UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Some Aspects of the Seismic Hazard Associated With Radioactive Waste Disposal

by

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INTRODUCTION

The importance of the earthquake hazard in the management of radioactive waste is a problem that has received relatively little attention. The long time periods involved in waste storage (millions of years) obviously make the evaluation of the seismic hazard and risk especially difficult. Seismic hazard is taken here to mean any physical phenomena (e.g. ground shaking, ground failure) associated with an earthquake which may produce adverse effects on human activities. Seismic risk is the probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at several sites, or in an area, during a specified exposure time*.

The seismic risk may occur in several ways: (1) strong ground shaking may result in direct failure of the waste container; (2) strong ground shaking may cause failure of the rock surrounding the container and subsequently cause the container to fail; (3) faulting may cause the container to fail. Obviously, these effects may occur in various combinations. Seismic design criteria must be developed and incorporated into the design of facilities for any site under consideration for waste disposal.

SCOPE

This report is limited to a consideration of the earthquake ground shaking hazard. The hazard associated with ground failures of various kinds and faulting is not considered directly. Faulting is, however, considered with regard to its effect on the distribution of ground shaking.

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*The definitions of seismic hazard and risk used here are those suggested by the Seismic Risk Committee of the Earthquake Engineering Research Institute.

OBJECTIVE

The objective of this study is to investigate the usefulness of probabilistic methods of earthquake hazard analysis when applied to the long exposure times of interest in waste disposal. Probabilistic methods are currently widely used to estimate the level of ground motion for relatively short exposure times of the order of 10-200 years at a site or over a region. Some level of risk is associated with every site (ie, no sites are "absolutely safe"). Probablistic methods of risk analysis, if indeed they can be applied over long exposure times, would provide a convenience method of evaluating the risk at a proposed site or for the selection of the best site in a particular region.

APPROACH

Introduction

Historically, both deterministic and probabilistic methods have been used to estimate seismic hazard. The use of the deterministic approach for the estimation of seismic hazard at a site or over a region essentially involves the use of the mean value (or some other measure) of each parameter in the analysis. These "deterministic" values of each parameter are then analyzed to produce an estimate of hazard. The estimate is a single valued function of time. For a stochastic process, the estimate of hazard is a distribution function which contains time as a parameter. Unfortunately deterministic hazard analyses has led to the use of terms such as "maximum credible earthquake" or "maximum credible acceleration". While these terms might be useful if well defined, they have, in general, not been carefully used in the literature. There use is discouraged.* From a practical point of view, the use of such terms as "maximum credible earthquake" are troublesome because they provide no systematic estimate of the uncertainty in the result. This is a criticism that can be made of most deterministic estimates of seismic hazard.

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*A recent report (1979) by the Seismic Risk Committee of the Earthquake Engineering Research Institute recommends that terms of this kind be abandoned.

The process that results in the occurrence of an earthquake (or any process) can be described in two ways, either by its history or by its dynamics. Both ways are equivalent. If we know the complete history of the process, it is unnecessary to know (or understand) the dynamics of the process. Conversely, nothing need be known about the history of a process if the dynamics of the process are completely understood. Our understandings of the dynamics of earthquake occurrence is, at present, quite incomplete while the historical record of earthquake occurrence is similarly incomplete. We are therefore forced to use simple models of earthquake dynamics together with limited data on the historical occurrence of earthquakes to estimate parameters of interest for the engineering design of structures and for decision making. The earthquake process is therefore best treated as a probabilistic phenomena for the purpose of estimating earthquake hazard.

A probabilistic estimate of ground motion in the contiguous United States was published by Algermissen and Perkins in 1976. The quantity mapped is the maximum acceleration in rock in a 50 year period at the 90 percent probability level (fig. 1). The basic assumptions in preparing the map are that: (1) the earthquakes are a Poisson process in time and the magnitude and location of successive events are independent; (2) the earthquakes are exponentially distributed with magnitude with the distribution being truncated at appropriate upper and lower magnitude levels; and (3) earthquake activity can be grouped into "seismic source areas" (fig. 2). Earthquake magnitude distributions are developed for each of the seismic source areas. The earthquakes are assumed to occur with equal probability anywhere within each source area. A more complete discussion of the assumptions and details of the hazard assessment are given by Algermissen and Perkins (1976). The uncertainty in the model parameters were not included in the hazard calculation although a discussion of the effects of parameter uncertainty was included in the original paper using variational techniques. Parameter variability has been expanded upon in a subsequent paper by Perkins (1978). Parameter variability is an important consideration in hazard analysis when long exposure times are considered. Figure 3 shows the principal steps in the calculation of acceleration values for the Algermissen-Perkins map. Known historical or postulated earthquake activity is grouped into seismic source areas as idealized in figure 3a. The magnitude distribution of earthquakes in each source area is determined (fig. 3b). The occurrence of earthquakes within each source zone is assumed to be equally likely at any location in the source zone. This is shown schematically in figure 3a by dividing each of the source areas up into a number of small cells, each of equal area. Assuming a uniform spatial distribution of earthquakes within each source zone and

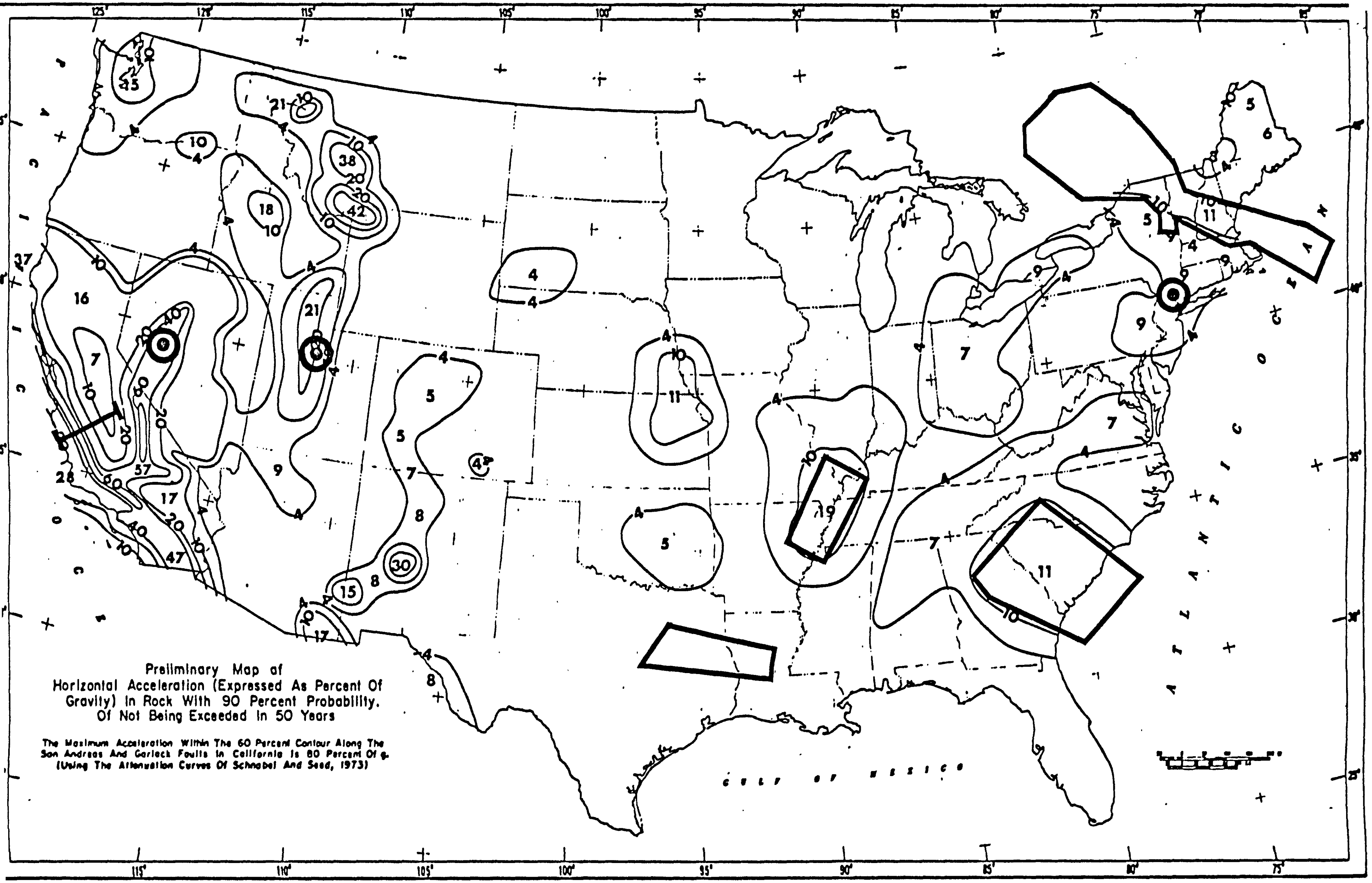

Figure 1.--Contiguous United States hazard (acceleration) map (after Algermissen and Perkins, 1976). The map also shows specific seismic sources of Algermissen and Perkins together with other areas studied in this report.

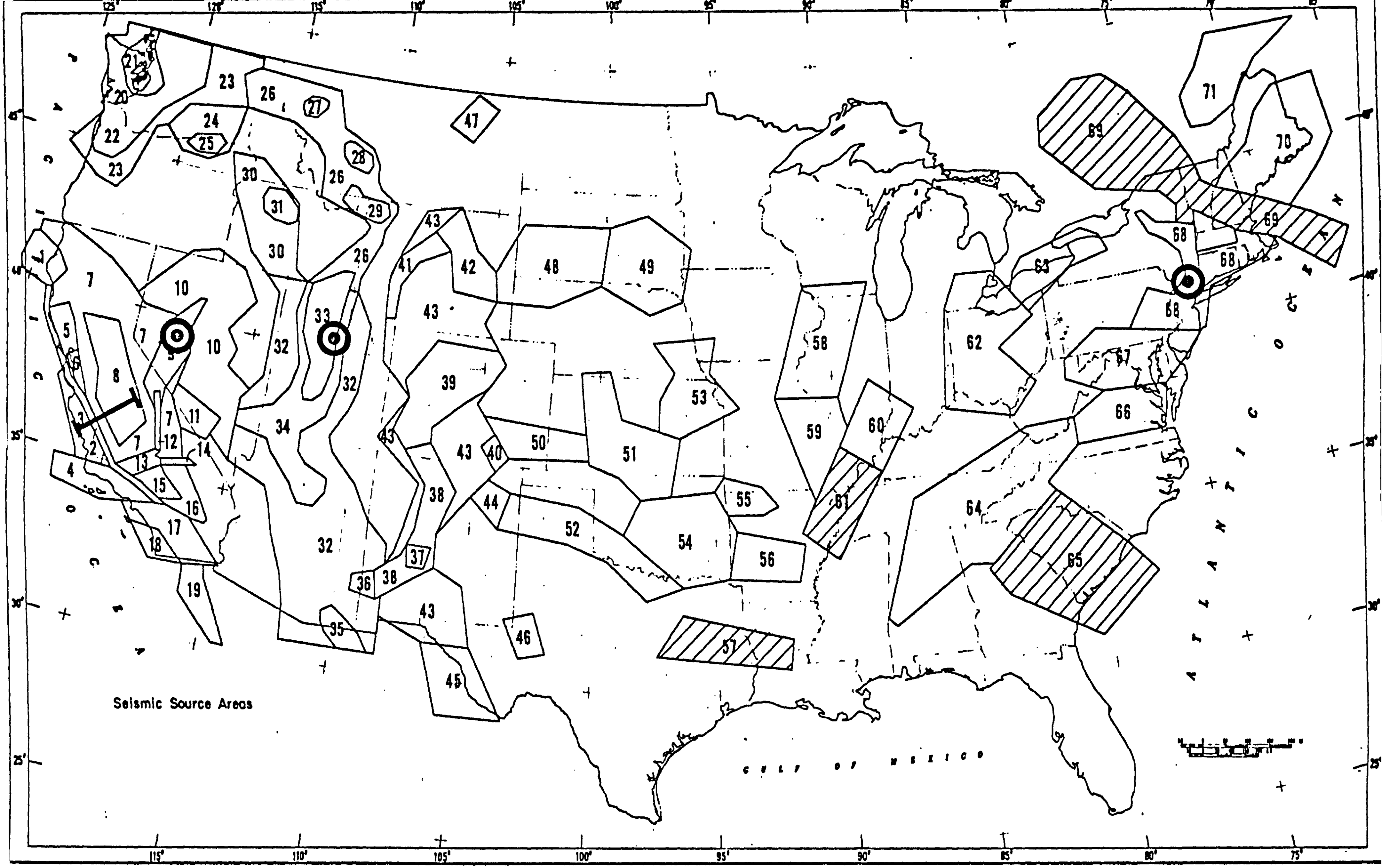

Figure 1a.--Seismic source zones for the contiguous United States (after Algermissen and Perkins, 1976). Seismic source zones and other areas considered in this report are indicated. The seismic sources used are numbers 57, 61, 65, and 69. Other areas are the Ramapo fault in northern New Jersey and southern New York, the Wasatch fault in Utah, a hypothetical fault in central Nevada and a profile across the San Andreas fault in central California.

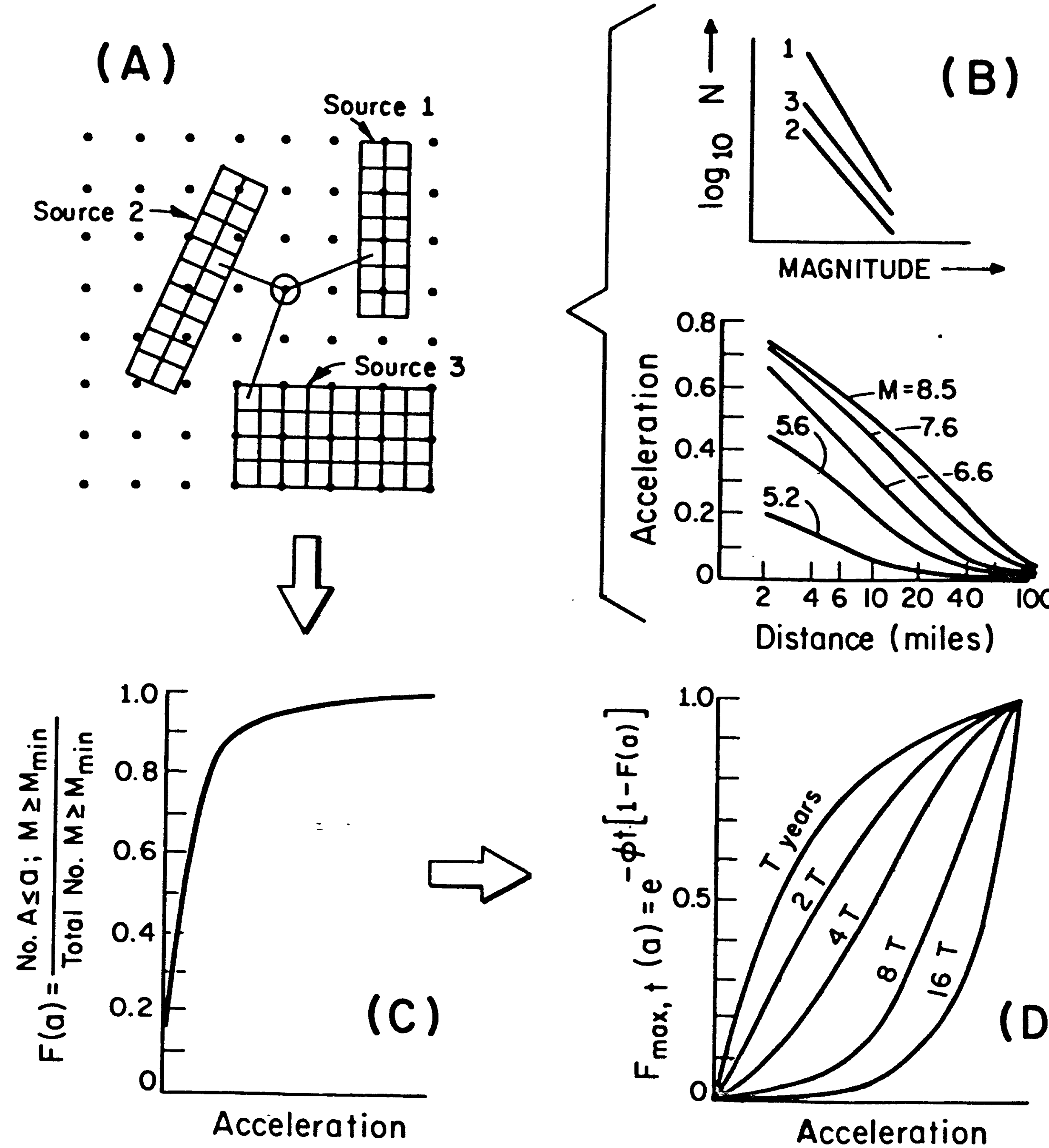

Figure 2.--Elements of the hazard calculation:

(A) Typical source areas and grid of points at which the hazard is to be computed.

(B) Statistical analysis of seismicity data and typical attenuation curves.

(C) Cumulative conditional probability distribution of acceleration.

(D) The extreme probability $F_{max,\ t}(a)$ for various accelerations and exposure times (T).

suitable attenuation functions, (acceleration attenuation functions are shown in fig. 3b), the cumulative conditional probability distribution F(a) of the ground motion (acceleration in this case) is computed for every site of interest. This is essentially the ground motion history of each site derived from a specific magnitude distribution of earthquakes modeled in each source zone. Further assuming that the earthquakes occur according to a Poisson process in time, the extreme cumulative probability is given by

$$F_{mx,t}(a) = e^{-\phi t[1-F(a)]} \tag{1}$$

where t = period of interest (exposure time)

a = ground motion parameter (accleration, in this case)

ϕ = mean rate of occurrence of earthquakes

F(a) = cumulative conditional probability distribution.

Figure 3d shows some idealized plots of $F_{mx,t}$ (a) versus acceleration for various values of t (t = T, 2T, 4T, etc). The extreme probability for any level of acceleration can be obtained from a graph of the type shown in figure 3d. Conversely, the maximum acceleration associated with any level of extreme probability and exposure time can also be obtained.

Another quantity, the return period is sometimes used in expressions of probablistic hazard. The return period of a particular level of ground motion is the average length of time necessary to produce that particular ground motion. Implicit in the definition of return period is the requirement that a long time interval may be necessary to obtain an average which approximates the return period, since earthquakes, especially large earthquakes, are comparatively rare events. In addition, confusion seems to arise in the use of return period because a common belief is that a return period of RP years implies a cyclic reoccurrence of earthquakes. If the earthquake occurrences closely resemble a Poisson process, as has been shown for southern California (Gardner and Knopoff, 1974), the earthquakes may appear to be clustered since for a Poisson model there are more short intervals between events than long intervals.

The return period RP, assuming a Poisson model, is related to the extreme probability $F_{mx,t}$ (a) and the exposure time T by:

$$F_{mx,t}(a) = e^{\frac{T}{RP}} \qquad (2)$$

or:

$$RP = \frac{T}{\ln\,[F_{mx,t}(a)]} \qquad (3)$$

For the Algermissen-Perkins map of the United States, the extreme probability is 0.90 and the exposure time is 50 years. The return period is then

$$RP = \frac{50}{\ln(.90)} = \frac{50}{.1054} = 475 \text{ years} \tag{4}$$

The map prepared by Algermissen and Perkins was subsequently used as the basis for the estimation of ground motion for earthquake resistant design by the Applied Technology Council (1978).

Parameters in Hazard Analyses

Central to an evaluation of the usefulness of probabilistic hazard analyses for long exposure times is a consideration of the parameters that are used in the analysis and the uncertainty associated with each parameter. In addition, uncertainty in any parameter must be considered in terms of the techniques and computer programs currently available to analyze the effect of particular uncertainties. The effects of parameter uncertainties is discussed here principally in the context of a computer program originally developed by McGuire (1978). This computer program has been extensively modified (principally by Bernice Bender and Michael McGrath of the U.S. Geological Survey) to improve its operational efficiency and in some instances to correct minor errors in the computional procedures. The computer program used does not permit the explicit inclusion of probability distributions for all parameters in the hazard analysis. Table 1 lists the parameters used in the hazard analysis, the treatment of variability and related data about the program. The discussion of the treatment of parameters and their uncertainty that follows is designed to relate to the computer program and, it is hoped, provides some insight into various aspects of the problem of parameter variability.

Table 1

Analysis of Computer Program Capability

Parameter	Parameter variability?	Distribution
<u>Seismicity</u>		
a) magnitude distribution	no	--
c) spatial distribution (zone boundaries)	no	--
d) temporal distribution	yes	Poissonian
b) upper bound magnitude	yes	discrete probabilities assigned to range of magnitudes
<u>Faulting</u>		
a) distribution of fault rupture length with magnitude	yes	lognormal
b) strike	no	--
<u>Attenuation</u>	yes	lognormal or normal depending on the ground motion parameter

Seismicity: The spatial, temporal and size distribution of earthquakes are important parameters in hazard estimation. Normally, historical seismicity is grouped spatially into "seismic source zones", that is, areas that are believed to be seismotectonically similar (for an example and discussion see figure 2 and Algermissen and Perkins, 1976). Within each zone the "size" distribution is taken as (Richter, 1958).

$$\log_{10} n_m = a-bM \qquad (5)$$

where n_m is the number of earthquakes with magnitudes greater than or equal to M in a source area and a and b are constants characteristic of the source area examined. The temporal seismicity distribution considered is Poissonian, that is, the events occur randomly in time with mean rate ϕ. The computer program does not have a provision for the treatment of uncertainty in the spatial or magnitude distribution of seismicity. The program does permit the use of a discrete distribution rather than a point estimate for the maximum possible magnitude M assumed for each source zone. Thus, uncertainties in the maximum magnitude, if known or estimated using professional judgment, may be expressed in the program by assigning discrete probabilities to various estimates of the maximum magnitude. For example one might estimate that the probability is around .7 that the maximum magnitude in a particular zone is 7.0 and .3 that the maximum magnitude is 8.0.

Fault rupture length: The rupture length and orientation of the rupture during an earthquake may be an important parameter for earthquakes with magnitudes greater than 6.5-7.0. Algermissen and Perkins (1976) in their United States map use finite rupture lengths for large earthquakes in California and point sources elsewhere in the country. There is a question concerning the importance of fault rupture length in the eastern United States. Evernden (1975) believes that the length of faulting in the east is relatively short compared with earthquakes in California and Nevada. If this hypothesis is true, fault length would not be a significant factor in estimating ground motion for earthquakes in the east.

The fault length-magnitude relationship is usually taken to be of the form

$$\log_{10}L = c + d\,M \qquad (6)$$

where L is length, M is magnitude and c and d are constants. The program can consider the distribution of the rupture lengths to be lognormal, that is, the logarithm of the lengths are normally distributed, or use only the mean value of L given by expression (6). It does allow for uncertainties in strike of the faulting.

Attenuation: Attenuation of ground motion (however specified) from the earthquake source zones to any site of interest is one of the most troublesome parameters in probabilistic hazard analysis. McGuire (1976) assembled a representative list of attenuation relationships. It is included here in a somewhat abstracted and updated form to illustrate the diversity of attenuation relations that have been developed and which, for the most part are derived from approximately the same data sets (table 2). The mean attenuation of acceleration, velocity or displacement is commonly (but not exclusively) represented by an expression of the form

$$G = b_1 e^{b_2 M} R^{-b_3} \tag{7}$$

where G is acceleration, velocity or displacement that is supposed to occur at a site underlain by a "standard" material such as "hardrock", "stiff soil", etc. and R is defined as either the hypocentral or epicentral distance. Equation (7) is often modified by replacing R by R+r in order to limit ground motions at small distances. When the form shown in equation (7) is used to represent ground motions such as accelerations, velocity or displacement, the ground motion is assumed to be lognormally distributed. If ground motion is represented as Modified Mercalli intensity (MMI) an attenuation relationship of the form

$$I_R = C_1 + C_2 I_o + C_3 \ln (R + r_i) \tag{8}$$

is representative. I_o is the maximum MMI and R is the distance from the center of strong shaking to the site and r_i is a constant used to limit the values of I at small distances. MMI values are assumed to be normally distributed (rather than lognormally). The computer programs allow for the inclusion of uncertainty in attenuation.

Table 2
SELECTED ATTENUATION FUNCTIONS

Reference	Data Source	Distance Parameter	Dependent Variable	Equation	Standard Deviation
Blume (1966)	Southern California	Epicentral distance Δ (mi)	Peak ground acceleration a_g (g)	$a_g = \frac{a_o}{1+(\Delta/h)^2}$ where a_o is epicentral acceleration, h is focal depth	Not reported
Cloud and Perez (1971)	North and South America	Epicentral distance or distance to fault Δ (mi)	Maximum single component ground acceleration a_g (g)	$a_g = 3.0 - 2 \log (\Delta + 43)$ $a_g - 3.5 - 2 \log (\Delta = 80)$	Not reported
Cornell and Merz (1971)	Northeastern United States, rock sites	Epicentral distance Δ (mi)	Modified Mercalli Intensity	$I - 2.6 + I_e - 1.3 \ln \Delta$ $\Delta \geq 10$ mi	$\sigma_I = 0.2$
Donovan (1974)	San Fernando, all sites	Distance to energy center R (km)	Peak ground acceleration a_g (gals)	$a_g = 5.165 \times 10^5 (R+25)^{-2.04}$	$\sigma_{\ln a_g} = 0.481$
Donovan (1973)	Worldwide	Hypocentral distance, epicentral distance, or distance to fault R (km)	Peak ground acceleration a_g (gals)	$a_g = 1320\, e^{0.58M} (R+25)^{-1.52}$	$\sigma_{\ln a_g} = 0.84$
Gupta and Nuttli (1975)	Central United States	Epicentral distance to isoseismal Δ (km)	Modified Mercalli Intensity	$I = I_e + 3.7 - 0.0011\, \Delta - 2.7 \log \Delta$	Not reported
McGuire (1978)	West Coast of United States	Nearest point of rupture R (km)	Peak ground acceleration a_g (gals)	$\ln a_g = 3.4 + 0.89\, M - 1.17 \ln R$	$\sigma_{\log a_g} = 0.62$
Milne and Davenport (1969)	Western United States, Central America, Chile	Epicentral distance Δ (km)	Peak ground acceleration a_g (g)	$a_g = \frac{0.69\, e^{1.64M}}{1.1\, e^{1.1M} + \Delta^2}$	Not reported
Orphal and Laboud (1974)	California	Hypocentral distance R (km)	Peak ground acceleration a_g (g)	$a_g = 0.066 \times 10^{0.4M} R^{-1.39}$	See reference
	California and nuclear explosions	--------do----------	Peak ground velocity v_g (cm/sec)	$v_g = 0.726 \times 10^{0.52M} R^{-1.34}$	------do-----
	--------do---------	--------do----------	Peak ground displacement d_g (cm)	$d_g - 0.0471 \times 10^{0.57M} R^{-1.18}$	------do-----
Schnabel and Seed (1973)	Western United States	Distance to fault	Peak ground acceleration	Graphical	Not reported

For attenuation and for fault rupture length uncertainties, the assumption of a distribution (lognormal or normal), in addition to the mean and the standard deviation are sufficient to specify the uncertainty. Unfortunately, the means and standard deviations of some very useful attenuation relationships are not readily available because the attenuation curves have been published as empirical curves. An example is the acceleration attenuation curves of Schnabel and Seed (1973) which were used by Algermissen and Perkins (1976) for their United States map. If curves of this type are used, the empirical curve can be assumed to be the mean and the standard deviation approximated, using a standard deviation similar to one obtained by analytical curve fitting of similar data sets. This procedure is not very rigorous but it provides a useful estimate of the uncertainty in such attenuation curves. In the computer program used in this study, the attenuation distribution is truncated for values larger than two standard deviation.

Standard deviations of attenuation curves tend to be large for several reasons. All measurements of ground motion, whether instrumental or observational, are influenced by site amplification effects. Site amplification may generally be taken to mean the modification of ground motion characteristics caused by the properties and layering of material for roughly the first hundred meters beneath a site. These effects are difficult to remove from attenuation data because normally there are insufficient geotechnical data available on the properties of the soil and rock underlying the sites at which strong motion is recorded to accurately estimate the site effect. In addition, radiation of seismic energy from a fault results in a complicated pattern of ground motion which contribute to large standard deviations for attenuation data when ground motion attenuation is approximated by relatively simple attenuation relations such as those in Table 2.

Site Amplification: The response of materials beneath a site of interest greatly affects the resulting ground motions at the site. As already discussed, this effect is not normally taken into account in regional hazard mapping. It should be clearly understood that site effects may be large and must be evaluated at some stage of the hazard evaluation.

Probabilistic Models

Selected seismic source zones of Algermissen and Perkins (1976) are used (fig. 2) to investigate the levels of ground motion that would be obtained throughout the United States if the general approach to hazard analyses used by them for an exposure time of 50 years is extended to very long exposure times (of the order of 100,000 years). The importance of parameter variability in probabilistic hazard analysis is given particular attention. Simple, single fault models are used to estimate long term hazard in areas where this approach seemed appropriate. In all cases the temporal model of earthquake occurrence is Poissonian, there being no particularly reliable data available that would warrant the use of a time dependent model. The Algermissen-Perkins seismic source zones are used so that the ground motion levels obtained for long exposure times could be compared with their hazard map of the United States. The seismic source zones used are shown in figures 1 and 2 together with the locations considered for other special studies.

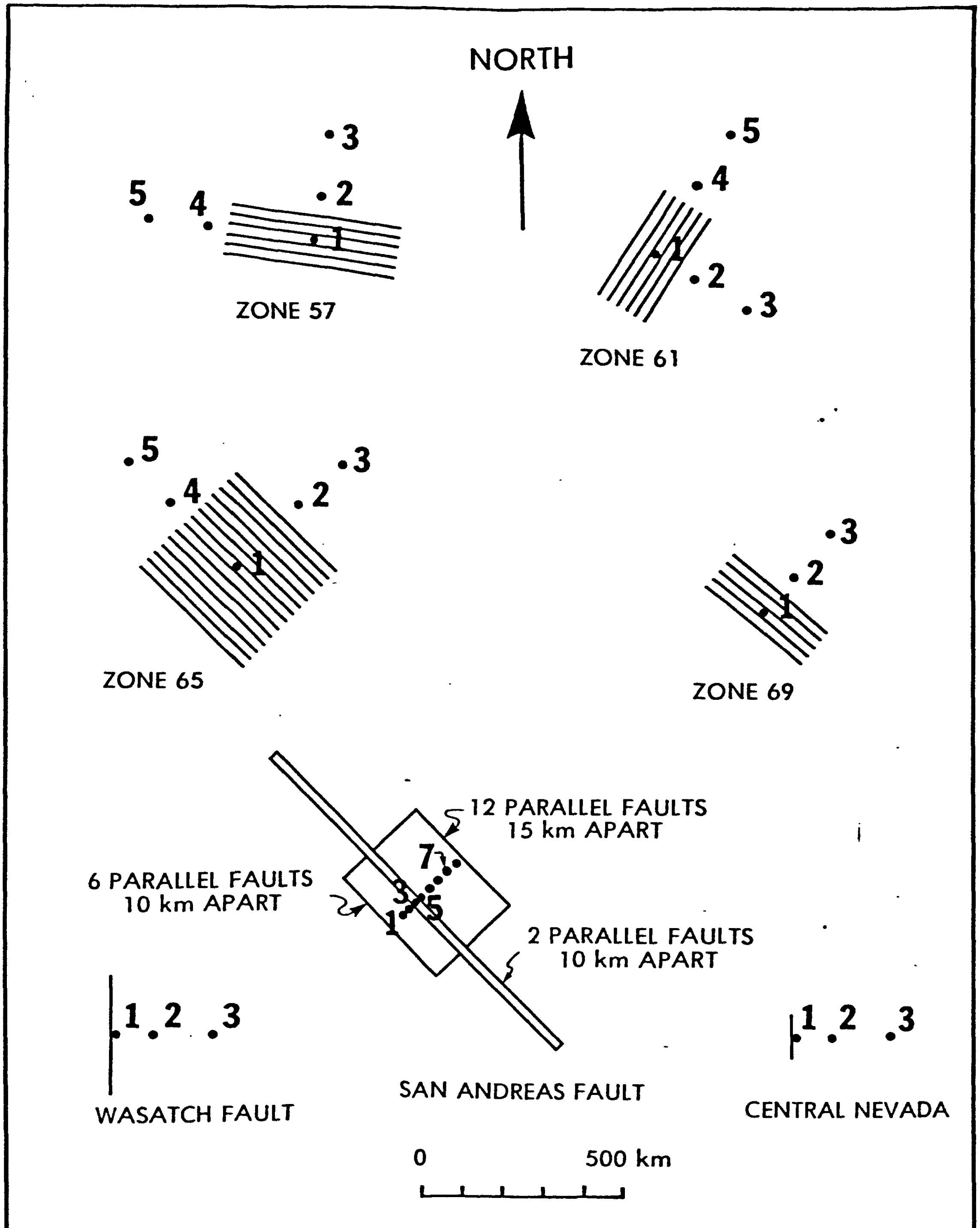

Figure 3.--Geometry of faults used to model the seismic source areas and other areas shown in figures 1 and 2. Additional data on the models are displayed in Table 3. The faults are oriented correctly geographically. The points and numbers refer to sites at which the hazard was computed. The faults shown for zones 57, 61, and 65 model these zones quite accurately; because of the complicated geometry of zone 69, only the central portion of the zone is modeled by the faults shown.

ESTIMATION OF LONG TERM HAZARD

Probabilistic estimates of acceleration in rock for exposure times of from 10 to 100,000 years (return periods of from 95 to 950,000 years) were computed both with and without attenuation and fault rupture length variability for eight different geographical areas of the United States. The geographical areas considered and the models used for the hazard calculations are listed in Table 3 and shown in figures 1 and 2. The geometry of the faults used for modeling are shown in figure 4. Three acceleration attenuation relations were used: (1) the empirical curves of Schnabel and Seed (1973); (2) the Schnabel and Seed curves as modified for the eastern United States by Algermissen and Perkins (1976); and (3) $\ln a_g = 3.4 + 0.89 M - 1.17 \ln R_c$ (McGuire, 1978) where a_g is acceleration in cm/sec^2, M is magnitude and R_c is the distance from the site to the nearest point of fault rupture. The attenuation curves are shown in figure 5. The standard deviation for acceleration was taken to be σ_ϕ=.62 and the standard deviation for fault rupture length was taken as σ_L=.52 (McGuire, 1979).

Each of the seismic areas modeled is discussed individually.

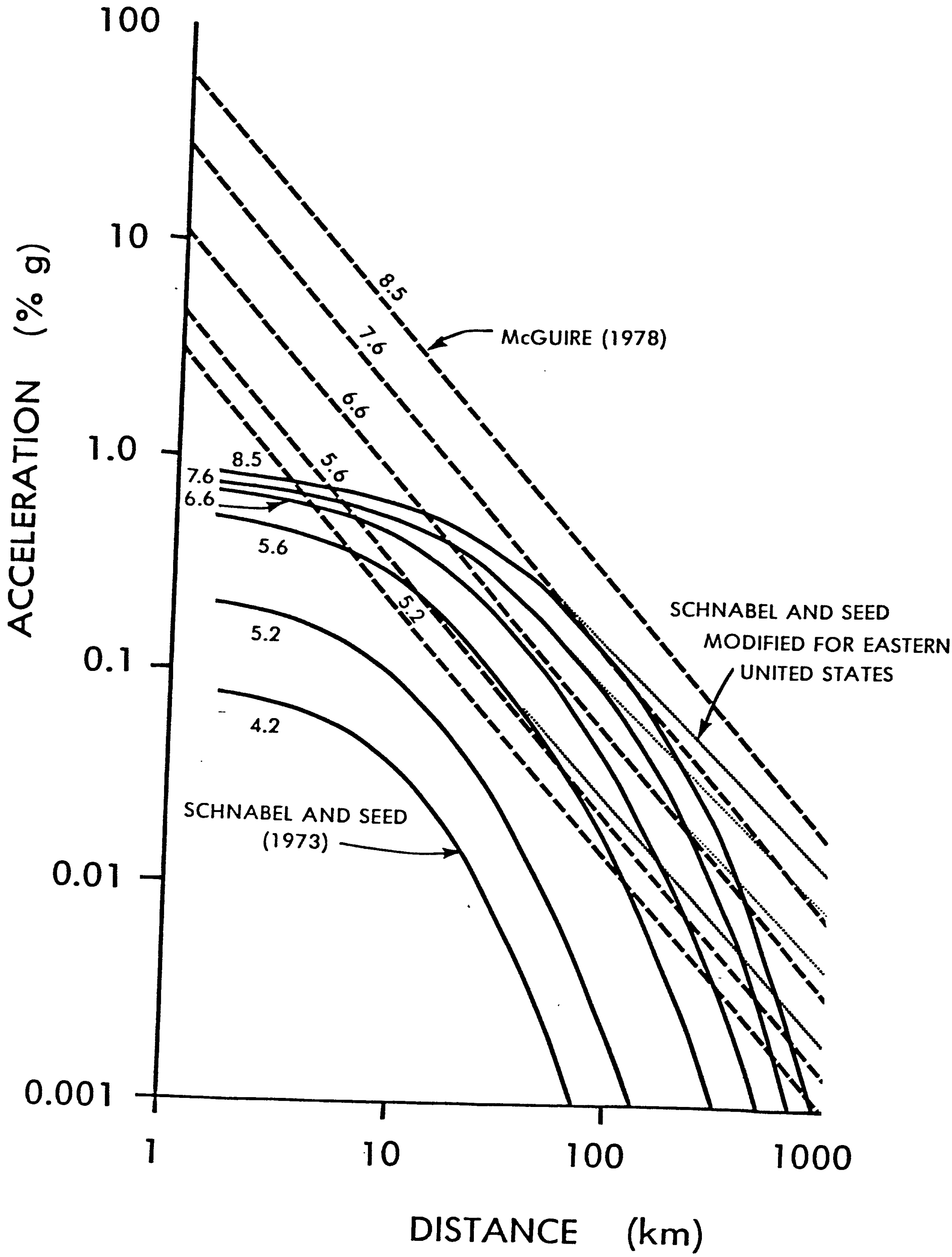

Figure 4.--Attenuation curves used in this study.

Seismic Source Zone 57

Zone 57 is a zone of low seismicity (see table 3) in east Texas and western Louisiana. Examination of figures 1 and 2 shows that the level of historical seismicity in the zone was insufficient to produce accelerations equal to or greater than 0.04 g and thus the effects of the zone do not result in any contours on the Algermissen-Perkins map. The accelerations at site 1, at the center of zone 57, and site 2, 50 km outside the zone (see figs. 1, 2, and 4), for exposure times from 10 to 100,000 years are shown in figure 6. The probability that the acceleration will not be exceeded is 90 percent. The Schnabel and Seed (1973) attenuation curves modified for the eastern United States (fig. 5) were used and accelerations were computed both with and without parameter variability included. The four curves in figure 6 show several interesting properties of seismic hazard. Note that the acceleration curves for sites 1 and 2 computed without attenuation and fault rupture variability included approach constant values of acceleration for exposure times of more than about 10,000 years (curves 2 and 4, fig. 6). Accelerations at site 2 (outside the source area) approach a relatively constant value at slightly lesser exposure times than site 1 (inside the source area).

The curves computed with variability do not approach a limiting value of ground motion even for an exposure time of 100,000 years. For an exposure time of 100,000 years the acceleration at site 1 computed including parameter variability is 3.9 larger than the acceleration computed when parameter varaibility is not included (.97 g compared with .25 g). The conclusion is that even for a very minor zone of seismicity and the magnitude distribution bounded at 5.8, accelerations at sites within the zone reach large values when attenuation and fault rupture length variability are included in the hazard calculation.

Table 3

Geographical Areas, Models and Parameters Selected for Long-Term Hazard Estimation

Area and Calculation Numbers[1]	Model	M_{mx}	ϕ^2	β^3	Attenuation relation	$\sigma_a{}^4$	Fault relation	$\sigma_L{}^5$
ZONE 57 (Texas-Louisianna)								
1.	6 parallel faults, 25 km apart and each 425 km in length	5.8	0.0183	2.110	Schnabel & Seed (1973)	0.62	Mark (1977)	0.52
2.	"	"	"	"	Schnabel & Seed (1973) modified	"	"	"
3.	"	"	"	"	McGuire (1978)	"	"	"
ZONE 61 (South-East Missouri)								
1.	6 parallel faults, 25 km apart and each 300 km in length	7.5	0.2050	1.99	Schnabel & Seed (1973)	0.62	Mark (19)	0.52
2.	"	"	"	"	Schnabel & Seed (1973) modified	"	"	"
3.	"	"	"	"	McGuire (1978)	"	"	"
ZONE 65 (So. Carolina)								
1.	14 parallel faults, 25 km apart and each 350 km in length	7.5	0.0260	1.266	................Same cases as for ZONE 61...............			
2.	"	"	"			"		
3.	"	"	"			"		

Table 3--(Continued)

Area and Calculation Numbers[1]	Model	M_{mx}	ϕ^2	β^3	Attenuation relation	$\sigma_a{}^4$	Fault relation	$\sigma_L{}^5$
ZONE 69 (New England)								
1.	5 parallel faults, 25 km apart and each 200 km in length	7.0	0.0316	2.280	................Same Cases as ZONE 61................			
NEW JERSEY								
1.	Ramapo fault modeled as a single fault 120 km in length	5.5	0.0600	1.680	Schnabel & Seed (1973) modified	0.62	Mark (1977	0.52
2.	"	"	"	"	McGuire (1978)	"	"	"
3.	"	7.5	"	"	Schnabel & Seed (1973) modified	"	"	"
4.	"	"	"	"	McGuire (1978)	"	"	"
UTAH								
1.	Wasatch fault modeled as a single fault 350 km in length	7.5	0.2381	0.9609	Schnabel & Seed (1973)	0.62	Mark (1977)	0.52
2.	"	"	"	"	McGuire (1978)	"	"	"
CENTRAL NEVADA								
1.	Single fault, 120 km in length	7.5	0.2282	2.260	Schnabel & Seed (1973)	0.62	Mark (1977)	0.52
2.	"	"	"	"	McGuire (1978)	"	"	"

Table 3--(Continued)

CENTRAL CALIFORNIA								
1.	San Andreas fault and adjacent seismicity	8.5	0.0814 1.0251 0.1195 0.0098	1.727 1.535 2.034 1.880	Schnabel & Seed (1973)	1.62	Mark (1977)	0.52
		(ϕ's and β's given for zones from west to east)						

[1]"Zones" refer to seismic source zones used by Algermissen and Perkins (1976). The zones used are shown hachured in figure 2.

[2]The number of earthquakes per year per fault greater than magnitude 4.

[3]β = (ln 10)(b) where log N = a-b M (Gutenberg & Richter, 1956). N is the number of earthquakes equal to or greater than M (see page 10).

[4]The standard deviation used for acceleration attenuation. For the Schnabel and Seed curves, $\sigma_{\underline{a}}$ is only an estimate.

[5]The standard deviation used for fault rupture length.

[6]"Schnabel and Seed (1973) modified" means the attenuation curves for acceleration developed by Algermissen and Perkins (1976) for use in the eastern United States".

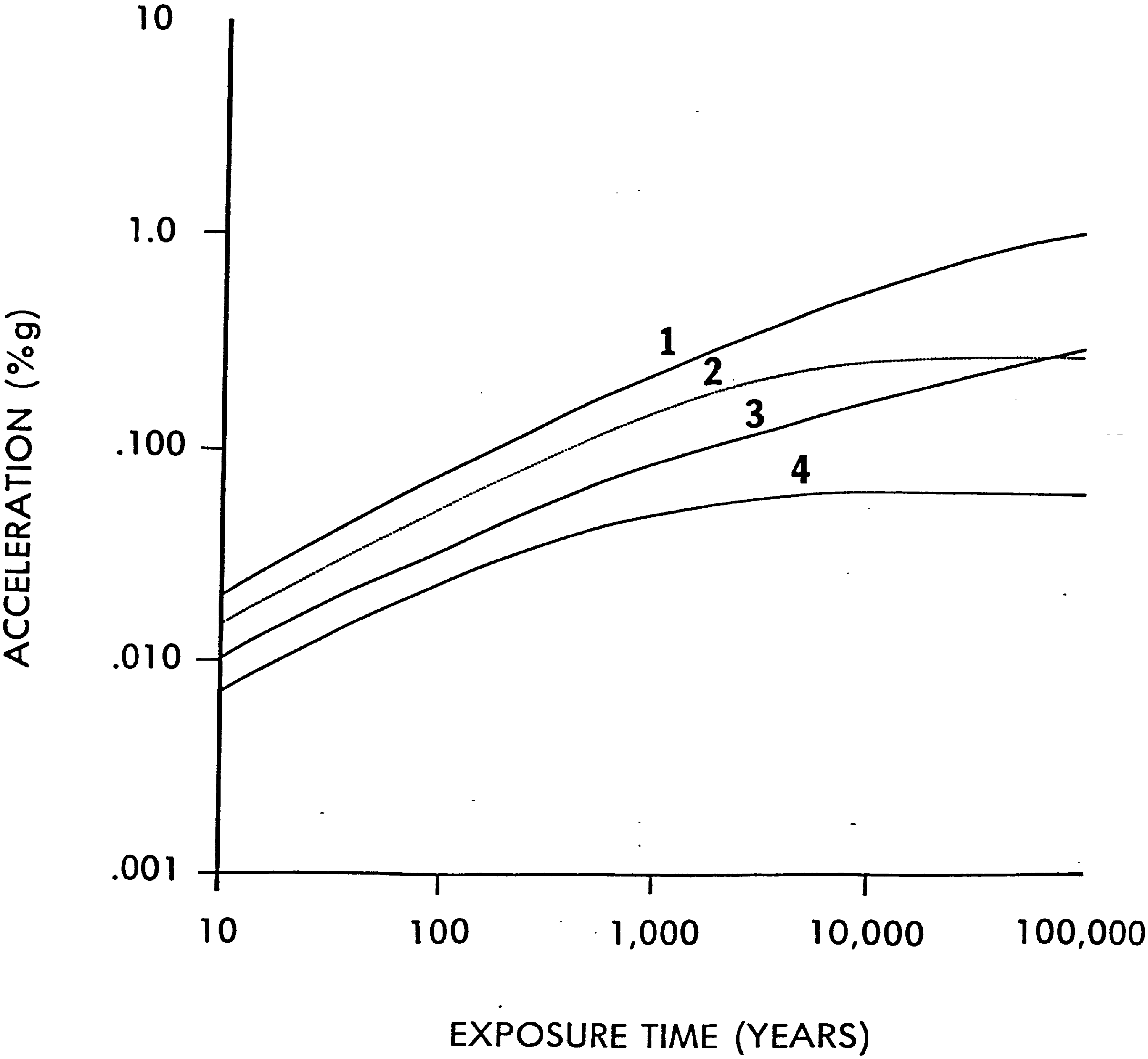

Figure 5.--Accleration in rock at sites 1 and 2; seismic source zone 57, 90 percent probability of not being exceeded, Schnabel and Seed (1973) attenuation modified for the eastern United States. Curves 1 and 2: Hazard at site 1 with and without parameter uncertainty. Curves 3 and 4: Hazard at site 2 with and without parameter uncertainty.

Seismic Source Zone 61

The great seismic events of 1811 and 1812 occurred within zone 61. The zone is one of current moderate seismicity. Figure 7 shows the hazard at five sites using the Schnabel and Seed (1973) attenuation curves modified for use in the eastern United States. The hazard at site 2 is also shown with parameter variability included using both the Schnabel and Seed eastern curves and the McGuire (1978) curves. The two curves (2a and 2b in fig. 6) are quite similar. This similarity does not necessarily hold for all sites. Site 2 is in a distance range from the seismic source in which the two different attenuation curves (see fig. 5) produce roughly comparable values of acceleration. For sites close to the source, the McGuire curves yield much larger accelerations. Note that for site 2 (outside the source zone) the accelerations (with variability included) for exposure time greater than about 3,000 years are greater than the acceleration for site 1 (inside the source zone) when parameter variability is not included. Curves 4 and 5 in figure 7 show the ground motion at two sites in line with the strike of the faults. Sites 2 and 4 are the same distance from faulting, and sites 3 and 5 are the same distance from faulting, but the geometrical relation of sites 4 and 5 to the faults is different than sites 2 and 3. Sites 4 and 5 would have considerably lower values of acceleration if a point source model for faulting had been used for probabilistic hazard calculations.

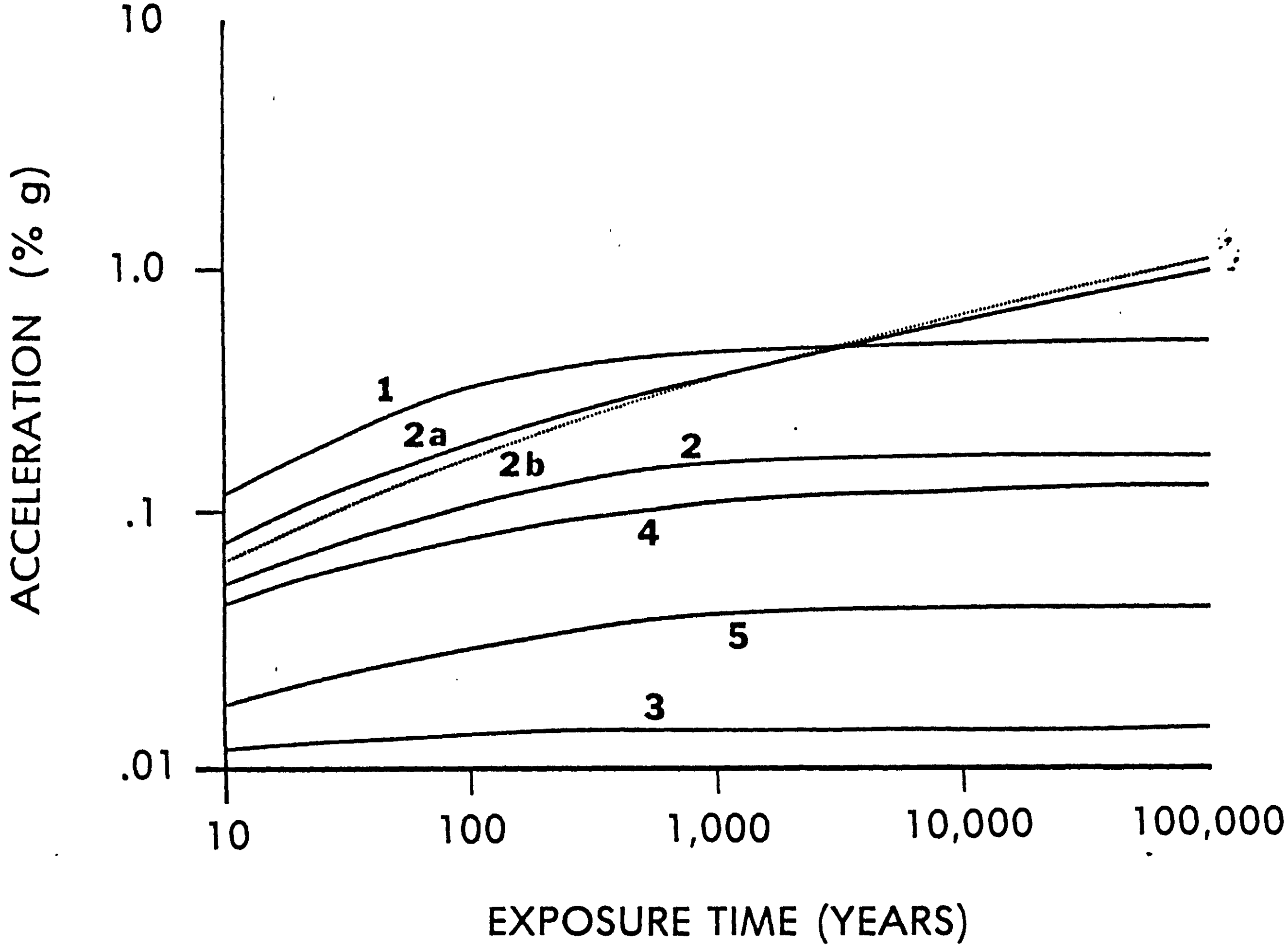

Figure 6.--Acceleration in rock, seismic source zone 61, 90 percent probability of not being exceeded; exposure times from 10 to 100,000 years. Curves 1 and 2: Hazard at site 1 and 2, Schnabel and Seed (1973) attenuation modified for the eastern United States, no parameter uncertainty. Curve 2a: Site 2, Schnabel and Seed (1973) attenuation modified for the eastern United States, parameter uncertainty included. Curve 2b: Site 2, McGuire (1978) attenuation, parameter uncertainty included. Curves 3, 4, and 5: Hazard at sites 3, 4, and 5, Schnabel and Seed (1973) attenuation modified for the eastern United States, no parameter uncertainty.

Seismic Source Zones 65 and 69

The Charleston, South Carolina earthquake of 1886 occurred within zone 65. The area has been one of minor seismicity since that time. Zone 69 is a zone of moderate seismicity across New England together with a portion of the seismically active St. Lawrence Valley and eastern Canada. Figure 8 shows the acceleration at site 2 with and without parameter uncertainty. Zones 65 and 69 have similar characteristics and similar seismic hazards associated with them.

Ramapo Fault

The Ramapo fault, which bounds the Triassic-Jurassic Newark graben has recently been discussed in some detail by Aggarawal and Sykes (1978). Using their data for ϕ and β (table 3), the hazard associated with the Ramapo fault was computed at distances of 12.5, 50 and 100 km from the fault on a line perpendicular to the fault. Two separate assumptions were made about the maximum magnitude that might occur on the fault: (1) a magnitude of 5.5 which is consistant with the known historical maximum magnitude on the fault; and (2) a magnitude of 7.5 which might be regarded as a reasonable upper bound for earthquakes in this area of the country. Figure 9 shows accelerations plotted along the profile using a variety of assumptions. The curves show some additional important features of probabilistic hazard calculations. The 50 year exposure time hazard profiles are consistent with values on the Algermissen and Perkins (1976) United States hazard map. Different attenuation curves give reasonably compatible results when parameter uncertainty is included in the computation. If parameter uncertainty is included and it is assumed that a magnitude 7.5 fault can be generated on the Ramapo fault, the long term (100,000 year exposure time) hazard becomes very large at the fault, although it drops off rapidly away from the fault.

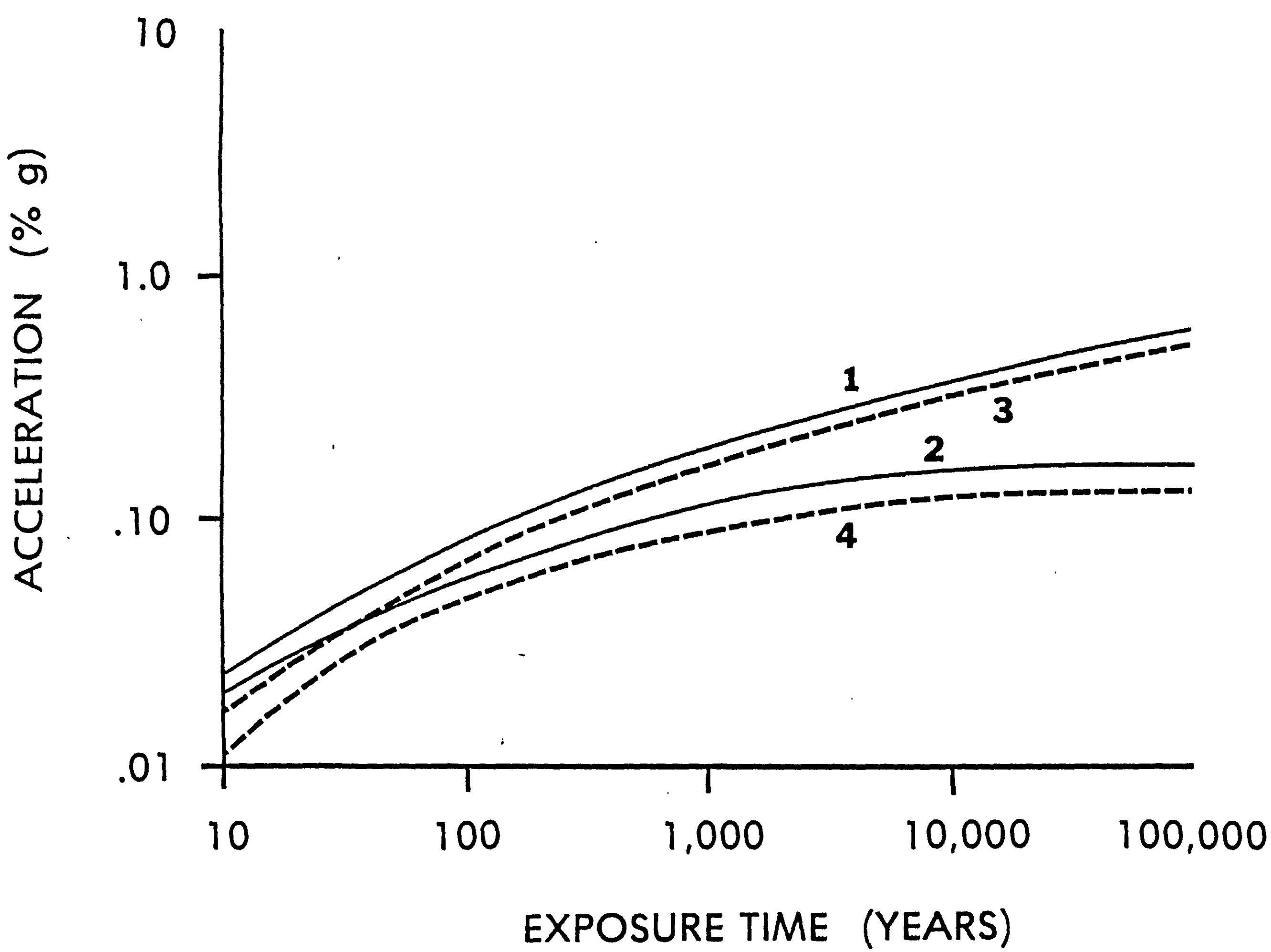

Figure 7.--Acceleration in rock at site 2, seismic source zones 65 and 69; 90 percent probability of not being exceeded, exposure times from 10 to 100,000 years. Curves 1 and 2 are computed with and without parameter uncertainty at site 2 in zone 65; curves 3 and 4 are computed with and without parameter uncertainty at site 2 in zone 69. All compulations made with Schnabel and Seed (1973) attenuation curves modified for the eastern United States.

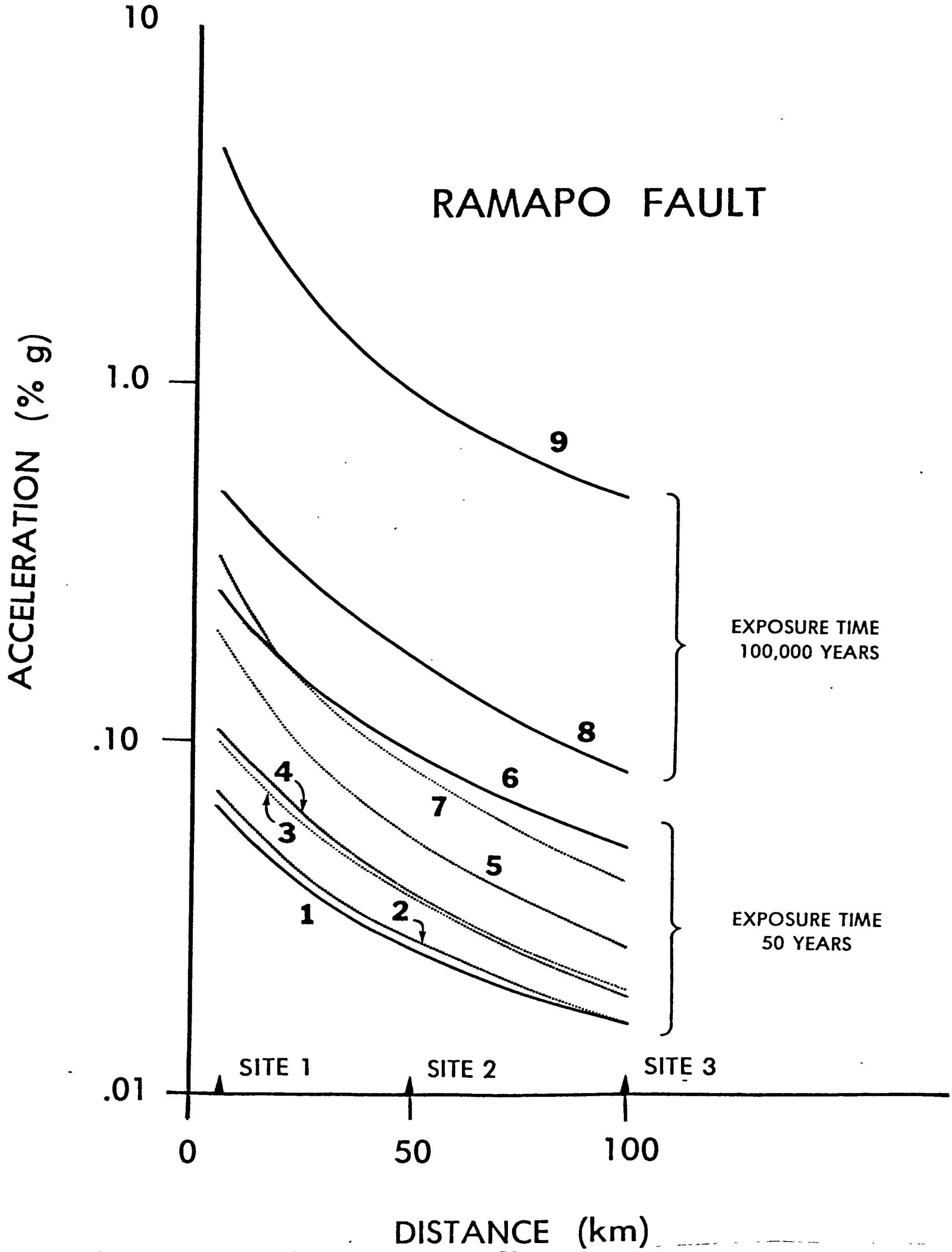

Figure 8.--Acceleration in rock at three sites along a profile perpendicular to the Ramapo fault. 90 percent probability of not being exceeded in 50 years. Curves 1, 2, 3, 4, 6, 8, and 9 are computed using the Schnabel and Seed (1973) attenuation curves modified for use in the eastern United States. Curves 5 and 7 are computed using McGuire's (1978) attenuation. Curves 1, 5, and 8 do not include parameter uncertainty; curve 2 includes only fault rupture length uncertainty; curve 3 includes only attenuation uncertainty; curves 4, 6, 7, and 9 include both fault rupture length and attenuation uncertainty. Curves 1 through 5 computed assuming a maximum magnitude of 5.5. Curves 6, 7, 8, and 9 computed assuming a maximum magnitude of 7.5.

Wasatch Fault, Central Nevada and the San Andreas Fault

Figure 9 illustrates the change of hazard with exposure time for three additional seismotectonic settings: (1) the Wasatch fault; (2) a hypothetical fault in central Nevada; and (3) the San Andreas fault in central California. Values of ϕ and β on the Wasatch fault were assigned taking into account both historical seismicity and recent information concerning Holocene fault slip (Bucknam, Algermissen, and Anderson, 1979). In Nevada, ϕ and β were derived from the data of Algermissen and Perkins (1976) for their seismic source zone 9 (fig. 2).

It is interesting to note that if an alternate procedure is used and the seismic activity ϕ and the rate β are obtained from a consideration of Holocene fault slip rates found over a broad area of Nevada (Wallace, 1978) combined with an analysis of historical seismicity over the same broad area, it is possible to obtain a value of ϕ for this broad area that is quite similar to the value of ϕ determined from a rather short historical record of seismic activity on the Ramapo fault. If this alternate approach is correct the conclusion would be that over a very restricted area in northern New Jersey and southern New York the seismic hazard would be approximately the same as over large portions of Nevada and possibly Utah. The conclusion depends heavily on the assumption that it is possible for an earthquake as large as magnitude 7.5 to occur on the Ramapo fault.

The San Andreas fault was modeled by making use of the statistical data on California earthquakes used by Algermissen and Perkins (1976).

Figure 10 shows a comparison of the hazard computed for the three areas computed for exposure times from 10 to 100,000 years. The behavior of the acceleration values for long exposure times is approximately the same as for the zones in the midwest and eastern part of the country with the exception that the hazard curves approach more or less constant values of acceleration at shorter exposure times (100-200 years) than for areas in the eastern United States. This occurs because of the somewhat higher levels of seismic activity in the western part of the country.

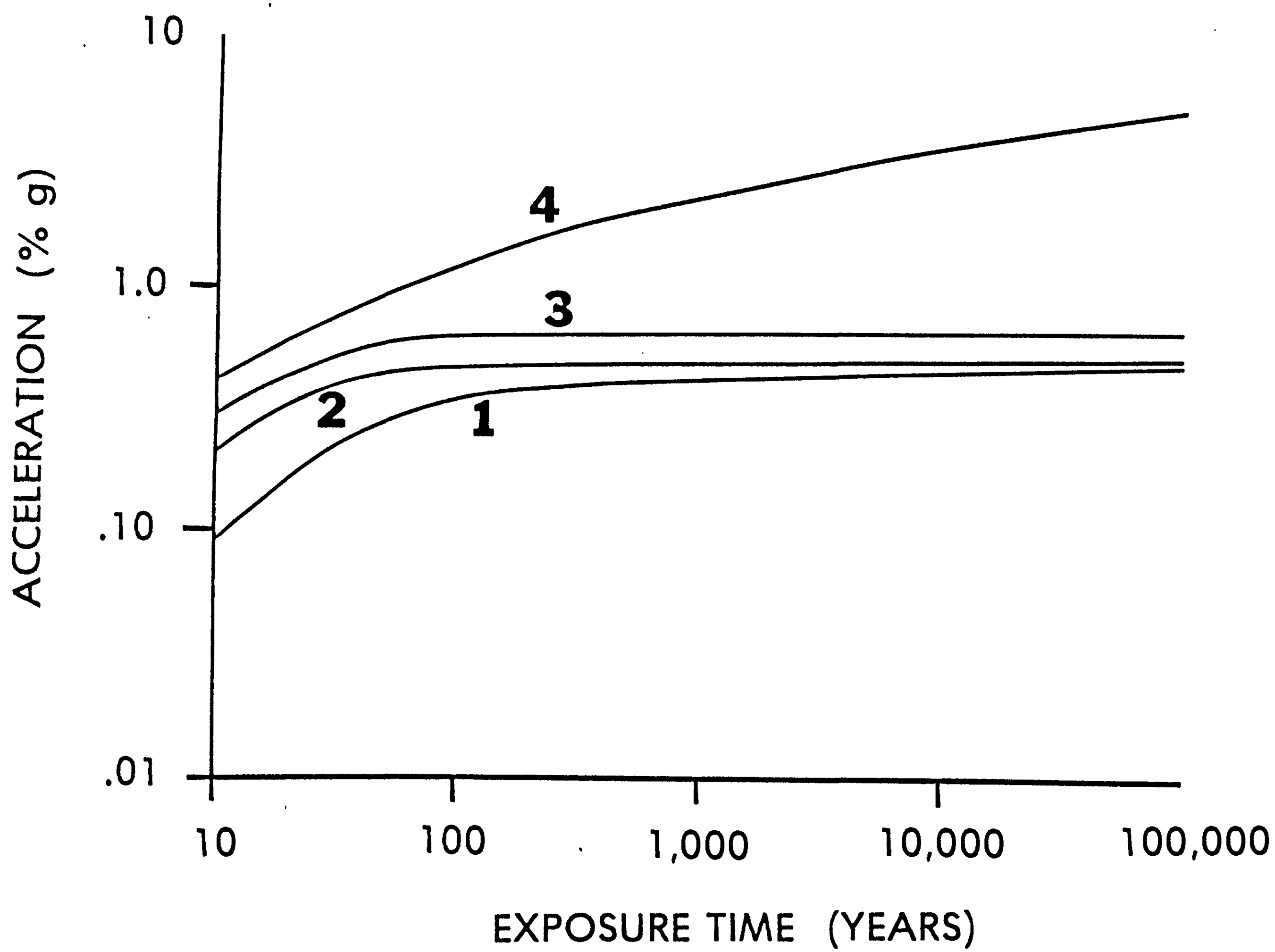

Figure 9.--Accelerations in rock for three western seismic areas. 90 percent probability of not being exceeded in 50 years. Curve 1 is for site 1 on a fault in central Nevada; curve 2 is for site 1 on the Wasatch fault; curve 3 and 4 for site 3 on the San Andreas fault; curves 1, 2, and 3 are computed without parameter uncertainty; curve 4 includes uncertainty in both fault rupture length and attenuation.

DISCUSSION

The data assembled in Tables 4 and 5 is an effort to summarize the behavior of the acceleration hazard computed for eight models and a wide range of exposure times. Table 4 contains a comparison of maximum accelerations computed for all of the models. The acceleration values given in the table are the 50 year exposure time accelerations at the 90 percent probability level and the ratio of the 1,000 and 100,000 year exposure time accelerations to the 50 year values. These values are all given both with and without parameter uncertainty. Table 5 contains the same comparisons for accelerations at sites outside each seismic source zone or, in the case of fault models, at a distance of 100 km from the fault. The interpretation of the data in the two tables is complicated by several factors. For example, ratio of the 1,000 year hazard to the 50 year hazard appears to be a much more stable quantity than the ratio of the 100,000 year hazard to the 50 year hazard. This result is due in part to the difficult problem of actually computing the probabilistic ground motion for very long exposure time. Several changes were made in the available computer program during the course of this study to improve the resolution of the program for long exposure times but additional program refinements are required. In addition, accelerations at long exposure times computed outside the source areas or at some distance from the fault models are more stable than those computed for sites close to the fault model or within the source zone. This may be in part related to the problem of interpolating the attenuation tables used for large accelerations at short distances. Despite the computational problems, some trends emerge.

It is clear from the results obtained from all of the models that accelerations approach a constant value for much shorter exposure times when parameter variability is not included in the hazard computation. To illustrate this result in a summary manner, accelerations were computed for an idealized model: two parallel faults, each 300 km long, separated by 20 km. The value of β was set at 2.0 and the maximum magnitude was taken to be 8.5. The rate of earthquake activity, ϕ, was varied from .001 to 1.5 earthquakes greater than magnitude 4.0 per year per fault. The accelerations obtained with and without including parameter uncertainty for a site midway between the two faults are shown in figure 11 and 12. The accelerations without parameter variability are shown in figure 12. The limiting values of acceleration (for exposure times greater than 100,000 years) for the set of curves that do not include parameter uncertainty (figure 12) are nearly an order of magnitude less than those that include parameter uncertainty (figure 11). For a site 110 km from the site shown in figures 11 and 12 and perpendicular to the faults the limiting values of acceleration for long exposure times (greater than 100,000 years) are much less. For ϕ=.5, the acceleration for an exposure time of 500,000 years with parameter uncertainty included is about 0.6 g; without parameter uncertainty, the acceleration is about 0.1 g. Thus, for sites removed a reasonable distance from earthquake sources, the accelerations are much lower.

Table 4

COMPARISON AMONG MAXIMUM ACCELERATIONS, FOR AN EXTREME PROBABILITY OF 90 PERCENT FOR VARIOUS SOURCE ZONES AND FAULT MODELS FOR SELECTED EXPOSURE TIMES*

	No Parameter Uncertainty			Parameter Uncertainty Included		
Model	Acceleration (%g) in a 50 year exposure time	$\frac{H_{1,000}}{H_{50}}$**	$\frac{H_{100,000}}{H_{50}}$	Acceleration (%g) in a 50 year exposure time, parameter	$\frac{H_{1,000}}{H_{50}}$	$\frac{H_{100,000}}{H_{50}}$
Zone 57	.03	4.1	6.7	.05	4.2	17.6
Zone 61	.26	1.8	1.8	.44	2.7	10.9
Zone 65	.09	3.9	5.5	.14	3.4	25.0
Zone 69	.08	4.0	5.5	.11	4.8	19.3
Ramapo fault (M_{mx}=5.5)	.07	2.0	2.0	.11	2.9	7.6
Wasatch fault	.44	1.1	1.1	.72	6.5	5.0
Central Nevada fault	.30	1.7	1.7	.37	3.1	12.9
San Andreas fault	.60	1.2	1.2	.98	4.0	5.1

*Accelerations computed at site 3 for San Andreas fault model and site 1 for all other faults and models (see figure 3).

**Means the hazard (acceleration in 1,000 years divided by the acceleration in 50 years); analgous meaning for columnar headed $\frac{H_{100,000}}{H_{50}}$

Table 5
COMPARISON AMONG ACCLERATIONS, FOR AN EXTREME PROBABILITY OF 90 PERCENT FOR SITES 100 KMS FROM THE CENTER OF VARIOUS SOURCE ZONES AND FAULT MODELS*

	No Parameter Uncertainty			Parameter Uncertainty Included		
Model	Acceleration (%g) in a 50 year exposure time	$\frac{H_{1,000}}{H_{50}}$**	$\frac{H_{100,000}}{H_{50}}$	Acceleration (%g) in a 50 year exposure time	$\frac{H_{1,000}}{H_{50}}$	$\frac{H_{100,000}}{H_{50}}$
Zone 57	.02	2.8	4.3	.02	3.5	11.9
Zone 61	.09	1.9	2.0	.15	2.5	6.4
Zone 65	.05	2.3	3.7	.06	3.2	10.3
Zone 69	.04	2.4	3.7	.05	3.7	11.7
Ramapo fault (M_{mx}=5.5)	.03	1.3	1.3	.04	2.6	6.8
Wasatch fault	.05	1.1	1.1	.07	2.5	6.1
Central Nevada fault	.02	2.4	2.4	.03	3.3	10.0
San Andreas fault	.21	2.1	2.3	.35	2.7	13.0

*Accelerations computed at site 5 for San Andreas fault model and site 2 for all other faults and models (see figure 3), Schnabel and Seed (1973) attenuation curves.

**Means the hazard (acceleration in 1,000 years divided by the acceleration in 50 years); analgous meaning for columns headed $\frac{H_{100,000}}{H_{50}}$

For consideration of the earthquake ground shaking hazard for long exposure times, how suitable are probabilistic estimates obtained without explicit inclusion of parameter uncertainties? McGuire (1979) has pointed out that for best (mean value) estimates of the seismic hazard, inclusion of uncertainties in most parameters is unnecessary. This is particularly true for sites specially selected for storage of dangerous material. For selected sites, it is possible to reduce the uncertainty associated with attenuation of ground motion by special site studies. Careful geological investigations can reduce the possibility of a site being chosen near an "active" fault system, however "active" is defined.

Another consideration is the suitability of peak acceleration as a measure of the ground shaking hazard at a site. The ground motion parameters needed to specify, in detail, the hazard associated with a waste disposal site cannot be defined unless the specific characteristics of the disposal facility are known. However, McGuire and Hanks (1979) have shown that RMS acceleration is proportional to peak acceleration and consequently it appears that peak acceleration, if not an optimal parameter for long term hazard assessment, is at least suitable for this preliminary study.

CONCLUSIONS

This report is concerned with only one small aspect of the estimation of ground motion over long time intervals namely, an evaluation of the usefulness of conventional methods of probabilistic hazard analysis to long term hazard estimation. While there are many aspects of the problem that will require additional study, some conclusions are possible.

1. The computer program used in this study was designed to compute probabilistic ground motions for relatively short exposure times, of the order of less than a few hundred years. While a number of modifications have been made to the program to extend the exposure time so that estimates of ground motion can be made for much longer exposure times, the program may still require additional refinements.

2. Estimates of ground acceleration do not approach limiting values of acceleration for the range of seismic activity present in the contiguous United States for exposure times of at least 100,000 years for sites close to seismic sources.

3. The acceleration at sites of the order of 100 or more kilometers from known seismic sources, except the most active sources, show only moderate ground motion. In addition, ground motion in the distance range of 100-200 km from known sources is more reliably estimated that at close distances because the available attenuation data was recorded largely in this distance range.

4. This report has been based in an analysis of acceleration in rock using only three of a large number of possible interpretation of available strong motion acceleration data. The three acceleration attenuation relations used (Schnabel and Seed, 1973) modified for the eastern United States and McGuire (1978) are representative of the data but it should be understood that other interpretations of the acceleration data are possible which might result in larger computed ground motions.

5. Characteristics of strong ground motion other than accelerations (velocity, displacement, duration, spectral response, etc.) have not been considered. Acceleration may not be the most appropriate characteristic of ground motion to investigate, depending upon the engineering design of the disposal facility.

6. Reduction of the dispersion of attenuation data and fault rupture length data will obviously result in better estimates of long term hazard but the prospects for reducing this dispersion in the next few years is not encouraging.

7. The acceleration values computed in this report using the Schnabel and Seed (1973) attenuation curves probably represent the minimum acceleration practical for planning long term facilities for the following reasons. First, the curves are interpretative, high frequency peaks having been smoothed out of the data, and second, the accelerations are in rock. Few surface facilities are in rock and accelerations in other materials may be higher or lower.

8. The probability of faulting has not been considered for this report but reasonable estimates of the probability of faulting within a defined area of interest can be made if reliable data are available on the age and distribution of faulting.

9. For shallow burial facilities within the depth range of materials with liquefaction potential, liquefaction should be considered. Recent earthquake experience has shown that materials can liquefy at rather low levels of ground motion (of the order of 0.1 g).

RECOMMENDATIONS

Areas of the country with known moderate or high historical seismicity will all be exposed to rather large ground accelerations for time periods greater than a few thousand years. If seismic ground shaking is deemed an important factor in the design of disposal facilities, waste disposal sites should be sought out in regions of the country judged to be seismically stable after a consideration of recent studies of regional seismotectonics together with a careful review of the seismic history. Such a regional investigation of seismogenic zones coupled with a review of the historical seismicity is currently being undertaken in the Office of Earthquake Studies as a preliminary step in the development of a new, improved probabilistic hazard map of the country.

ACKNOWLEDGEMENTS

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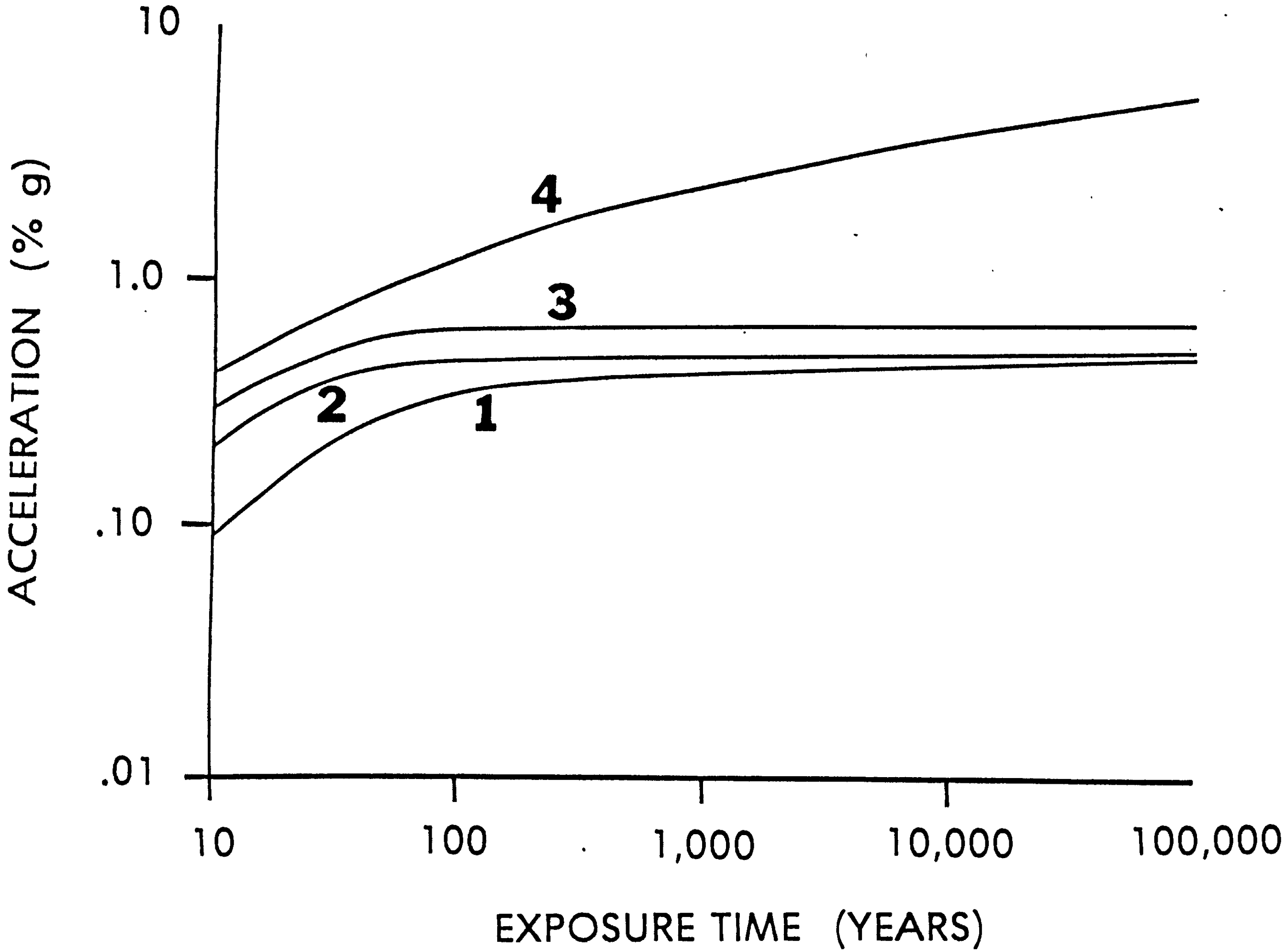

Figure 10.--Accelerations in rock for three western seismic areas. 90 percent probability of not being exceeded in 50 years.- Curve 1 is for site 1 on a fault in central Nevada; curve 2 is for site 1 on the Wasatch fault; curve 3 and 4 for site 3 on the San Andreas fault; curves 1, 2, and 3 are computed without parameter uncertainty; curve 4 includes uncertainty in both fault rupture length and attenuation.

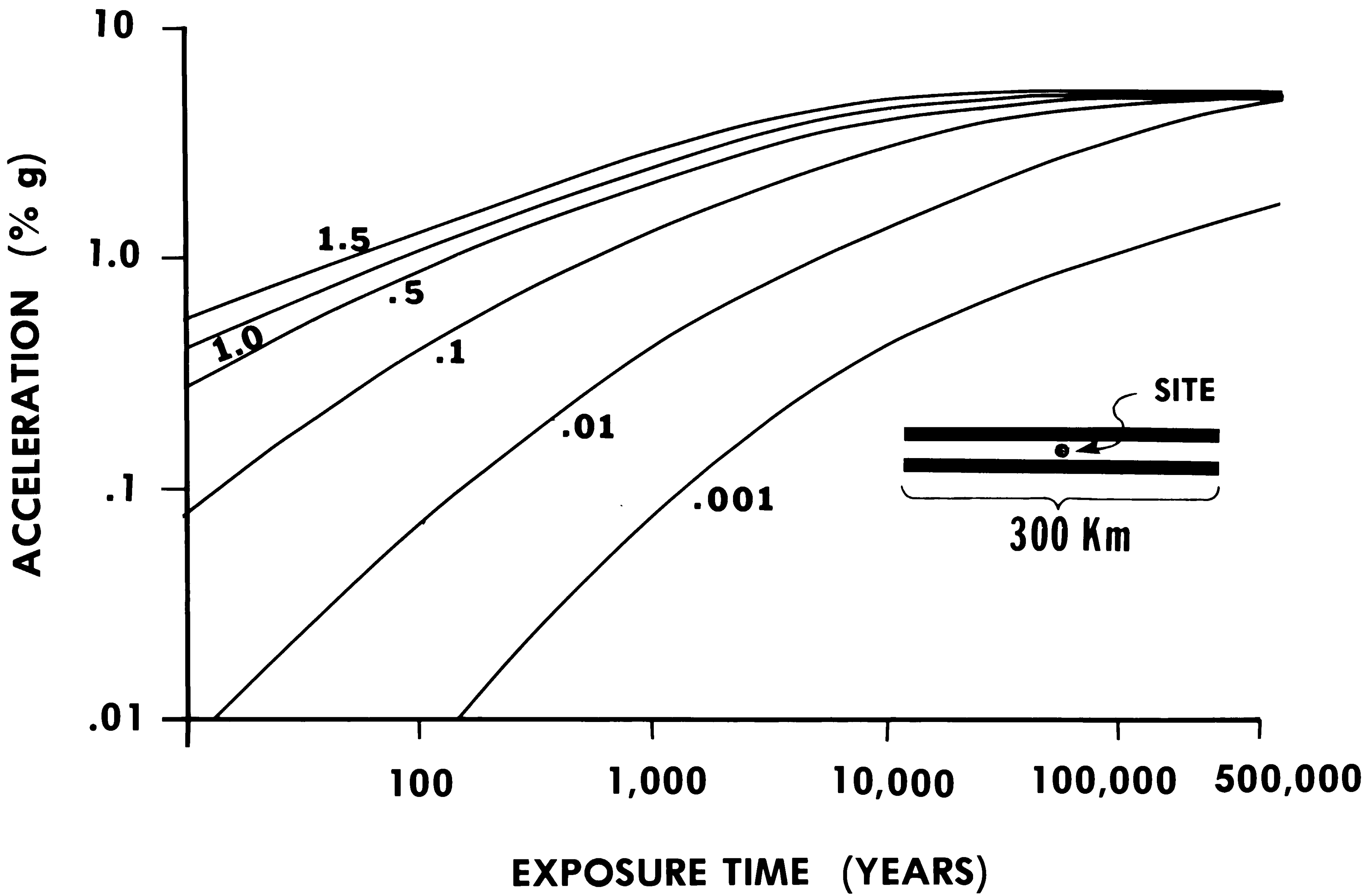

Figure 11.--Accelerations in rock at a site between two parallel faults. Schnabel and Seed (1973) attenuation curves, $\beta = 2.0$, maximum magnitude 8.5, $\sigma_a = 0.6$, $\sigma_L = 0.5$, were used in the calculations. The curves are for various levels of seismic activity ϕ, as labeled. ϕ equals the number of earthquakes greater than magnitude 4 per year per fault.

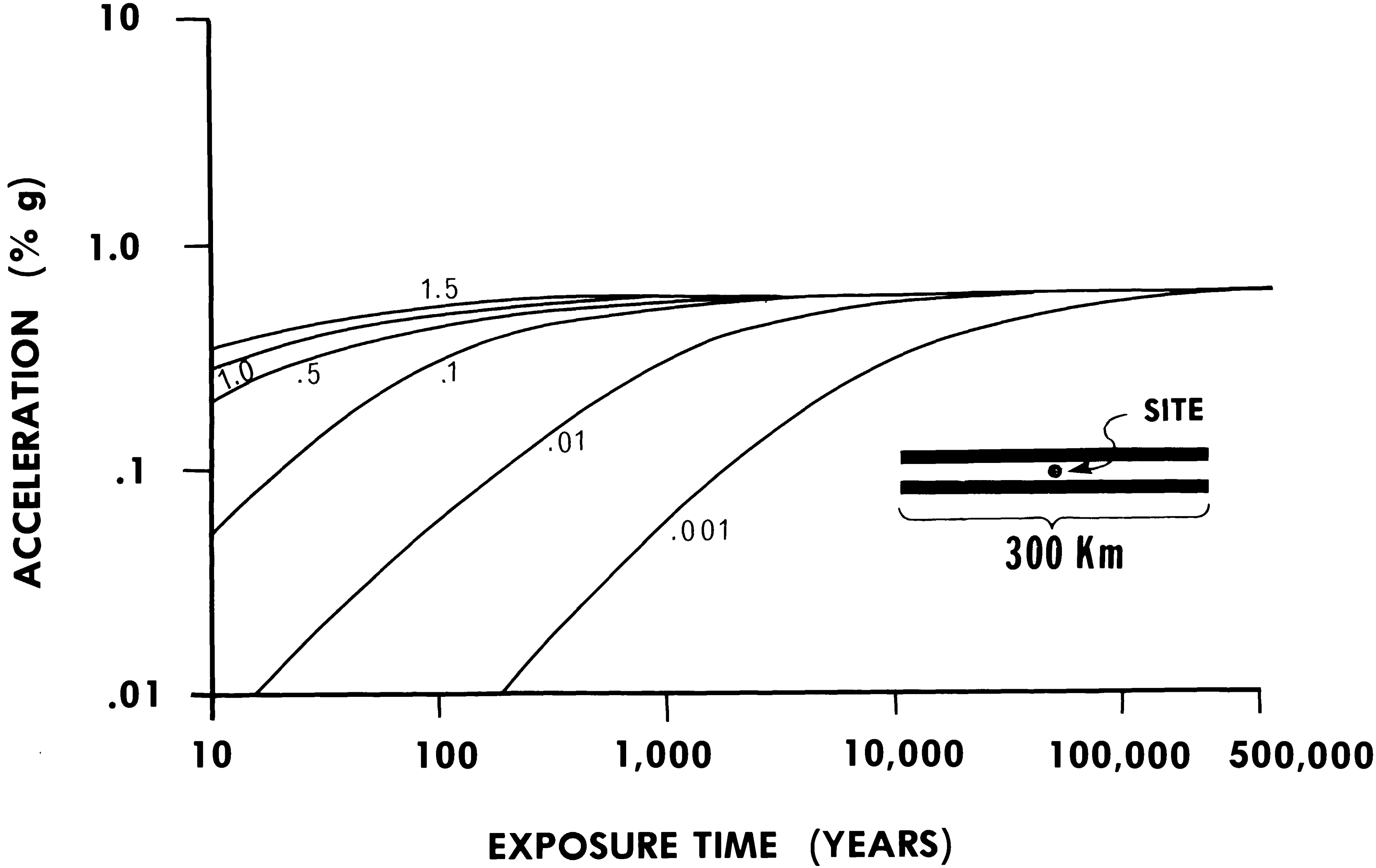

Figure 12.--Acclerations in rock at a site between two parallel faults. Schnabel and Seed (1973) attenuation curves, $\beta = 2.0$ maximum magnitude 8.5 with no parameter uncertainty, were used in the calculations. The curves are for various levels of seismic activity ϕ, as labeled. ϕ equals the number of earthquakes greater than magnitude 4 per year per fault.