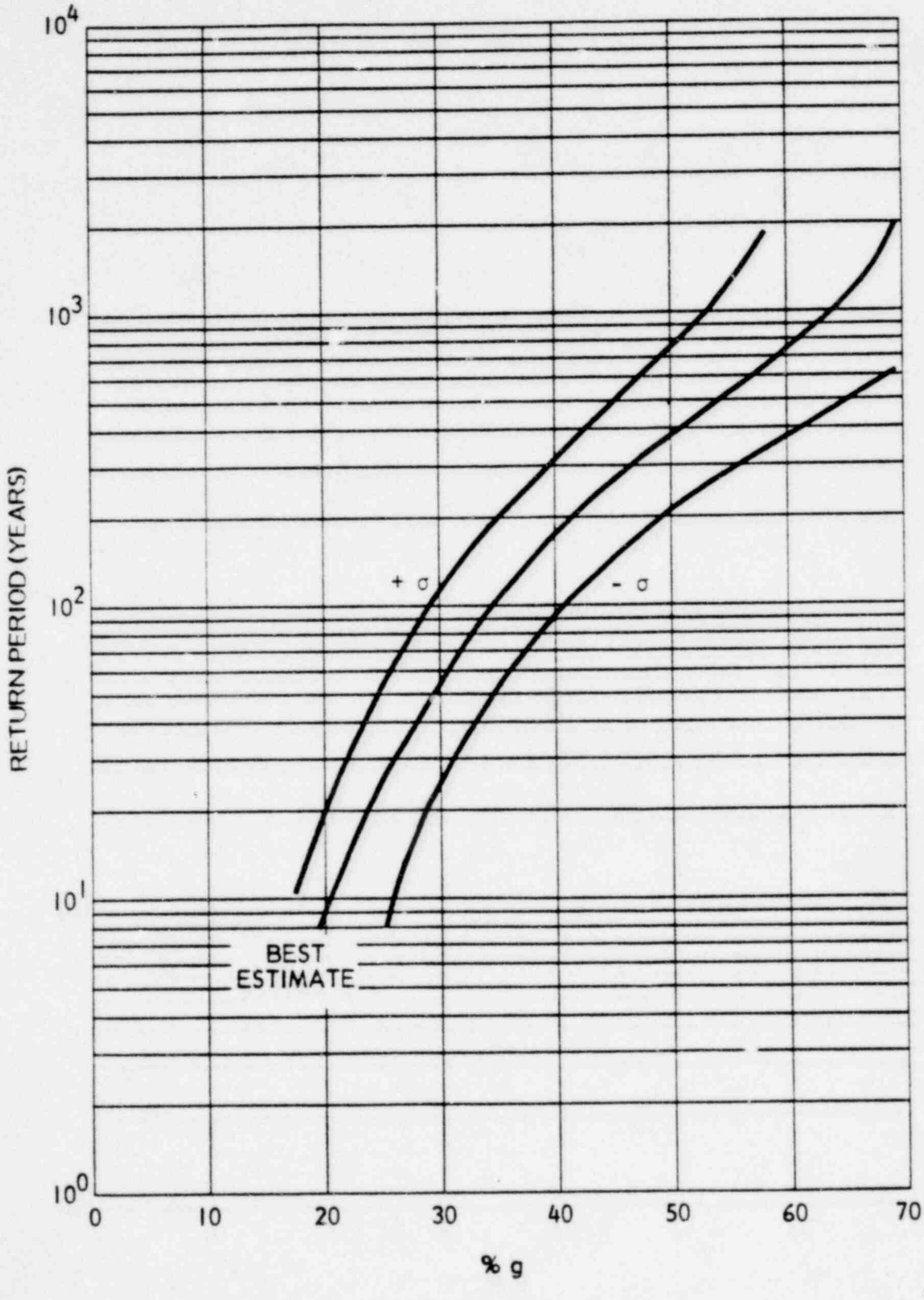

FIGURE 5-7

RETURN PERIOD - ACCELERATION FOR THE NMDF

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TERA CORPORATION

the ground motion. The response spectrum for the site clearly cannot be developed in association with a specific earthquake; our return period accelerations represent an integrated effect at the site from an extraordinary variety of earthquakes and the response spectrum must reflect this. Accordingly, we judge that the shape of the spectrum should be similar to the Newmark-Blume statistically-based spectra from which Regulatory Guide 1.60 evolved. Accordingly, it is our judgment that the mean response spectrum for rock presented in WASH 1255 is the most appropriate for analysis of the NMD Facility. The uncertainties in this judgment are, however, large; there is probably a 20 percent probability that the spectral accelerations could exceed the 75 percentile accelerations in WASH 1255.

In summary we have combined the best available input data with the most credible tools of seismic risk analysis to determine the return period of acceleration at the NMD Facility. The results, shown in Figure 5-7 account for all the significant uncertainties in the input. Response spectral accelerations can be determined by scaling the mean response spectrum in WASH 1255 to the desired peak acceleration.

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