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Computation of USGS Soil UHS and Comparison to NEHRP and PC 1 Seismic Response

by

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DISCLAIMER

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EXECUTIVE SUMMARY

Recently, new site-specific seismic design response spectra were developed for Savannah River Site (SRS) performance category (PC) 1,2,3 and 4 structures, systems and components (SSCs) (WSRC, 1997, 1998) in accordance with DOE Standards. The lower performance categories (PC1 and PC2) site-specific design basis were not compatible with the response spectrum generated if building code guidelines were used (National Earthquake Hazard Reduction Program Recommended Provisions for Seismic Regulations for New Buildings, (NEHRP), 1997). These differences in criteria and approach should be documented and understood. Thus, Westinghouse Savannah River Company (WSRC) initiated this study to evaluate the difference between the building code hazard assessment (NEHRP) and the site-specific hazard evaluations used for SRS design.

Using methodologies previously developed (WSRC, 1998) site-specific soil surface hazard was derived from the USGS hard-rock hazard. A site-specific uniform hazard spectrum (UHS) having the same criterion (2/3 of 2500-year return period) as the NEHRP (1997) spectrum was developed from the soil surface hazard and compared to the NEHRP spectrum for the SRS.

The National Map and NEHRP-97 recommended seismic provisions are a significant improvement and accomplishment in building code development. However, for a southeastern U.S. deep-soil site, such as the SRS, serious over-conservatism in the spectral level and bias in the NEHRP-97 spectral shape is apparent from the site-specific evaluation. When National Map consistent hazard curves are developed for SRS hard-rock outcrop and site-specific soil conditions the USGS soil surface hazard is found to be generally greater than Electric Power Research Institute (EPRI) (NEI, 1994) and the Lawrence Livermore National Laboratory (LLNL) (Savy, 1996)) soil PSHAs (WSRC, 1998). Averaging the computed EPRI, LLNL and USGS soil hazard would result in an increase in the SRS design basis.

On the basis of the comparison of the USGS soil UHS and the NEHRP-97 spectrum for the SRS (Figures 8 and 10), it appears application of NEHRP-97 guidance could seriously overestimate (and in some instances underestimate) the design spectrum for other deep soil sites in the southeast U.S.

There are several conclusions based on the results of this evaluation: (1) computation of a site-specific correction to the National Map should be a consideration before using a building code spectrum for a site like the SRS (the cost of a site-specific assessment, using an available bedrock PSHA and disaggregation, may be minor compared to the high cost due to potential design basis excess or underestimation); (2) availability of National Map hard-rock hazard disaggregations would be helpful for routine site-specific hazard assessments; (3) detailed site-specific assessments may not comply with the requirement that a site-specific UHS fall within 20% of the NEHRP spectrum; and (4) NEHRP spectral shape and site classification criteria may not be appropriate for deep soil sites.

INTRODUCTION

Since the release of the National Earthquake Hazard Reduction Program Recommended Provisions for Seismic Regulations for New Buildings (NEHRP, 1997) there has been interest by the Department of Energy (DOE) in comparing these recommended building codes to site-specific analysis conducted for their facilities. In 1997 and 1998 the Defense Nuclear Facilities Safety Board (DNFSB) made specific requests for comparisons of Savannah River Site (SRS) design basis to the NEHRP (1997) spectrum (Kimball, 1998). Review of NEHRP (1997) guidelines for the SRS showed that the level of the NEHRP (1997) spectrum is higher than the site-specific Performance Category 1 (PC1) design basis spectrum (WSRC, 1998). Also, the shape of the NEHRP (1997) spectrum was different from the SRS PC1 spectrum (WSRC, 1998).

The SRS PC1 spectrum (WSRC, 1998) and the NEHRP (1997) (hereafter referred to as NEHRP-97) spectrum for the SRS are illustrated in Figure 1. The PC1 spectrum was derived using mean hazard from the EPRI and LLNL hard-rock probabilistic seismic hazard assessments (PSHAs) that were then continued to the soil surface using site-specific soil amplification functions (WSRC, 1997). The computed soil surface hazards were averaged and fit with site-specific spectral shapes and then enveloped to create a smooth design basis spectrum. The NEHRP-97 spectrum was derived from soft-rock category spectral values taken from the United States Geological Survey (USGS) National Seismic Hazard Map (Frankel et al., 1996) (hereafter referred to as the National Map) and site soil class "D" scaling parameters. Although the NEHRP-97 spectrum was found inappropriate for the SRS, the NEHRP-97 criteria were adopted for SRS PC1 facilities by the DOE and WSRC (WSRC, 1998). Both SRS PC1 and NEHRP-97 spectra (Figure 1) are derived using the same hazard criteria (2/3 of the 2500-year return period).

There were several elements of the National Map and the NEHRP (1997) guidelines responsible for the differences with SRS PC1 design spectrum: (1) the National Map, used for ground motion input to NEHRP-97, contains a highly energetic Charleston source (Mw 7.3, $\Delta\sigma = 150$ bars, return period = 650 years) as compared to the Charleston sources contained in the hazard models used at the SRS (EPRI and LLNL); (2) ground motion attenuation models used in the National Map contain a conservative feature in the low-frequency portion of the source spectrum (Atkinson and Boore, 1998); (3) the crustal model incorporated in the National Map contains a low-speed gradient (the "soft-rock" outcrop) that is significantly slower than the observed bedrock shear-wave speeds at the SRS (note that the "hard rock" and "soft rock" bedrock distinctions are usually characterized by bedrock shear-wave speeds significantly higher or lower than 5,000 ft/sec respectively); and (4) the NEHRP-97 soil classification model and corresponding design spectrum may not adequately account for a deep soil site such as the SRS (WSRC, 1998). With these differences in mind, and because the DOE design guidance allows use of building code design (for PC1 and PC2 class facilities), it is important for the DOE to have a clear position on the applicability of the National Map and the NEHRP-97 spectrum to the DOE complex. A new SRS-specific soil surface hazard is computed using a (USGS prepared) hard-rock hazard model that is consistent with the National Map together with previously developed site-specific amplification functions. This hard-rock hazard is consistent with the source location, magnitude distribution, and rate of occurrence of earthquake sources used in the National Map. The National Map special source assumptions are very conservative as compared to the EPRI and LLNL PSHAs and this is addressed in the discussion section. The methodology to compute soil surface hazard is described in WSRC (1997, 1998), and requires a hard-rock Probabilistic Seismic Hazard Assessment (PSHA) including hazard disaggregation.

The uniform hazard spectrum (UHS) derived from the computed site-specific hazard (referred to as USGS soil surface hazard) is compared to the NEHRP-97 spectrum (for the SRS). This task is of particular interest for deep-soil eastern U.S. sites because it compares a building code design spectrum to a site-specific spectrum using the same hazard model and identical criteria. The USGS soil surface hazard is also compared to the EPRI and LLNL soil hazard and the SRS PC1 design basis spectrum (WSRC, 1998).

Another issue that is of potential concern for the SRS is the treatment of fault sources in the Charleston "special seismic zone" of the National Map. The impact on finite fault sources that extend outside the defined fault source region require additional study and the USGS was tasked to analyze the impact of these sources (WSRC, 1999). We also briefly review that work below.

DEVELOPMENT OF USGS HARD-ROCK HAZARD

In February 1999, the USGS completed a hard-rock PSHA for the SRS (WSRC, 1999). The scope of work for the USGS consisted of computing seismic hazard (including disaggregation) for a hard-rock outcrop site located centrally at the SRS. The seismic source zones and crustal models are consistent with those models used for the National Map. The ground motion attenuation models used are suitable for hard-rock outcrop sites but differ from those used for the National Map. Hazard disaggregation distance and magnitude bins are consistent with those computed in the EPRI and LLNL hazard studies. Ground motion attenuation models consist of three mutually agreed upon models, Atkinson and Boore (1995) (AB95), Toro et al., (1997) (TORO), and Frankel et al. (1996) modified for hard-rock outcrop conditions (USGS96). The USGS96 and TORO ground motion attenuation models are both single-corner semi-empirical models while the AB95 is a two-corner semi-empirical model.

In a meeting held February 17, 1999, the USGS and the DOE agreed that a composite of hazard models derived from 1- and 2-corner source models would be most appropriate for the southeastern U.S. It was also agreed that a 1/3 weighting for each of TORO, AB95 and USGS96 hazard models would best represent the hazard from a consensus opinion of ground motion experts.

The SRS hazard evaluation was done using the same source geometries and recurrence rates (including Charleston) as was done for the National Map. Hazard evaluations were done for oscillator frequencies of 1, 2, 3.33, 5, 10-Hz and peak ground acceleration (PGA). For each oscillator frequency considered, the USGS96 attenuation model produces the greatest hazard at the SRS. Figures 2a-2f illustrate the 1, 2, 3.33, 5, 10-Hz and PGA hazard computed for each of the models. At 1-Hz, the USGS96 model is about a factor of 3 higher in ground motion or a factor of 9 higher in hazard than the AB95 model as a result of the single corner model used in USGS96. Higher frequency hazard is somewhat more consistent among the models. The factors for ground motion and hazard are respectively: 1.9, 4 at 2 Hz; 1.6, 2.5 at 3 Hz; 1.4, 2.2 at 5 Hz; 1.2, 1.6 at 10Hz; and 0.9, 0.9 for pga. Review of disaggregations indicated that the four models produce consistent hazard contributions by magnitude and distance.

The USGS computed the composite probability of exceedance for hard-rock conditions at the SRS using the 1/3 weighting scheme (Frankel (1999) (this bedrock hazard model will hereafter be referred to as USGS bedrock hazard). The USGS bedrock hazard for 1, 2.5, 5, 10 Hz and PGA are illustrated in Figure 3 (the 2 and 3.33 Hz models were averaged to compare to 2.5 Hz). Comparisons of USGS hard-rock hazard to the EPRI and LLNL bedrock models currently used at the SRS are shown in Figures 4a-4e for 1, 2.5, 5, 10-Hz and PGA respectively. Of the three models, USGS bedrock hazard produces the greatest hazard at nearly all exceedances as compared to either EPRI or LLNL models for 1, 10-Hz, and PGA. However, the differences between LLNL and USGS bedrock hazard are less than the hazard differences between LLNL and EPRI. For 2.5 and 5 Hz, the USGS bedrock hazard is comparable to LLNL. Table 1 contains a comparison of 1,000, 2,500, and 10,000 year return period ground motions based on EPRI and LLNL SRS hard-rock hazard. Also shown in Table 1 are corresponding motions from the USGS96 (single corner model) and USGS weighted average model (includes 2-corner model).

USGS bedrock hazard disaggregations are illustrated in Figures 5a through 5f. For the smaller probabilties, the long-period (1-Hz) hazard is dominated by the Charleston earthquake; the short-period (10-Hz) and PGA is dominated by the Charleston earthquake and a smaller more local event. This differs somewhat from the LLNL and EPRI disaggregations that are not as spiked in magnitude and distance and show broad peaks that tend to show Charleston-type earthquakes controlling long periods and a closer, smaller event controlling the shorter periods.

EVALUATION OF THE USGS CHARLESTON SOURCE ZONE

The USGS Special Source Zones are a potential issue because of the way earthquake source rupture distance is computed for the ground motion attenuation model. The approach used in the development of the National Map is to create a grid of nodes within the confines of the special zone. For each site of interest (e.g., SRS), a line source having the appropriate length, consistent with the special zone magnitude (e.g., 7.3), is centered at each node. The line source orientation is randomized several times and the closest source to site distance of the oriented fault is averaged and then used in the ground motion attenuation model regardless of whether the closest distance is within the confines of the source zone. This algorithm effectively produces hypothetical ruptures outside of the source zone and potentially closer to the SRS.

At the request of WSRC, the USGS performed a sensitivity analysis to understand the effect of the Charleston source zone on hazards at the SRS. The SRS hazard was computed using an alternative representation of the Charleston source zone having the western edge of the zone relocated to the east by 30 km. This modified source zone would ensure that the hypothetical Charleston fault rupture would not extend closer than the original USGS Charleston source zone. Figures 6a through 6f illustrate the SRS hazard using the Frankel et al. (1996) attenuation model and two representations of the Charleston source zone for oscillator frequencies of 0.5, 1, 3.3, 5, 10-Hz and PGA respectively. Hazard differences are less than about 6% at any of the frequencies. Based on this analysis, the original USGS algorithm for computing hazard from finite sources was judged acceptable.

METHODOLOGY TO COMPUTE SITE-SPECIFIC SOIL HAZARD CURVES

The methodology for computation of soil surface hazard using bedrock hazard as input is described in detail in WSRC (1997, 1998). Cornell and Bazzuro (1997) prepared the mathematical formalism described below. Hazard at the surface of a non-linear soil column (soil surface hazard) can be derived using bedrock hazard disaggregation together with a set of frequency, magnitude and ground motion dependent soil amplification functions (SAFs). The discrete form of the soil surface hazard curve is given by:

$$G_Z(z) = \sum_{x_j} \sum_{m_i} \underbrace{G_{Y|M,X}(z/x|m_i, x_j)}_{(1)} * \underbrace{p_{M|X}(m_i|x_j)}_{(2)} * \underbrace{P[X = x_j]}_{(3)}$$

where the sums are over magnitudes (m_i) and bedrock motion amplitude levels (x_j) contained in the hazard disaggregation; $p_{M|X}(m_i|x_j)*P[X=x_j]$ is the probability mass function, and $G_{Y|M,X}$ is the conditional complementary cumulative distribution function (CCDF) on the amplification factor. The three factors in the equation represent:

(1) the conditional CCDF on the amplification of motion caused by the soil, given rock motion of amplitude X=x associated with earthquake of magnitude M=m, (from site amplification functions)
(2) the conditional probability of magnitude M=m, given rock motion X=x, (from hazard disaggregation)
(3) the probability of rock motion X=x (from the probability of exceedence)

The methodology requires disaggregation of bedrock hazard for a suite of bedrock motions. The hazard disaggregation represents the composition of the hazard by earthquake magnitude. For each (bedrock) level of motion, the disaggregated hazard is represented by a table of numbers, where rows represent source distance bins and columns represent source magnitude bins. The sum of all elements of the table is the total probability of exceedance Thus, for a given oscillator frequency and level of bedrock ground motion ($X=x_i$), each element of the hazard disaggregation corresponds to the probability of exceedance of rock ground motion for a specific earthquake magnitude range. For each oscillator frequency, the first differences are taken of the disaggregation elements between adjacent levels of bedrock motion. This results in tables of disaggregations for the probability of occurrence of the mean bedrock control motions. These probability of occurrence disaggregations determine the products of the probability mass function:

$$p_{M|X}(m_i|x_j)*P[X=x_j]$$

where x_j is the geometric average of the jth and j+1 disaggregated hard-rock motions.

$G_{Y|M,X}$, the CCDF on the amplification, is determined using the SAFs developed in WSRC (1997). Magnitude dependence of the SAFs is expressed by the approximate 5^{th}, 50^{th}, and 95^{th} percentile of the EPRI magnitude disaggregation (these three magnitudes are also expressed as ML, MM, and MH respectively). These SAFs for the three magnitudes are interpolated to span the range of the disaggregation magnitude bins (WSRC, 1997).

An exact soil surface hazard computed using this methodology requires disaggregation of bedrock hazard at sufficiently dense amplitudes to span an adequate range of bedrock levels of motion. The disaggregation must also be sufficiently dense in earthquake magnitude bins to account for magnitude dependence of the soil response. This methodology was implemented in FORTRAN Program SOILHAZF. See WSRC (1998) for discussion of SOILHAZF features and flowchart.

Development of equivalent linear soil surface response for the SRS was presented in detail in WSRC (1997). The basic approach to the development of SAFs is to disaggregate the bedrock hazard curves and use the disaggregated magnitudes to develop a suite of magnitude dependent bedrock spectra, or control motions. The site properties including soil column thickness, bedrock type, and the range in material and dynamic properties are then parameterized and randomized. A large number of realizations (30) of the randomized soil and bedrock properties are then derived to develop site response for two bedrock types and six ranges of soil column thickness that span the range of conditions for the SRS. By convolving each magnitude dependent bedrock control motion through the soil profile realizations, statistical distributions on site response are derived for each of the combinations of soil column thickness and bedrock type. Development of bedrock control motions, their site-specific response, frequency, magnitude, and ground motion dependency are discussed in detail in WSRC (1997).

Earthquake distance dependence of the SAF is not considered. It is expected that the effect of distance on the computed SAF is second-order except at the lowest POE's (largest ground motions).

USGS SOIL SURFACE HAZARD

The USGS bedrock hazard magnitude and frequency dependent disaggregated hard-rock seismic hazard results are used to compute the USGS soil surface hazard. The USGS hard-rock hazard results are considered mean values (Frankel, personnel communication) and can be compared directly to the earlier mean LLNL and EPRI hard-rock hazard for the SRS. For each of the five ground motion frequencies (1, 2.5, 5, 10-Hz and PGA), the hazard disaggregation is defined for a suite of bedrock spectral ground motions.

Assumptions and approximations used in the soil surface hazard development:

1. A cubic polynomial interpolation of bedrock hazard was used and appears to be a good approximation for USGS bedrock hazard for all oscillator frequencies based on the goodness of fit.
2. The hazard disaggregation, between bedrock levels of motion, is linearly interpolated on a log-log scale.
3. The three-point magnitude dependence contained in the SAFs is linearly interpolated to account for the magnitude dependence contained in the bedrock disaggregation.
4. The SAFs and corresponding control motions of WSRC (1997) are assumed to cover the necessary ranges of bedrock hazard motions. In addition, the SAFs are assumed to be log-normally distributed and linear interpolation of the log-normal distribution is assumed to be adequate for developing soil surface hazard.
5. Where USGS rock ground motions exceeded the range defined by the SAFs, SAF median and standard deviations were conservatively fixed at the limiting values.
6. A lower bound on the SAF of 0.5 is also applied for all frequencies to limit the non-linearity of the soil column.
7. Truncation of the probability of exceedance at $\pm 2\sigma$ was used to avoid accumulation of extremely low POE's.
8. The 100-Hz soil/rock spectral response was used for the PGA transfer function.

Computed USGS soil surface hazard, using the USGS bedrock hazard model are illustrated in Figures 7a through 7e for oscillator frequencies of 1, 2.5, 5, 10-Hz and PGA. The solid lines represent hazard at the top of the soil column. The dashed line in the figures are the USGS bedrock hazard. Open symbols on the dashed lines indicate extrapolation beyond the computed USGS bedrock hazard values. Each of the figures contain six hazard models that are appropriate for a site depending on whether the site is on crystalline or triassic rock and depending on soil column thickness. The legends are read as follows: the first number (1, 2p5, 5, 10, 100) is oscillator frequency; the first letter (u) is for USGS bedrock hazard disaggregation; the second letter is c or t for crystalline or Triassic bedrock; and the last number is 1, 2, or 3, for soil depth range. Thus, the hazard corresponding to "2p5ut3" corresponds to the 2.5 Hz USGS bedrock hazard for soil depth range 3 (1300-1500 ft) overlying Triassic bedrock. As expected, the level and features of these hazard curves are very similar to those of LLNL (WSRC, 1998). For oscillator frequencies of 1 and 2.5 Hz, non-linear effects of the soil column are evident for annual probabilities of exceedence of about 10^{-4} or less. For higher oscillator frequencies (5-, 10-Hz, and PGA), non-linear soil response is apparent for annual probabilities of 5×10^{-4}.

There are general features in common among the soil surface hazard curves. At higher annual probabilities, the soil surface hazard approximately parallels the rock hazard curve (i.e., nearly the same slope) until ground motions are sufficiently large that non-linear soil effects begin. For larger ground motions, frequency dependent nonlinear soil response increasingly reduces the probability of exceedance as compared to the bedrock hazard (soil surface hazard increasing slope). Significant nonlinear behavior of the soil, manifest in the soil surface hazard curves for the five frequencies, does not become clearly evident until annual probabilities of exceedance are less than about 10^{-4}. At much lower POEs ($\cong 10^{-6}$), the soil surface hazard curves again begin to parallel the bedrock hazard curve. This behavior occurs at lower annual probabilities because of the constraint placed on reduction of motion due to non-linear soil response. This is partially an artifact of the limited range of SAFs; however, the calculation of site response for the upper range of control motion is approaching the limits of the reliability of the equivalent linear method and the reliable range of measured strain-dependent damping for some soil layers used in the analysis (WSRC, 1996). For computation of very low probability soil surface hazard ($<10^{-6}$), limiting the upper range of control motions (or equivalently limiting the peak soil strains) adds more conservatism to those segments of the soil surface hazard curve than would otherwise be based on extrapolations of laboratory testing data. In addition, the added conservatism obtained by limiting the degree of soil degradation may compensate for the additional uncertainty in the equivalent linear approximation at these strain levels (WSRC, 1998).

Most of the assumptions and limitations of the computation of soil surface hazard, described in WSRC (1998), apply in this application as well. As discussed in WSRC (1998), there are two important assumptions. First, the soil hazard results depend critically on the reliability of the site amplification models. It is assumed that the equivalent linear model of wave propagation through the soil and the laboratory determined, strain-dependent soil modulus and hysteretic damping, are valid for bedrock control motions of up to 0.75g. It is also assumed that the site response distribution is fixed for motions exceeding that amount. Also, the importance of earthquake distance dependence in the soil SAFs has not been explored. For lower probabilities, the most likely event distance becomes small and angle of incidence effects could alter the soil/rock transfer function.

COMPARISON OF USGS SOIL UHS TO NEHRP-97 SPECTRUM

The NEHRP-97 spectrum applies the National Map for the reference soft-rock site category (2,500 < Vs < 5,000 ft/sec) (Frankel et al., 1996). Following the NEHRP-97 guidelines, USGS soft-rock spectral values (for the central SRS location) were adjusted for site class "D" which is characterized by shallow soils having shear wave speeds of 600< Vs <1,200 ft/sec and standard penetration test resistance values (N-values) of 15-50 in the upper 100 ft (the SRS median shear-wave speed is about 1,150 ft/sec and N-values typically range from about 10-70) (WSRC, 1997). In addition, as recommended in NEHRP-97, the design response spectrum was taken as 2/3 of the maximum considered ground motions (2500 year return period). The resulting NEHRP-97 spectrum for the SRS is illustrated in Figure 8.

The envelope of the USGS soil surface hazard curve is used to develop the USGS soil UHS at each frequency (Figure 8). The same NEHRP-97 design criteria (2/3 of 2500-year return period) were used to compute the USGS soil UHS. The difference in the two spectra is remarkable considering the difference is a result of generic vs. site-specific evaluation.

DISCUSSION

Bedrock Hazard

The National Map hazard, once corrected to account for SRS bedrock outcrop, is consistent with the mean LLNL bedrock hazard model for the SRS at oscillator frequencies of 2.5 and 5-Hz. The USGS bedrock hazard is significantly higher than both LLNL and EPRI at 1 and 10 Hz. This is not a surprising result as the National Map hazard model employs a large magnitude earthquake (Mw 7.3) having a short return period (650 yr.) that occurs in an area source zone as close as 80 km to the site. This source model is based on an end-member model developed from paleoseismic data recovered along the Georgia, North and South Carolina coasts (Obermeir et al. 1990; Amick et al. 1990). The National Map characteristic earthquake uses a best estimate of the 1886 earthquake, however, the return period is based on the highest recurrence computed from the average of the last four episodes of observed liquefaction. According to Amick et al., the minimum earthquake magnitude that could be associated with a given episode of liquefaction is about Mw 6 or lower. In the absence of any observable Quaternary tectonic deformation in the southeastern U.S., repeated large displacements expected from a Mw 7 earthquake (estimated to be 4-8 m), seem excessive for a best estimate or mean model. The LLNL and EPRI hazard models contain a range of earthquake recurrence rates, and to a degree the National Map model is contained as a subset. However, it is expected that the National Map characteristic earthquake model is considerably more conservative than the mean EPRI and LLNL probabilistic hazard models. We believe that the USGS characteristic earthquake model is considerably more conservative than the mean hazard model that would be derived from contemporary expert opinion on the Charleston source. Specifically, questions that should be addressed for the National Map, or incorporated as alternate models are:

- Should a mean or best estimate earthquake source model have only a Poisson model of a characteristic earthquake for the Charleston zone?
- Should the best estimate Charleston seismic zone have a western extent that runs over 100 km inland?

- Should the return period based on the paleoseismic data use only the last four episodes resulting in the shortest possible average period?
- Should the characteristic earthquake magnitude be based on the best estimate of the 1886 Charleston earthquake magnitude (Mw 7.3) when the paleoseismic data may be explained by the occurrence of Mw 6 earthquakes (Dave Amick, personal communication) and there is no indication of high deformation rates in the SEUS?
- How is a maximum magnitude of Mw 7.5 justified for seismic zones other than Charleston in the SEUS?

USGS Soil Surface Hazard and UHS

The methodology to compute soil surface hazard from USGS hard-rock hazard is identical to that used to develop site-specific hazard from the LLNL and EPRI hard-rock PSHAs (WSRC, 1998). The computed USGS soil hazard indicates significant non-linearity at annual exceedences of 10^{-4} or greater. At annual exceedences of 10^{-5} or less, the reliability of the hazard is significantly reduced because of the limitations on the equivalent linear model used to derive the site amplification functions.

Figure 9a illustrates the individual USGS, LLNL, and EPRI soil surface UHS using the criterion of 2/3 of 2500-year return period. The USGS soil UHS exceed both LLNL and EPRI UHS at 1 and 10-Hz. The average EPRI+LLNL UHS is compared to the average EPRI+LLNL+USGS UHS in Figure 9b. The USGS UHS exceed the EPRI and LLNL average by significant margins: 28% at 10-Hz, 12% at 5-Hz, 18% at 2.5 Hz and 60% at 1-Hz. At 1-Hz, the average EPRI+LLNL+USGS spectral value exceeds the average EPRI+LLNL spectral value by about 35%.

Comparison of NEHRP and USGS soil UHS for the SRS

There are significant differences between the NEHRP-97 spectrum prescribed for SRS soil conditions, and the USGS soil UHS derived using the same criteria (return period) (Figure 8). In the range of 1-10 Hz, the NEHRP-97 spectrum is about 70% greater than the USGS soil UHS. The National Map 1-Hz bedrock spectral acceleration is higher by about a factor of two as compared to the average of EPRI/LLNL. Atkinson and Boore (1998) have shown that the 1-Hz single corner attenuation model is biased-high as compared to two corner attenuation models.

The National Map expresses the probability of exceedence of ground motions for a "soft-rock" reference site condition to be consistent with the western U.S. hazard evaluation. That site condition is the boundary between NEHRP-97 classes B and C. This B-C Boundary is defined to have an average shear-wave speed of 2,500 ft/sec (760 m/sec) in the upper 30 m of the profile. At the SRS, directly measured shear-wave speeds in shallow bedrock range from about 8,000 to 11,000 ft/sec (2.4-3.3 km/sec), a "hard-rock" site condition.

In the development of the National Map used in NEHRP-97, two attenuation models were used. One was an internal USGS BLWN model that employed a "soft-rock" velocity profile. The other attenuation model was a published hard-rock attenuation model (Toro et al., 1993) with a correction applied for soft-rock site conditions. The soft-rock/hard-rock factors applied were 1.52, 1.76, 1.72, and 1.34 for PGA, 5-, 3.3, and 1-Hz response spectral values respectively (Frankel, et al., 1996). These factors were derived from the comparisons of the results of the internal model with and without the "soft-rock" velocity gradient. Note that the USGS96 model discussed above is the same internal model with a hard-rock profile that also contains a velocity gradient with additional site amplification factors. Kimball (1998) has indicated that the soft-rock to hard-rock amplification factors applied by the National Map are inconsistent with those assumed by NEHRP. This inconsistency would also increase the NEHRP design as compared to the site-specific assessment.

From Figure 8, it appears that the site-specific corrections account for the difference between the NEHRP-97 spectrum and the USGS soil UHS. Note that the the NEHRP-97 spectrum appears conservative at the five spectral values, at long periods the NEHRP-97 spectrum could be unconservative if the response of a deep soil column were not properly taken into account.

To better illustrate the long-period problem with the NEHRP-97 spectral shape, we fit a site-specific spectral shape from a deterministic earthquake to the long-period portion of the USGS UHS (Figure 10). The most likely earthquake controlling the long-period portion of the USGS spectrum is represented by the Mw 7.5 bin at 150 km, based on the USGS 1-Hz magnitude disaggregation (Figures 5a and 5b). A Charleston 50^{th} percentile spectrum (WSRC, 1997) derived assuming an Mw 7.3 at 150 km is scaled to the 1-2.5 Hz spectral average of the USGS UHS (scale factor of 1.24). As shown in Figure 10, the fundamental mode of the scaled site-specific spectrum falls well outside the NEHRP-97 spectrum. Clearly, the NEHRP-97 spectral shape for a deep soil site such as the SRS does not have adequate breadth. For the SRS, the large differences in the NEHRP-97 spectrum and the USGS soil UHS are a result of an inappropriate NEHRP-97 site response correction.

Comparison of USGS Soil UHS and PC1 Design Spectrum for the SRS

A detailed comparison of the design spectrum inferred from the USGS soil UHS as compared to the *PC1 design* spectrum is beyond the scope of this report. In order to make a detailed comparison, appropriate site-specific spectral shapes would be fit to the 1-2 and 5-10 Hz UHS and smooth enveloping curves would be drawn. A design basis spectrum based on the combined USGS, EPRI and LLNL soil UHS, with an appropriate enveloping shape, would be greater than the design spectrum using the combined EPRI and LLNL soil UHS.

NEHRP-97 Guidelines

The computation of USGS soil hazard from a hard-rock hazard disaggregation is illustrative of the methodology to develop a site-specific PSHA from a more general purpose hazard evaluation like the National Map. The site-specific PSHA is consistent with the earthquake source zones and recurrence rates assumed in developing the National Map. This evaluation, starting from a hard-rock disaggregation, is in principle, a suitable approach to make a site-specific assessment for any rock or soil site. If the National Map and the NEHRP-97 guidelines provide a hard-rock PSHA (with magnitude and distance disaggregation), a site-specific design spectrum could be easily developed following the necessary site characterization. Hard-rock hazard disaggregations add only a limited amount of additional tabular data that an agency can easily maintain, or if an online system is employed, the hazard disaggregation can be computed at the users request.

For the SRS, large differences between the NEHRP-97 spectrum and the USGS soil UHS are too great to be dismissed as a site-specific variation from the NEHRP-97 site classification criteria. NEHRP-97 criteria allow a 20% reduction in the design spectrum to account for possible reduction to accommodate a site-specific hazard assessment. One interpretation of the adjustment factor is that site-specific variability should be more or less within 20% of the NEHRP-97 spectrum. This investigation shows that site-specific effects can be much larger than the allowed ± 20%.

SUMMARY OF FINDINGS

Regarding the application of NEHRP-97 to the SRS the following statements are warranted:

- The National Map hazard is excessively conservative for a site such as the SRS;
- For frequencies greater than 1-Hz, the NEHRP-97 spectrum is overly conservative for the SRS and
- For deep-soil sites such as the SRS, the shape of the NEHRP-97 spectrum is unconservative at long periods.

Regarding development of SRS site-specific hazard from National Map input, the following statements are warranted:

- The hard-rock PSHA is consistent with the earthquake source definition and recurrence rates contained in the National Map but results in different hazard because of differences in the assumed bedrock conditions;
- The USGS hard-rock hazard is close to LLNL at 2.5 and 5-Hz, but is greater than LLNL and EPRI for 1, 10-Hz and PGA;
- The USGS hard-rock hazard is generally more conservative than either EPRI or LLNL hazard because of the highly energetic source assumed for the Charleston zone.
- The computed USGS soil surface hazard is less than the NEHRP spectrum recommended for shallow SRS soils;
- The computed USGS soil surface hazard is greater than the SRS design basis at 1 Hz and
- The methodology of WSRC (1998) is useful to derive site-specific soil surface hazard from hard-rock hazard disaggregation.

CONCLUSIONS

The National Map and NEHRP-97 recommended seismic provisions are a significant improvement and accomplishment in building code development, however, for a southeastern U.S. deep soil site, such as the SRS, the National Map ground motion attenuation adjustments and site response are not appropriate. Serious bias in the National Map ground motion hazard exists because of the inappropriate bedrock and NEHRP-97 spectral shape. When National Map consistent hazard curves are developed for SRS hard-rock outcrop and site-specific soil conditions the USGS soil surface hazard is generally greater than EPRI and LLNL soil hazard. The National Map hazard for the SRS is greater than EPRI and LLNL hazard because of the highly energetic source used for the Charleston special zone. Averaging the computed EPRI, LLNL and USGS soil hazard would increase the SRS design basis.

There are several conclusions based on the results of this evaluation: (1) computation of a site-specific correction to the National Map should be considered before acceptance of a building code spectrum (the cost of a site-specific assessment, using an available hard-rock PSHA and disaggregation, may be minor compared to the high cost due to potential design basis excess or underestimation); (2) availability of National Map hard-rock hazard disaggregations would be helpful for routine for site-specific hazard assessments; (3) detailed site-specific assessments may exceed the requirement that a site-specific UHS fall within 20% of the NEHRP spectrum; and (4) NEHRP spectral shape and site classification criteria may not be appropriate for deep soil sites.

FUTURE WORK

Additional work will be required to better clarify and understand the difference between EPRI, LLNL, and USGS hazard assessments including site response. There are three areas for comparison: (1) the USGS/NEHRP inferred site amplification from hard-rock to the Class D soil-site should be evaluated to compare directly to the SRS site amplification functions; (2) a comparison of 1- and 2-corner attenuation models used in all three hazard studies should be completed using the same Charleston source configuration. This will permit a direct comparison of the attenuation models and assist in the comparison of the source models; (3) PSHA sources, particularly Charleston should be compared for the SRS. This would entail selection of a small earthquake magnitude range and comparing probabilistic ground motion at SRS hard-rock for several frequencies. Based on inferences from the attenuation model study in 2, a rough comparison can be made of the Charleston source from the three studies.

The distance dependence of soil amplification functions and its impact on soil hazard should be evaluated. In general, it is possible that sites close to source zones could require site amplification functions incorporating non-vertical angles of incidence. An evaluation of the significance of this effect on site response could be easily evaluated.

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REFERENCES

Amick, D., R. Gelinas, R. Cannon, D. Moore, E. Billington, and H. Kemppinen, 1990. Paleoliquefaction features along the Atlantic Seaboard. NUREG/CR-5613 RA. Prepared for U.S. Nuclear Regulatory Commission by Ebasco Services Inc., 146 pp.

Atkinson, G.M., and D.M. Boore, 1995. New ground motion relations for eastern North America, Bull. Seis. Soc. Am., Vol. 85, 17-30.

Atkinson, G.M., and D.M. Boore, 1998. Evaluation of Models for Earthquake Source Spectra in Eastern North America, Bull. Seis. Soc. Am., Vol. 88, 917-934.

Bernreuter, D.L., 1997. Letter report from Don Bernreuter to Jeff Kimball. Lawrence Livermore National Laboratory, Fission Energy and Systems Safety Program, May 15, 1997, NTFS97-123.

Cornell, C.A., and P. Bazzurro, 1997. Efficient probabilistic hazard analysis for non-linear soil sites with uncertain properties.

Frankel, A. 1999. Letter report of calculation results to R.C. Lee, March 9, 1999.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E.V. Leyendecker, N. Dickman, S. Hanson, and M. Hopper, 1996. National Seismic Hazard Maps, June 1996, U.S. Geol. Surv. Open-File Rept. 96-532.

Kimball, J., 1998. Supplemental Response to Issues 3, 4, and 9. Seismic Action Items for Defense Nuclear Facilities Safety Board, WSRC letter from L.A. Salomone to A.H. Hadjian, PECD-SGS-98-0124, July 6, 1998.

NEHRP, 1997. National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions. For Seismic Regulations For New Buildings And Other Structures, Building Seismic Safety Council, Part 1 Provisions (FEMA 302).

NEI, 1994. Nuclear Energy Institute, Washington, D.C., Seismic Siting Decision Process, May 24, 1994.

Obermeir, S.F., R.B. Jacobson, J.P. Smout, R.E. Weems, G.S. Gohn, J.E. Monroe, and D.S. Powars, 1990. Earthquake induced liquefaction features in the coastal setting of South Carolina and in the fluvial setting of the New Madrid Zone, U.S. Geological Survey Prof. Paper 1504.

Savy, J.B., 1996. Fission Energy and Systems Safety Program, April 24, 1996, SANT96-147JBS, letter from J.B. Savy, Deputy Associate Program Leader Natural Phenomena Hazards to Jeff Kimball, DOE.

Toro, G., N. Abrahamson, and J. Schneider, 1993. Engineering model of strong ground motions from earthquakes in the central and eastern United States, in Guidelines for determining design basis ground motions, EPRI TR-102293, J.F. Schneider, ed., Electric Power Research Institute.

Toro, G., N. Abrahamson, and J. Schneider, 1997. Model of strong ground motion in eastern and central North America: best estimates and uncertainties, Seism. Res. Lett. Vol. 68, 41-57.

WSRC, 1996. Investigations of Nonlinear Dynamic Soil Properties at the Savannah River Site, by R.C. Lee,WSRC-TR-96-0062, Rev. 0.

WSRC, 1997. SRS Seismic Response Analysis and Design Basis Guidelines, by R.C. Lee, M.E. Maryak, and M.D. McHood,WSRC-TR-97-0085, Rev. 0.

WSRC, 1998. Soil Surface Seismic Hazard and Design Basis Guidelines for Performance Category 1 & 2 SRS Facilities, by R.C. Lee,WSRC-TR-98-00263, Rev. 0.

WSRC, 1999. Letter from Maryak to Hyman of 2/2/99, Funding for USGS Hazard Study, PECD-SGS-99-0021.

TABLE 1

Comparison of SRS hard-rock hazard models at return periods of 1000, 2500 and 10000 years. "USGS96" is a single corner attenuation model and "USGS wt. Ave." is a weighted average of 1- and 2-corner attenuation models.

Ret. Period (yrs)	**1-Hz Sa (g's)**			
	USGS96	USGS wt. Ave.	LLNL	EPRI
1000	0.080	0.057	0.033	0.013
2500	0.13	0.10	0.062	0.024
10000	0.27	0.20	0.12	0.061

Ret. Period (yrs)	**5-Hz Sa (g's)**			
	USGS96	USGS wt. Ave.	LLNL	EPRI
1000	0.18	0.14	0.14	0.061
2500	0.30	0.23	0.22	0.11
10000	0.58	0.48	0.48	0.21

Ret. Period (yrs)	**PGA (g's)**			
	USGS96	USGS wt. Ave.	LLNL	EPRI
1000	0.092	0.081	0.071	0.048
2500	0.17	0.15	0.12	0.078
10000	0.31	0.30	0.22	0.15

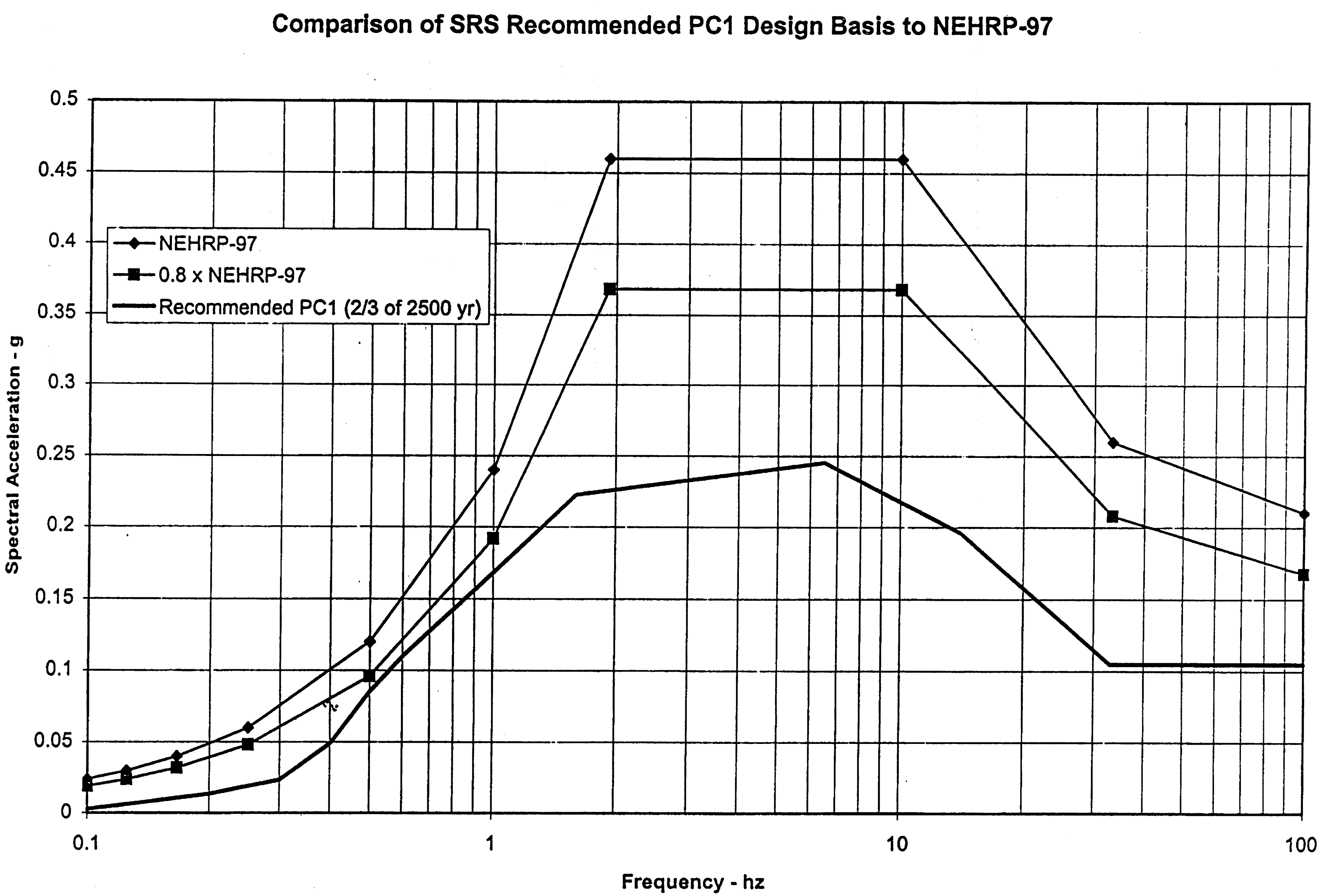

Figure 1 – Comparison of SRS PC1 spectrum to NEHRP-97 spectrum and 80% of NEHRP-97 spectrum for SRS (WSRC, 1998). The PC1 spectrum was derived using EPRI and LLNL hard rock hazard that was continued to the soil surface, averaged, and enveloped with a site-specific spectral shape. The NEHRP-97 spectrum was derived from soft-rock category spectral values taken from the National Map and site soil class "D" scaling parameters. Both spectra are derived using the same hazard criteria (2/3 of the 2500 year return period).

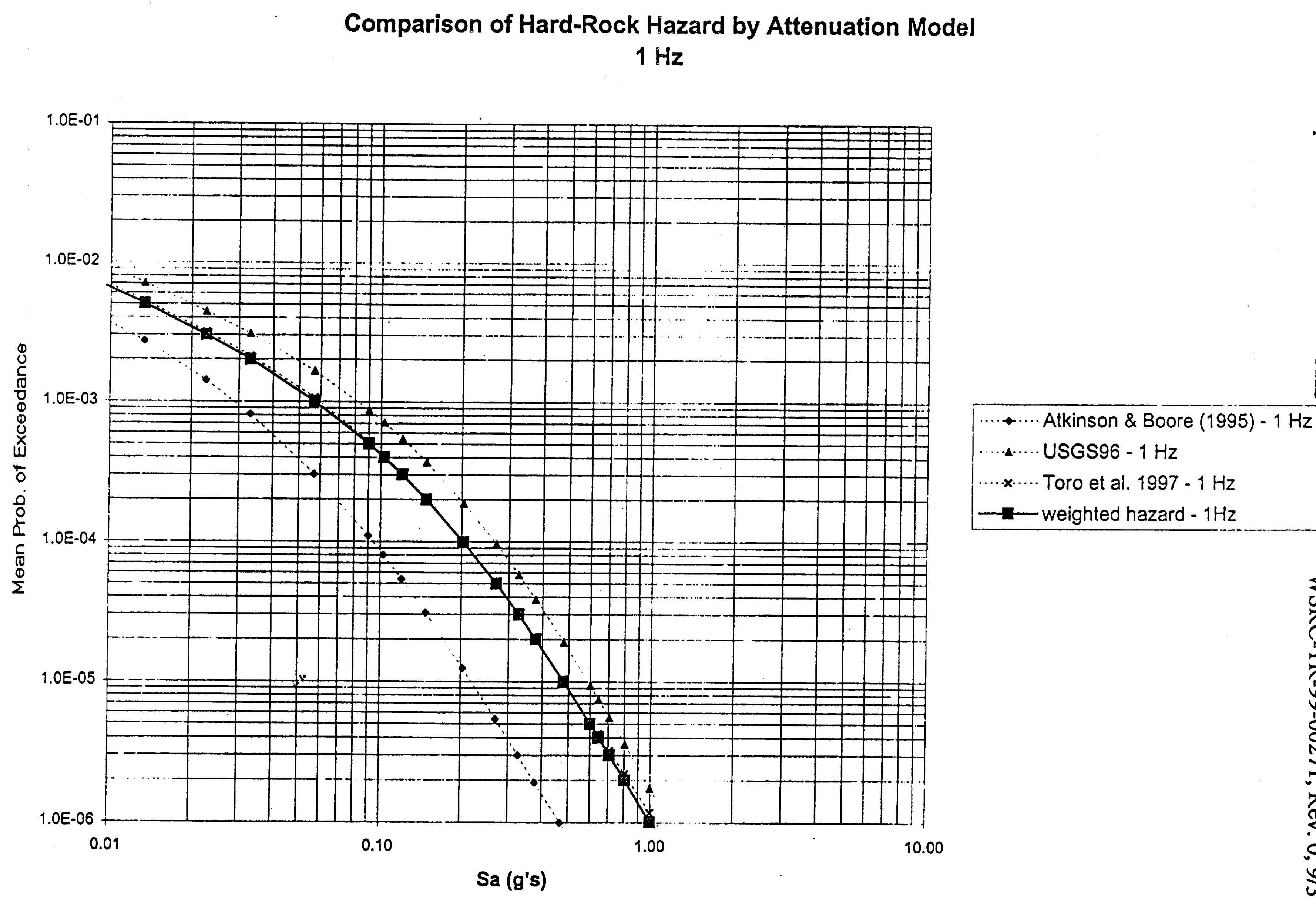

Figure 2a – USGS bedrock 1-Hz hazard computed using National Map source model assumptions and hard-rock site conditions for central SRS. Hard-rock attenuation models used are Atkinson and Boore (1995), USGS96 and Toro et al., 1997. Also shown (solid line) is the weighted hazard model.

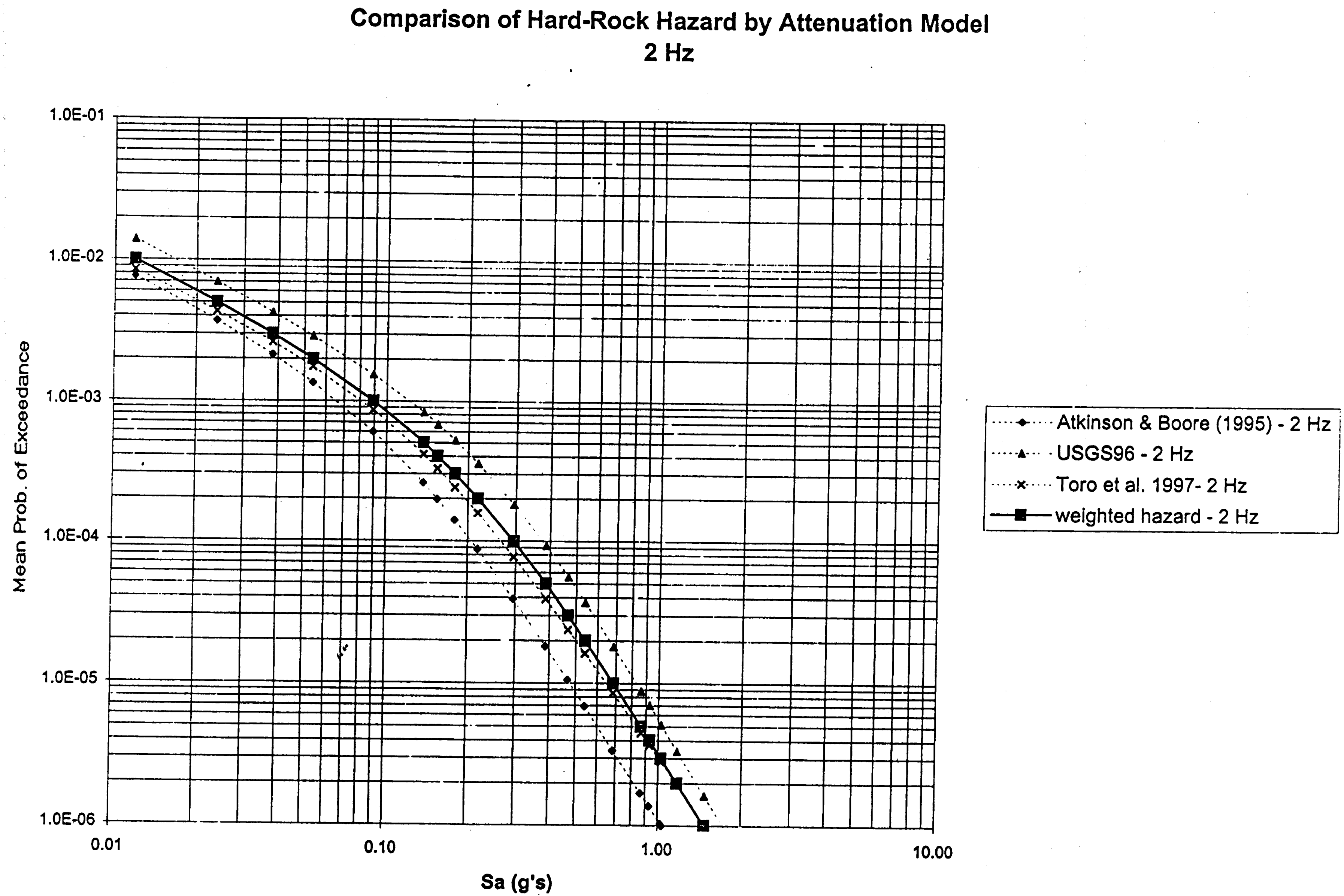

Figure 2b – USGS bedrock 2-Hz hazard computed using National Map source model assumptions and hard-rock site conditions for central SRS. Hard-rock attenuation models used are Atkinson and Boore (1995), USGS96 and Toro et al., 1997. Also shown (solid line) is the weighted hazard model.

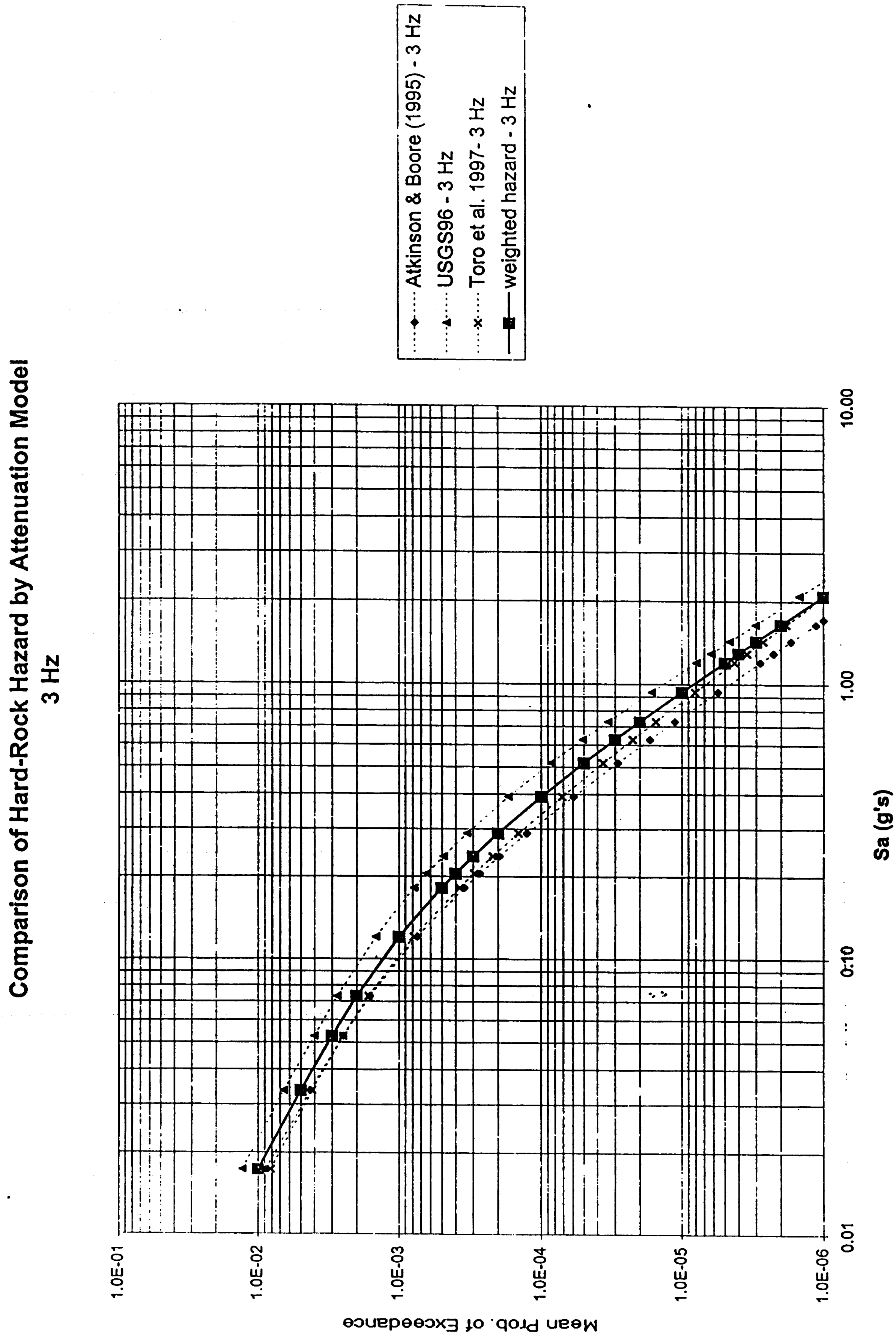

Figure 2c – USGS bedrock 3-Hz hazard computed using National Map source model assumptions and hard-rock site conditions for central SRS. Hard-rock attenuation models used are Atkinson and Boore (1995), USGS96 and Toro et al., 1997. Also shown (solid line) is the weighted hazard model.

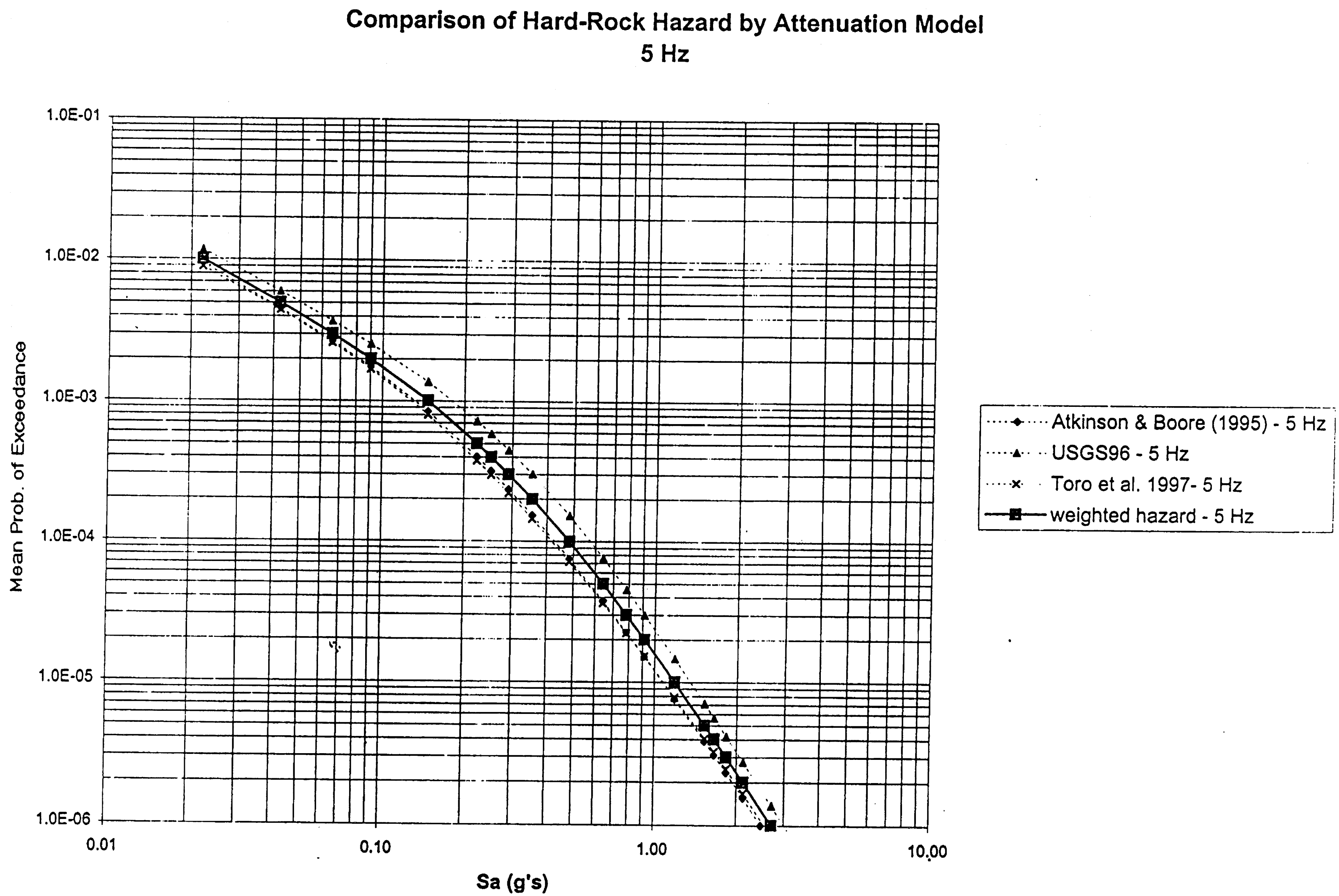

Figure 2d – USGS bedrock 5-Hz hazard computed using National Map source model assumptions and hard-rock site conditions for central SRS. Hard-rock attenuation models used are Atkinson and Boore (1995), USGS96 and Toro et al., 1997. Also shown (solid line) is the weighted hazard model.

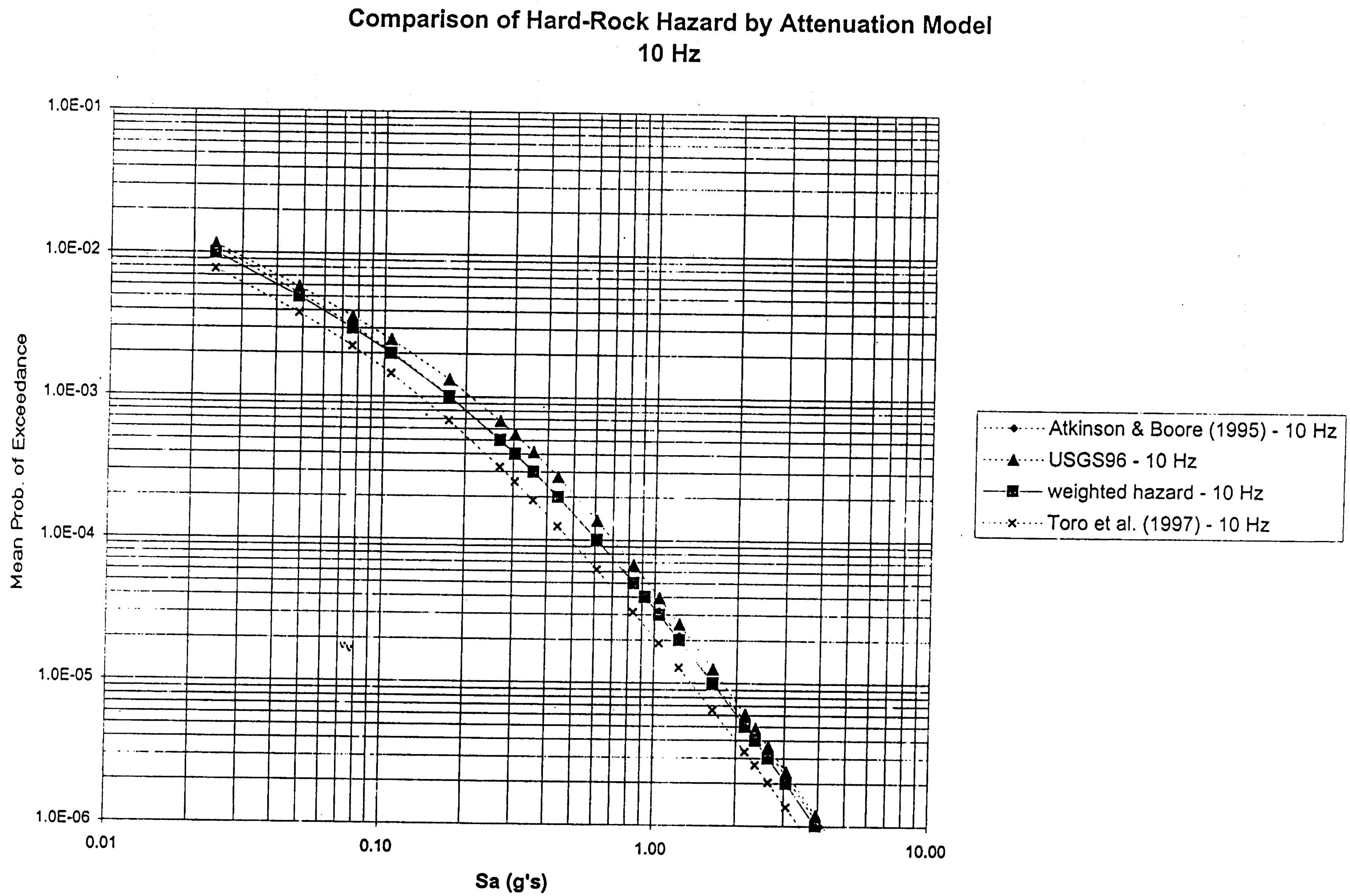

Figure 2e – USGS bedrock 10-Hz hazard computed using National Map source model assumptions and hard-rock site conditions for central SRS. Hard-rock attenuation models used are Atkinson and Boore (1995), USGS96 and Toro et al., 1997. Also shown (solid line) is the weighted hazard model.

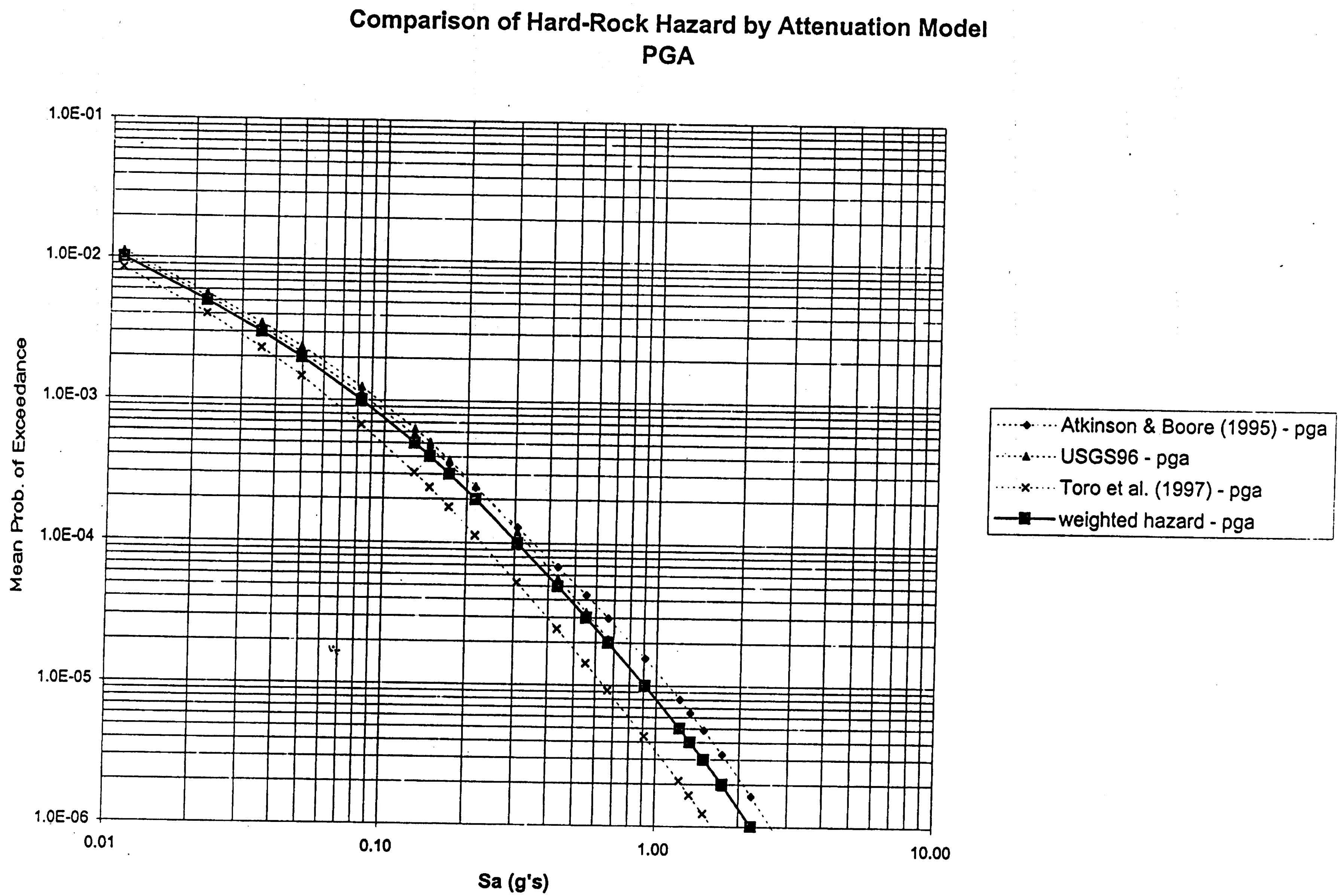

Figure 2f – USGS bedrock PGA hazard computed using National Map source model assumptions and hard-rock site conditions for central SRS. Hard-rock attenuation models used are Atkinson and Boore (1995), USGS96 and Toro et al., 1997. Also shown (solid line) is the weighted hazard model.

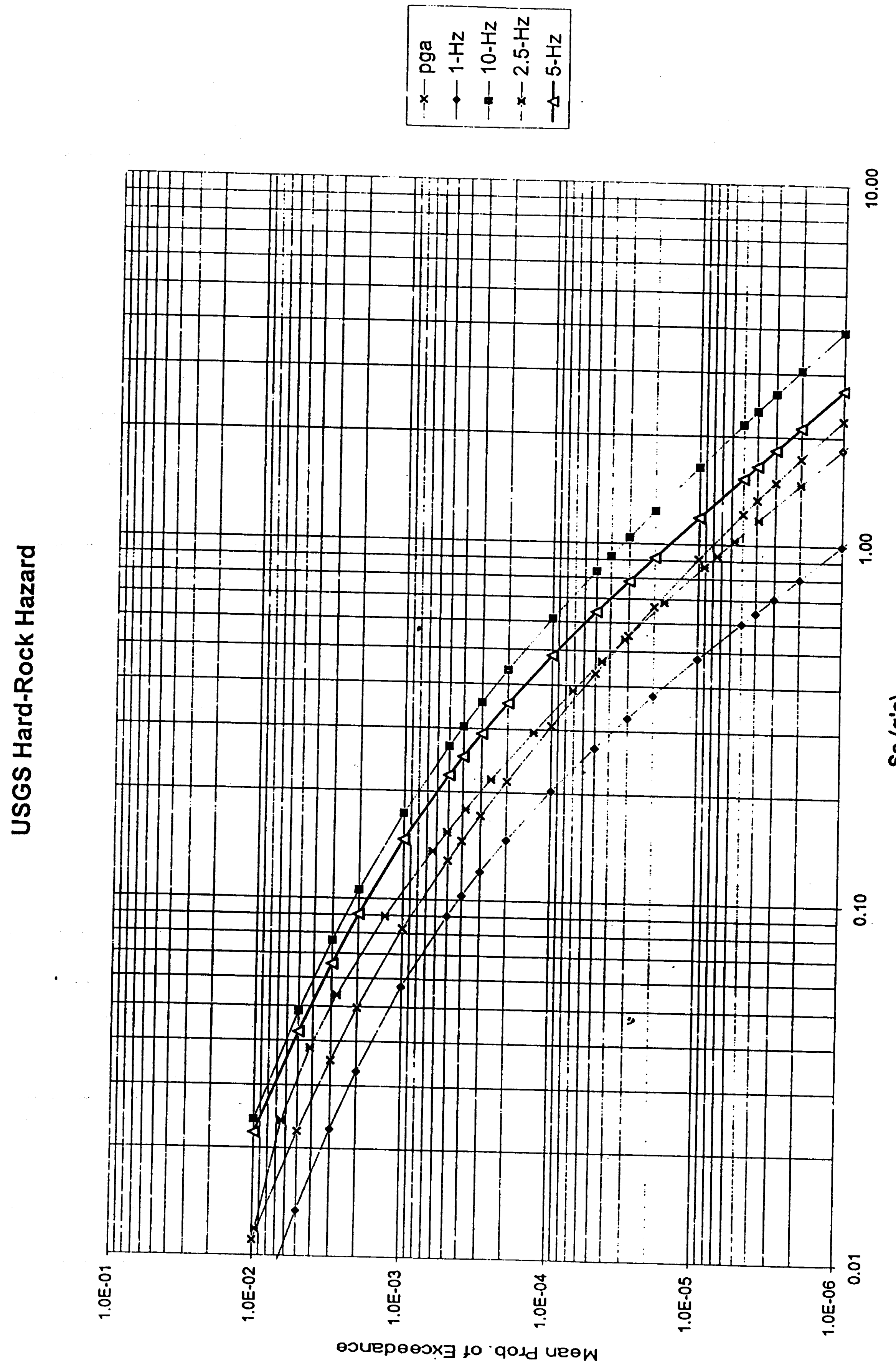

Figure 3 – Composite USGS bedrock hazard computed using National Map source model assumptions and hard-rock site conditions for central SRS.

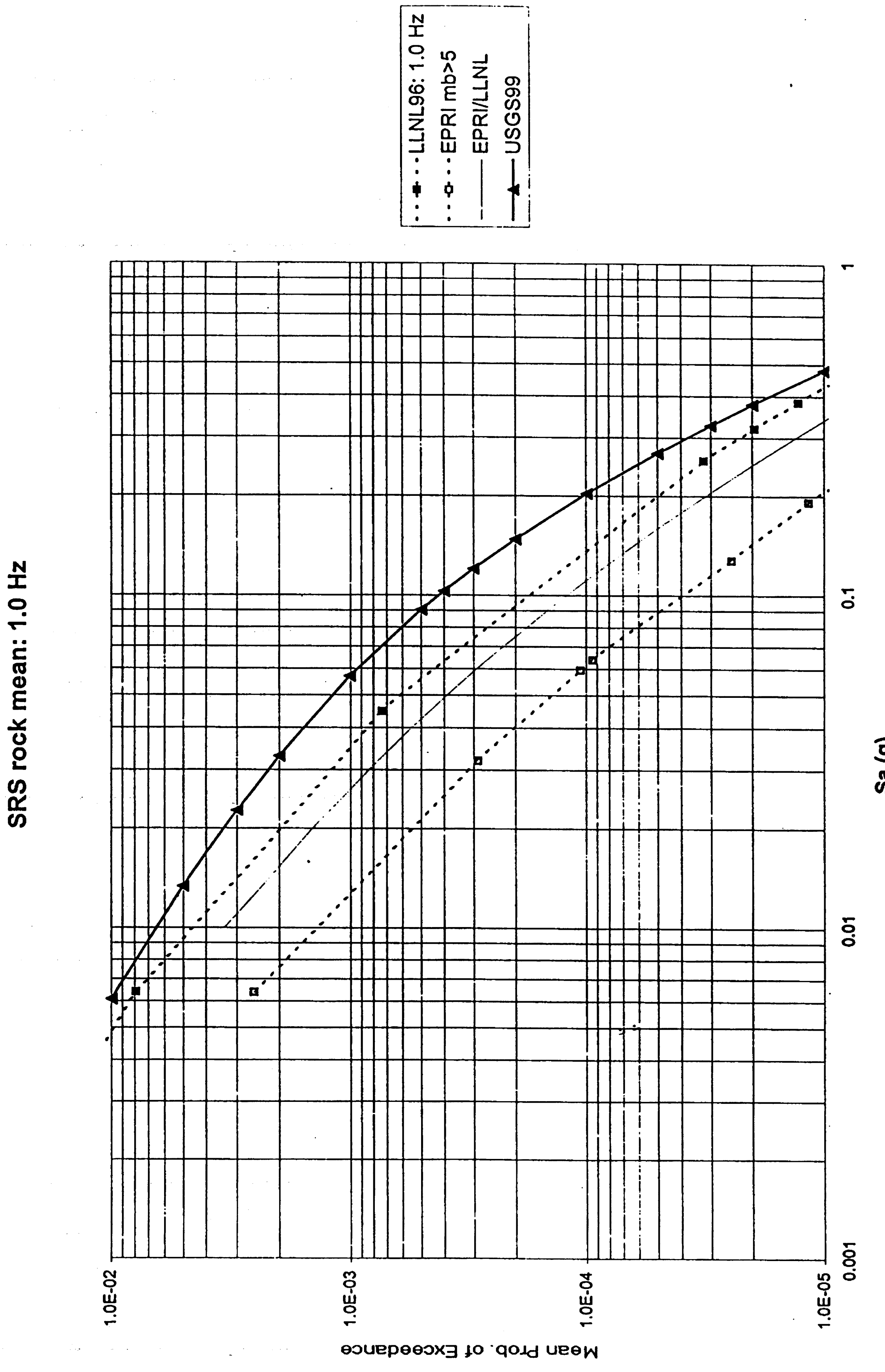

Figure 4a – Comparison of USGS bedrock 1-Hz hazard to EPRI and LLNL bedrock hazard for a central SRS site and hard-rock site conditions.

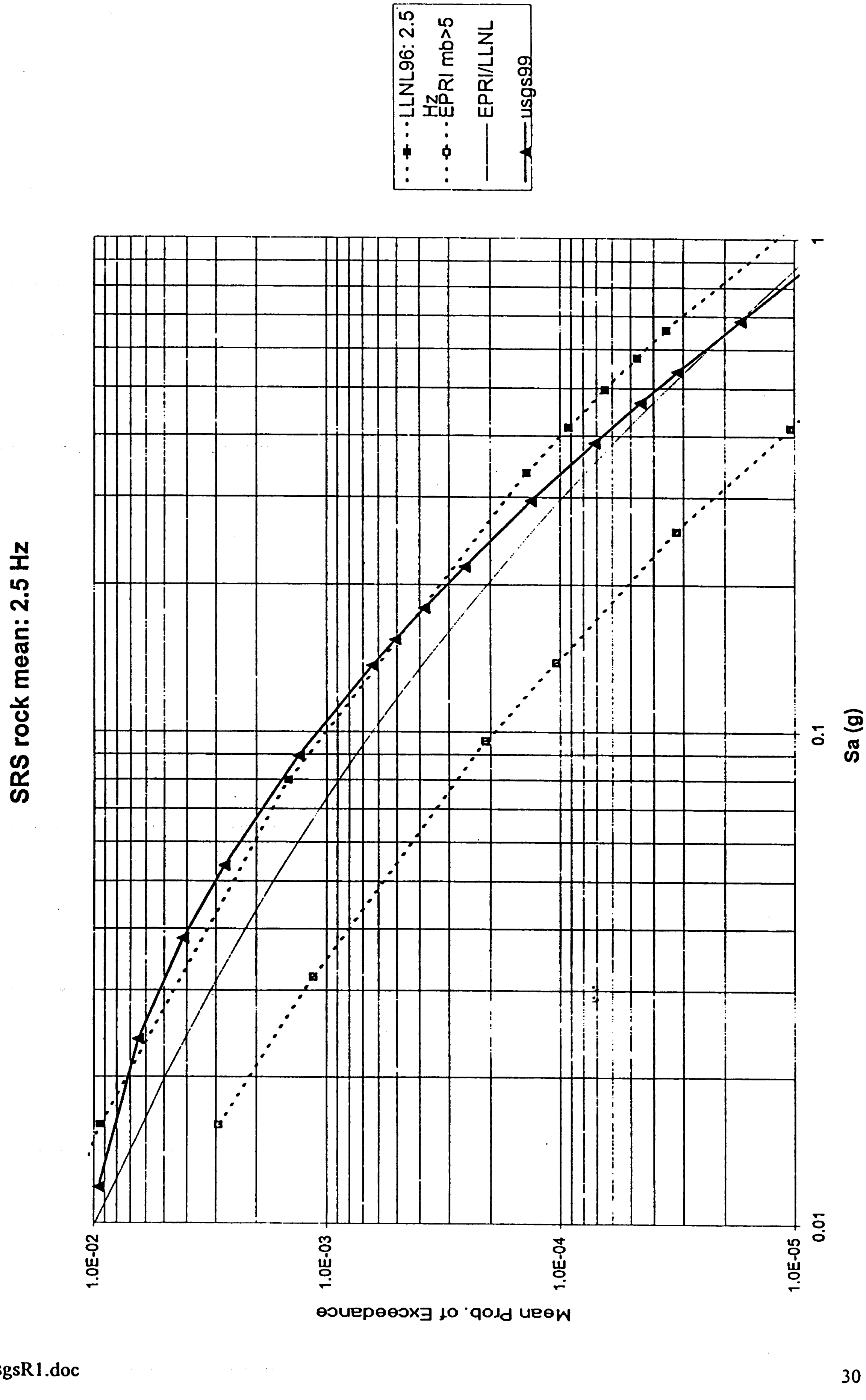

Figure 4b – Comparison of USGS bedrock 2.5-Hz hazard to EPRI and LLNL bedrock hazard for a central SRS site and hard-rock site conditions.

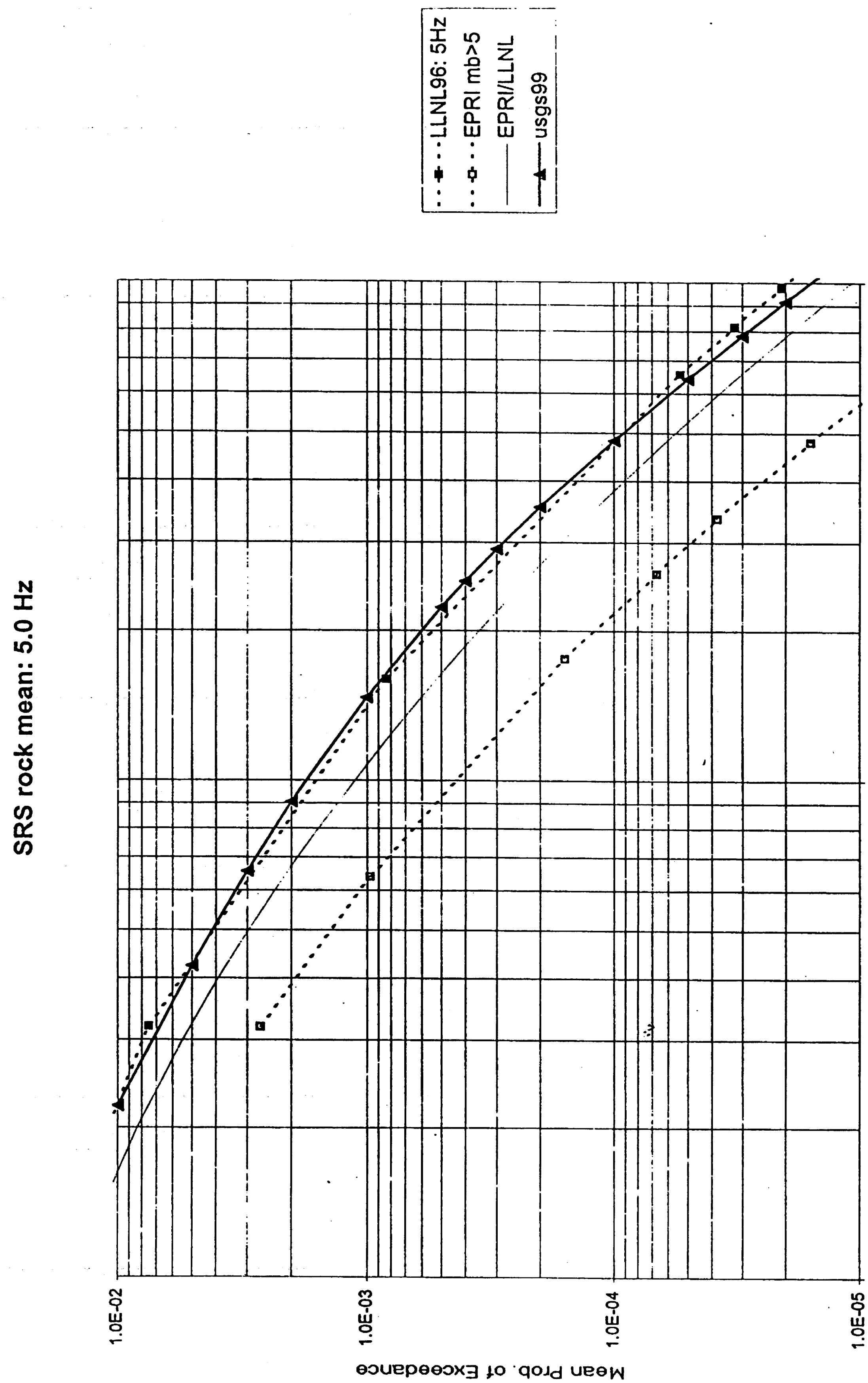

Figure 4c – Comparison of USGS bedrock 5-Hz hazard to EPRI and LLNL bedrock hazard for a central SRS site and hard-rock site conditions.

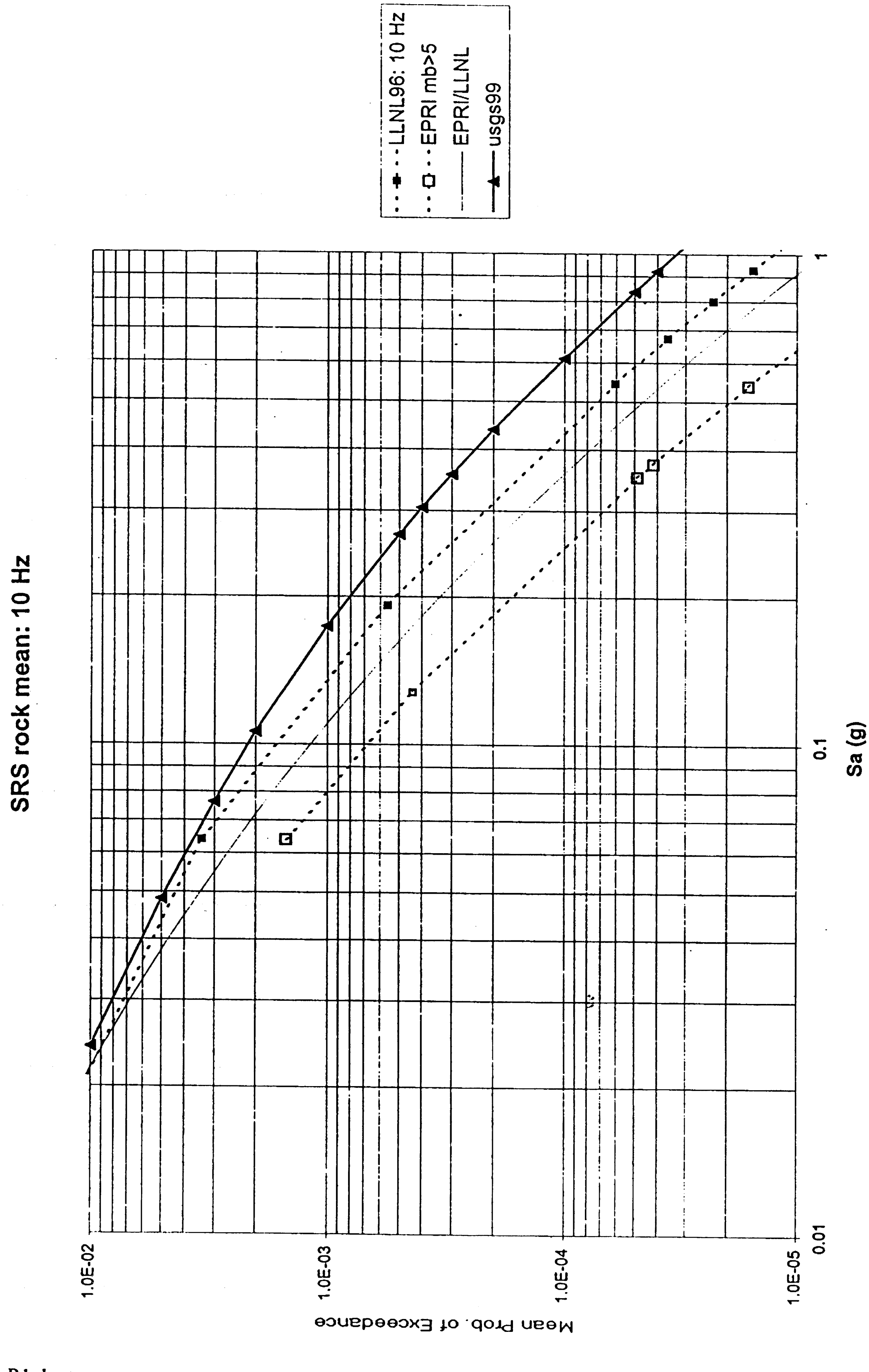

Figure 4d – Comparison of USGS bedrock 10-Hz hazard to EPRI and LLNL bedrock hazard for a central SRS site and hard-rock site conditions.

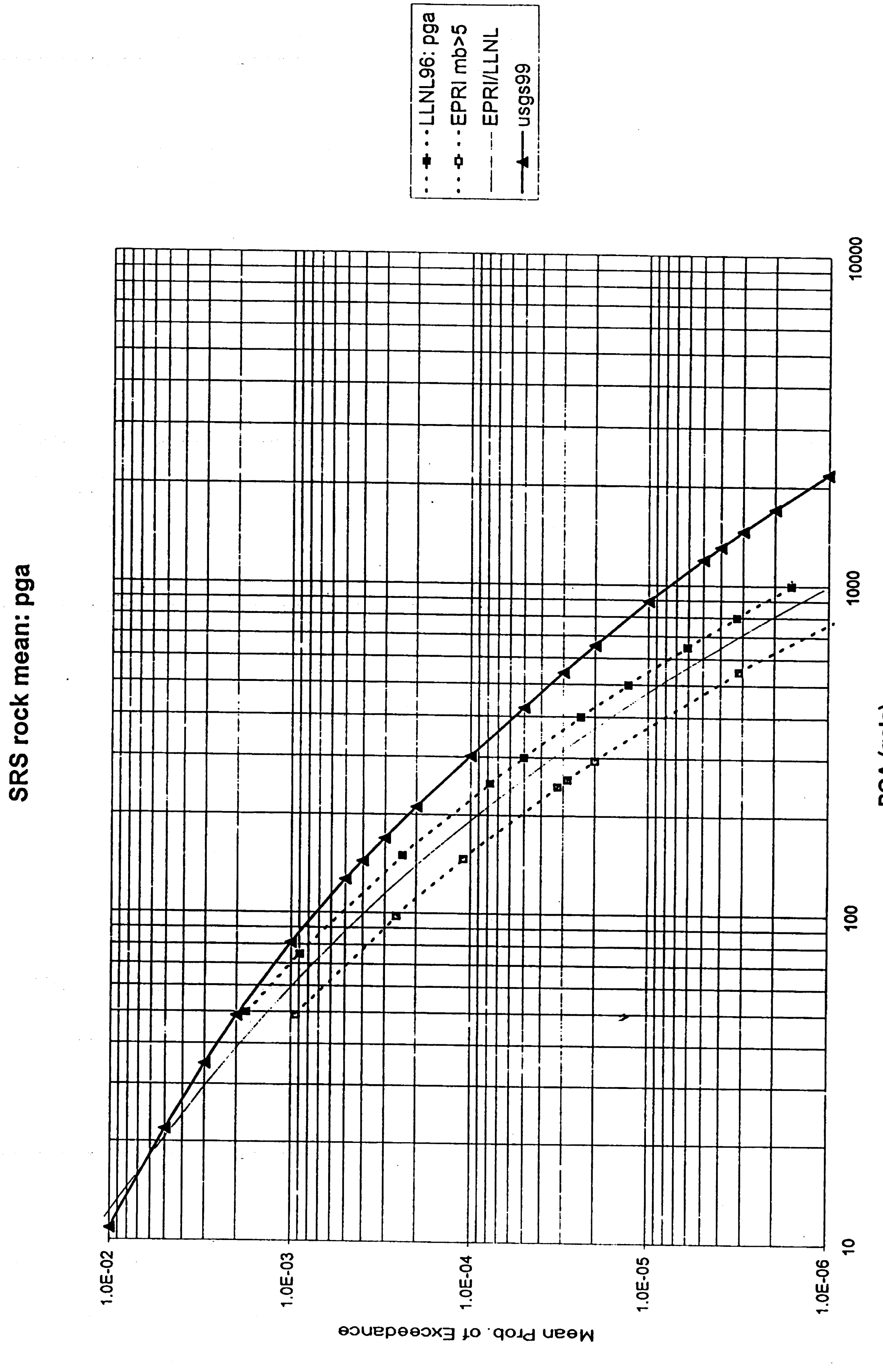

Figure 4e – Comparison of USGS bedrock PGA hazard to EPRI and LLNL bedrock hazard for a central SRS site and hard-rock site conditions.

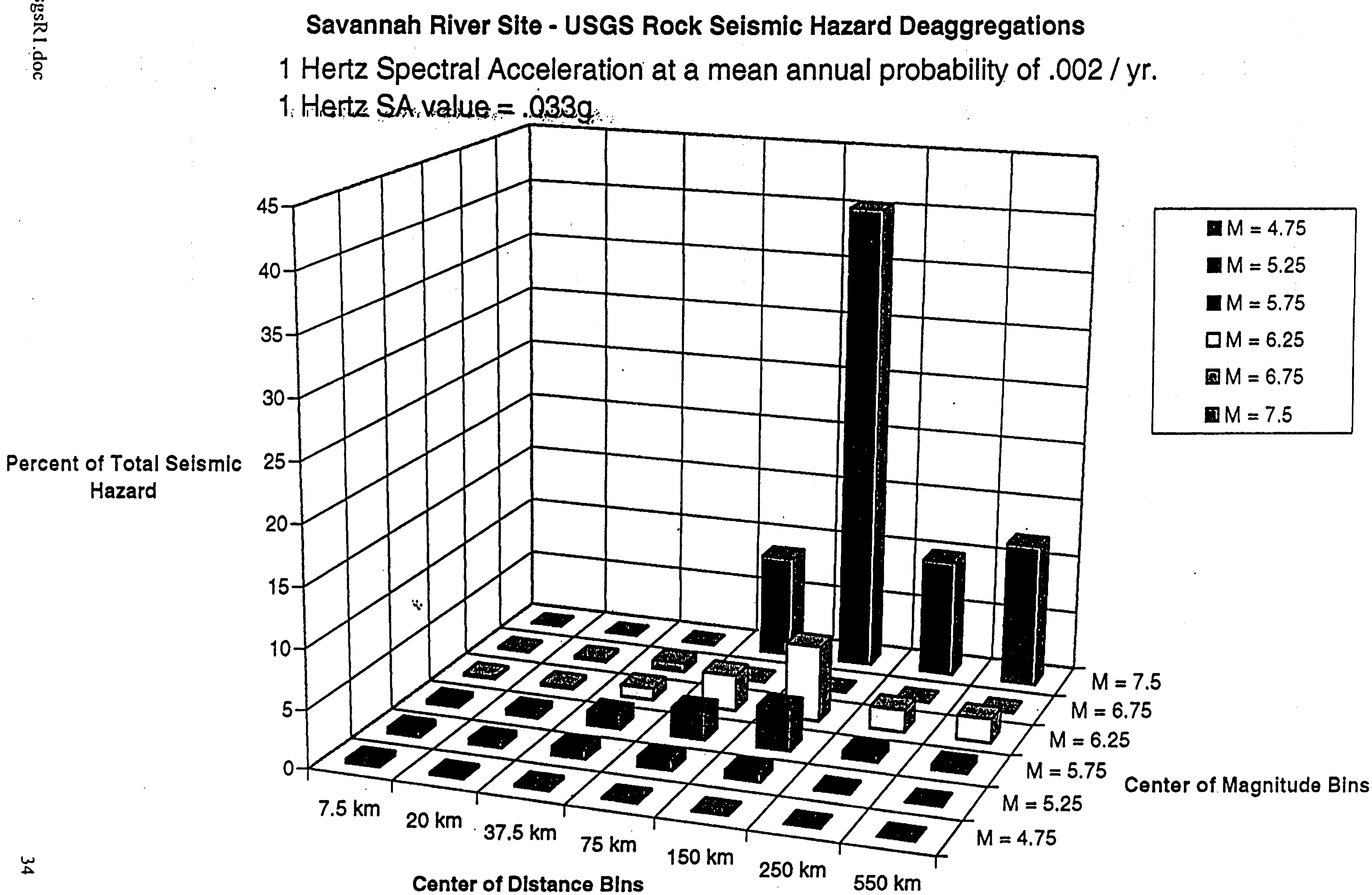

Figure 5a – USGS bedrock 1-Hz hazard disaggregation for SRS with mean annual probability of exceedence of $2x10^{-3}$.

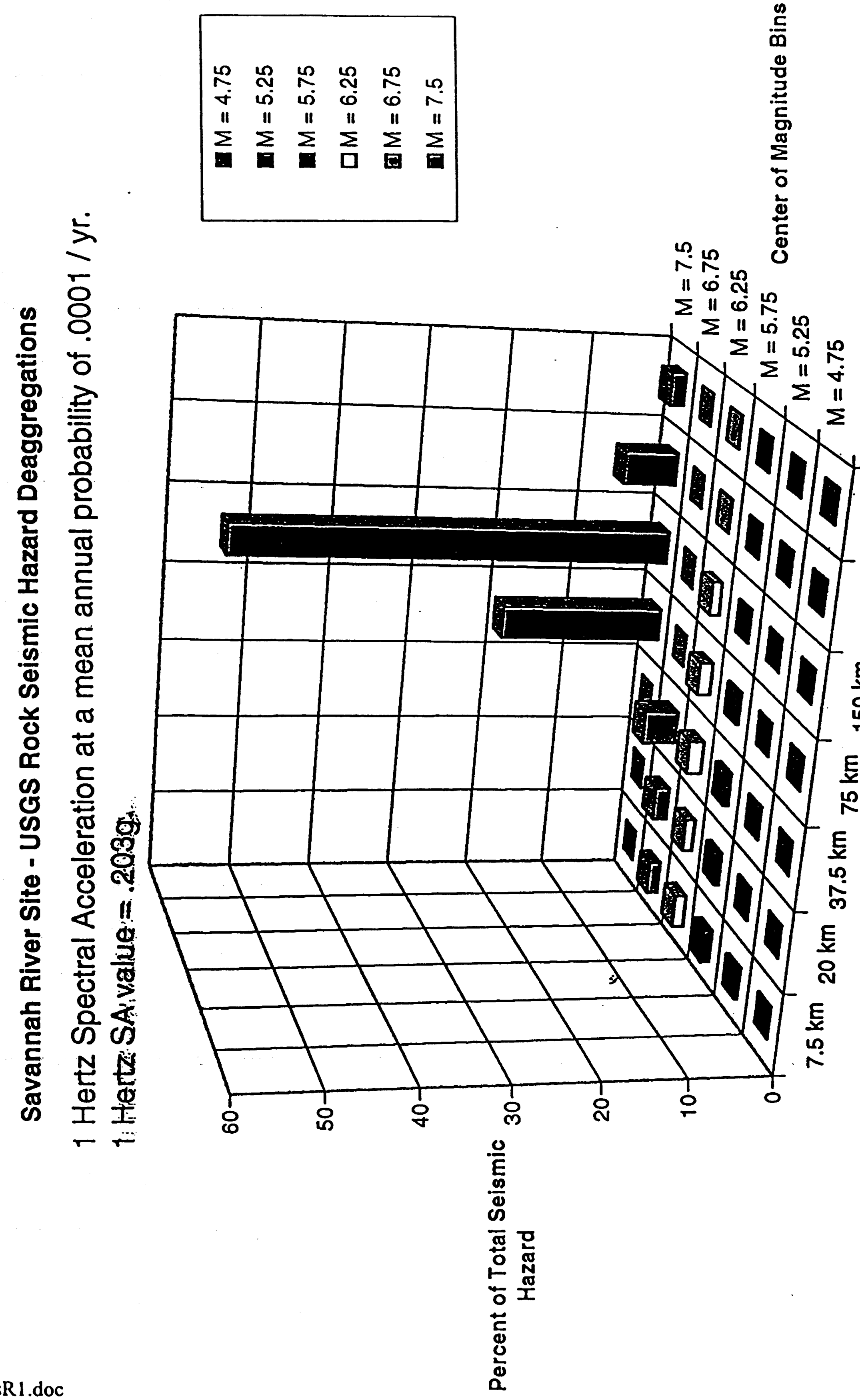

Figure 5b – USGS bedrock 1-Hz hazard disaggregation for SRS with mean annual probability of exceedence of $1x10^{-4}$.

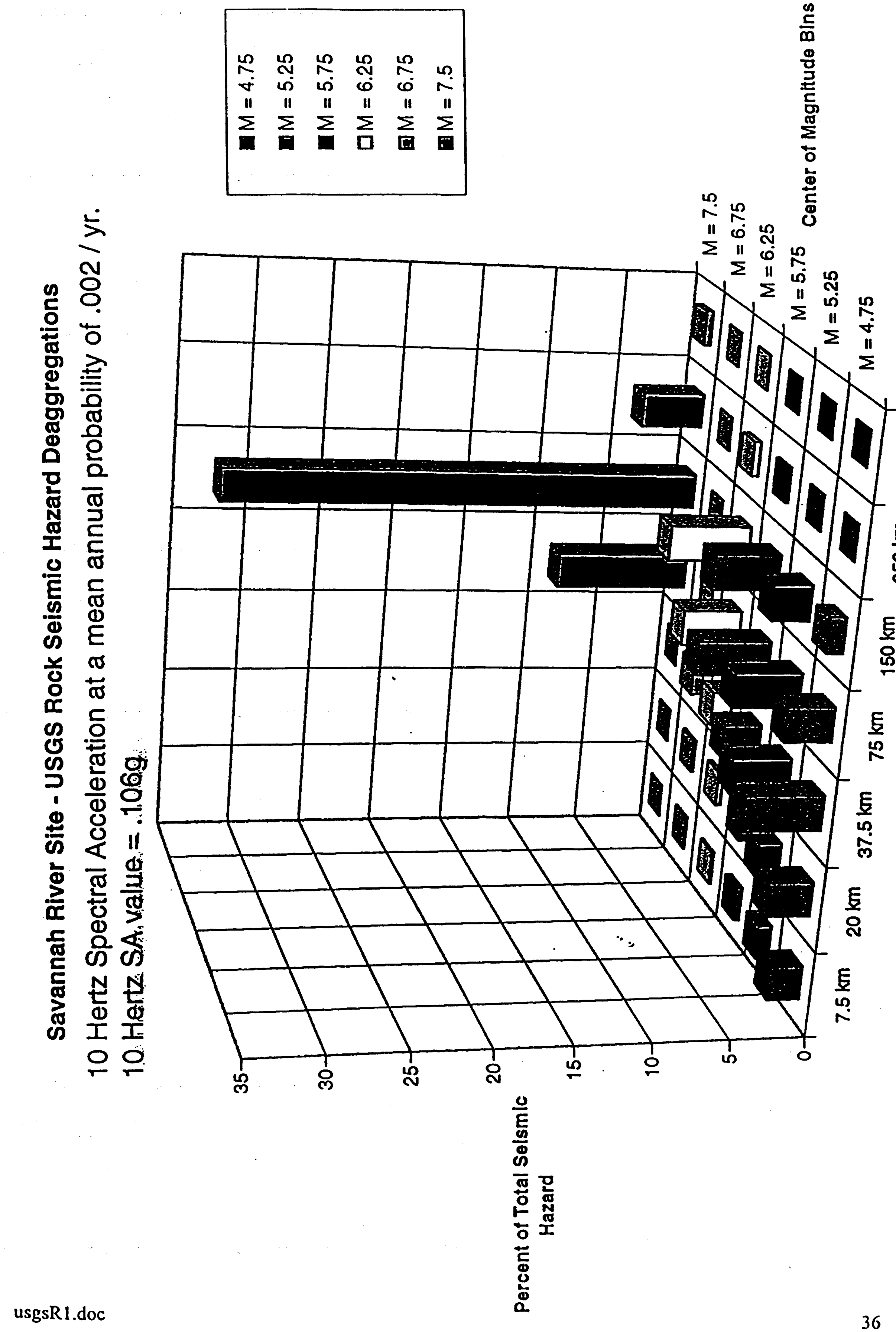

Figure 5c – USGS bedrock 10-Hz hazard disaggregation for SRS with mean annual probability of exceedence of $2x10^{-3}$.

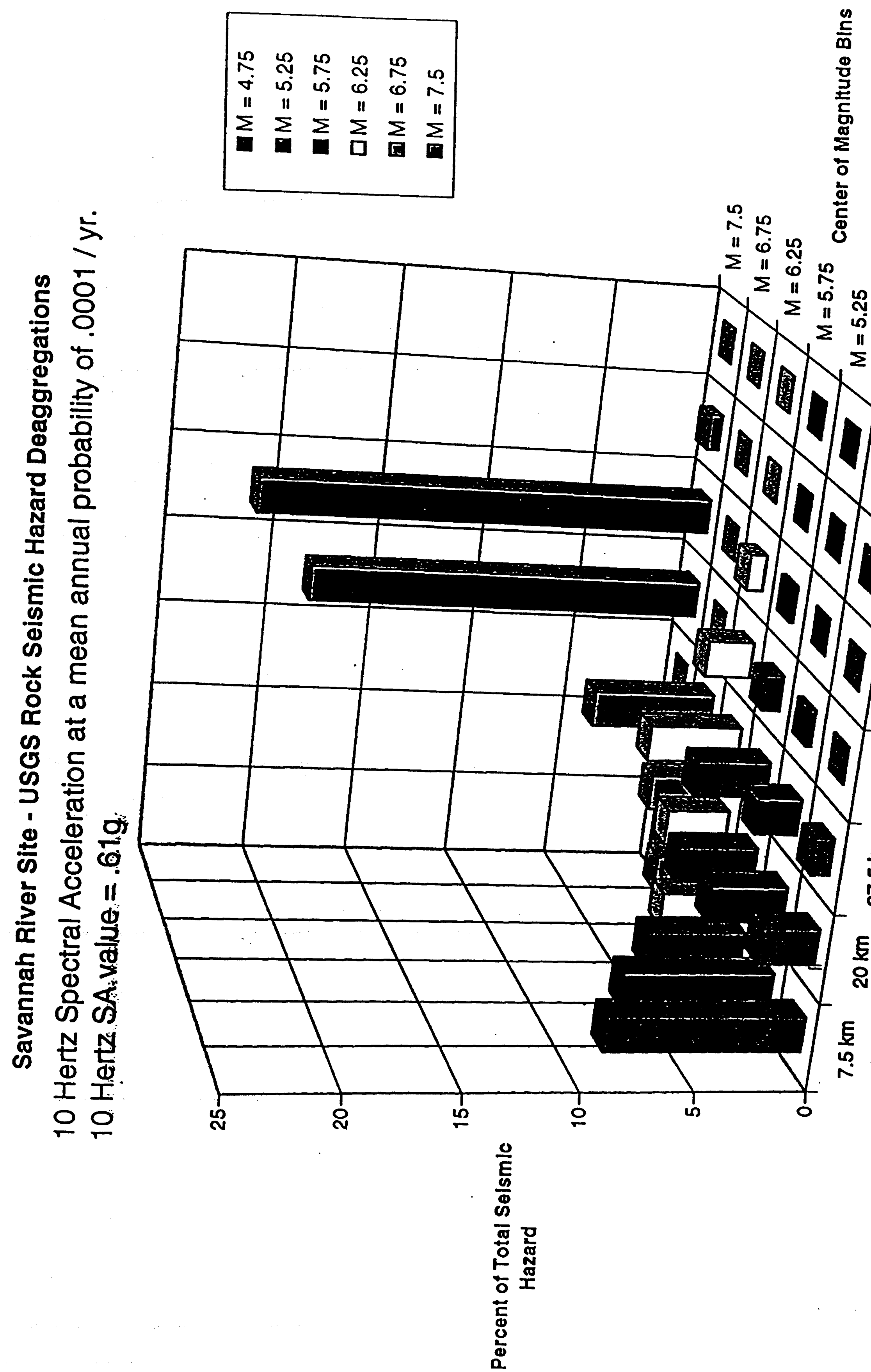

Figure 5d – USGS bedrock 10-Hz hazard disaggregation for SRS with mean annual probability of exceedence of $1x10^{-4}$.

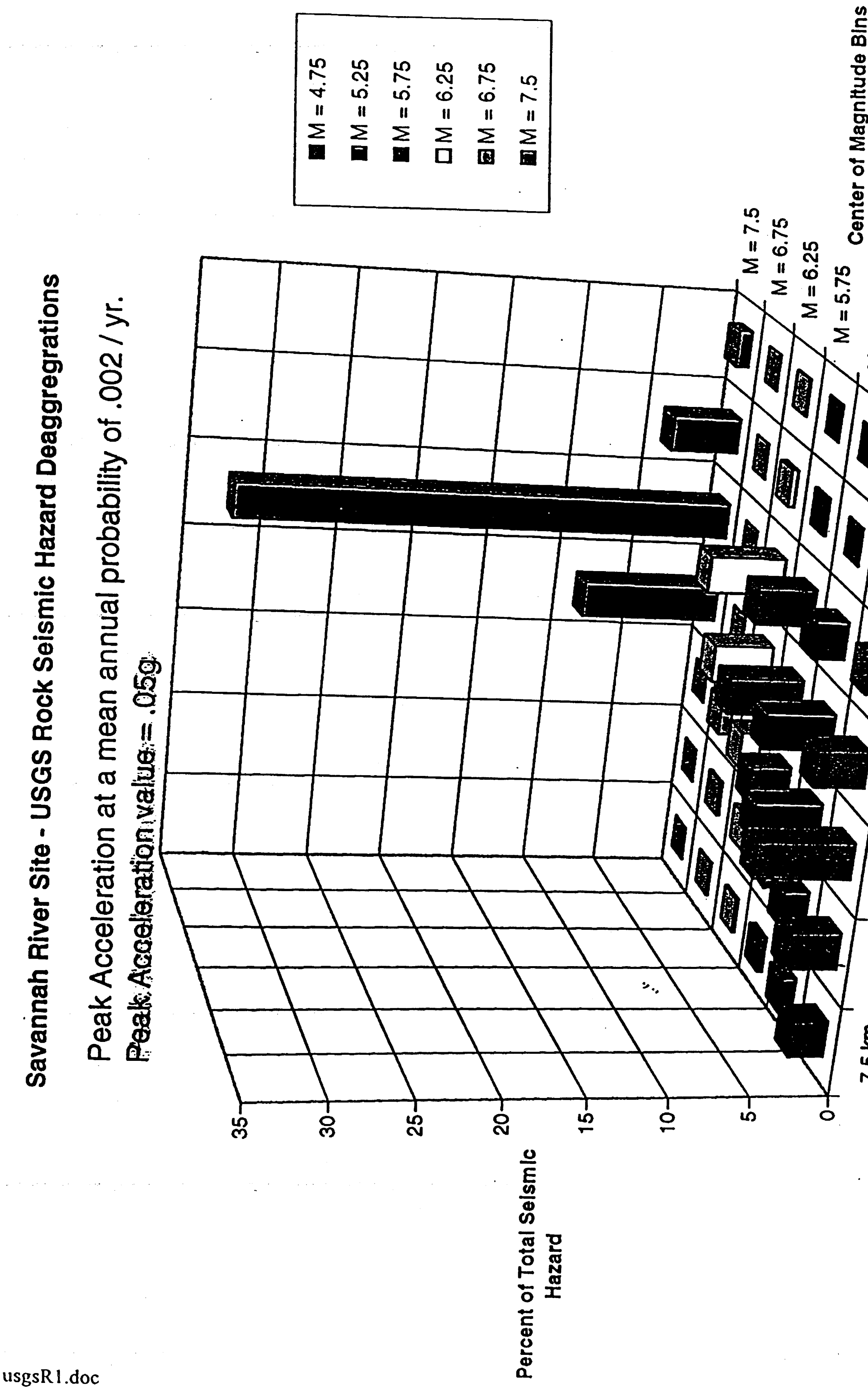

Figure 5e – USGS bedrock PGA hazard disaggregation for SRS with mean annual probability of exceedence of $2x10^{-3}$.

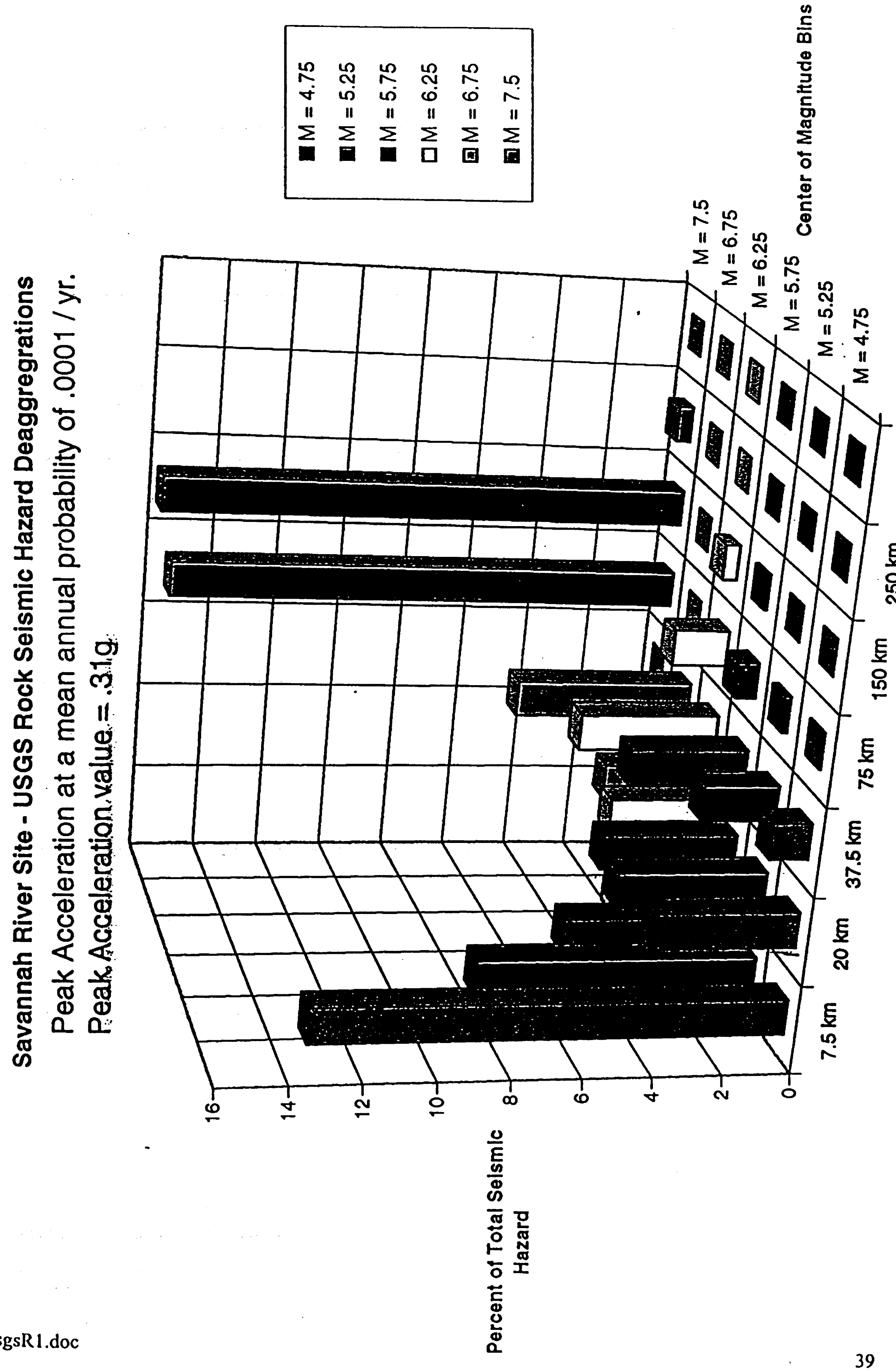

Figure 5f – USGS bedrock PGA hazard disaggregation for SRS with mean annual probability of exceedence of $1x10^{-4}$.

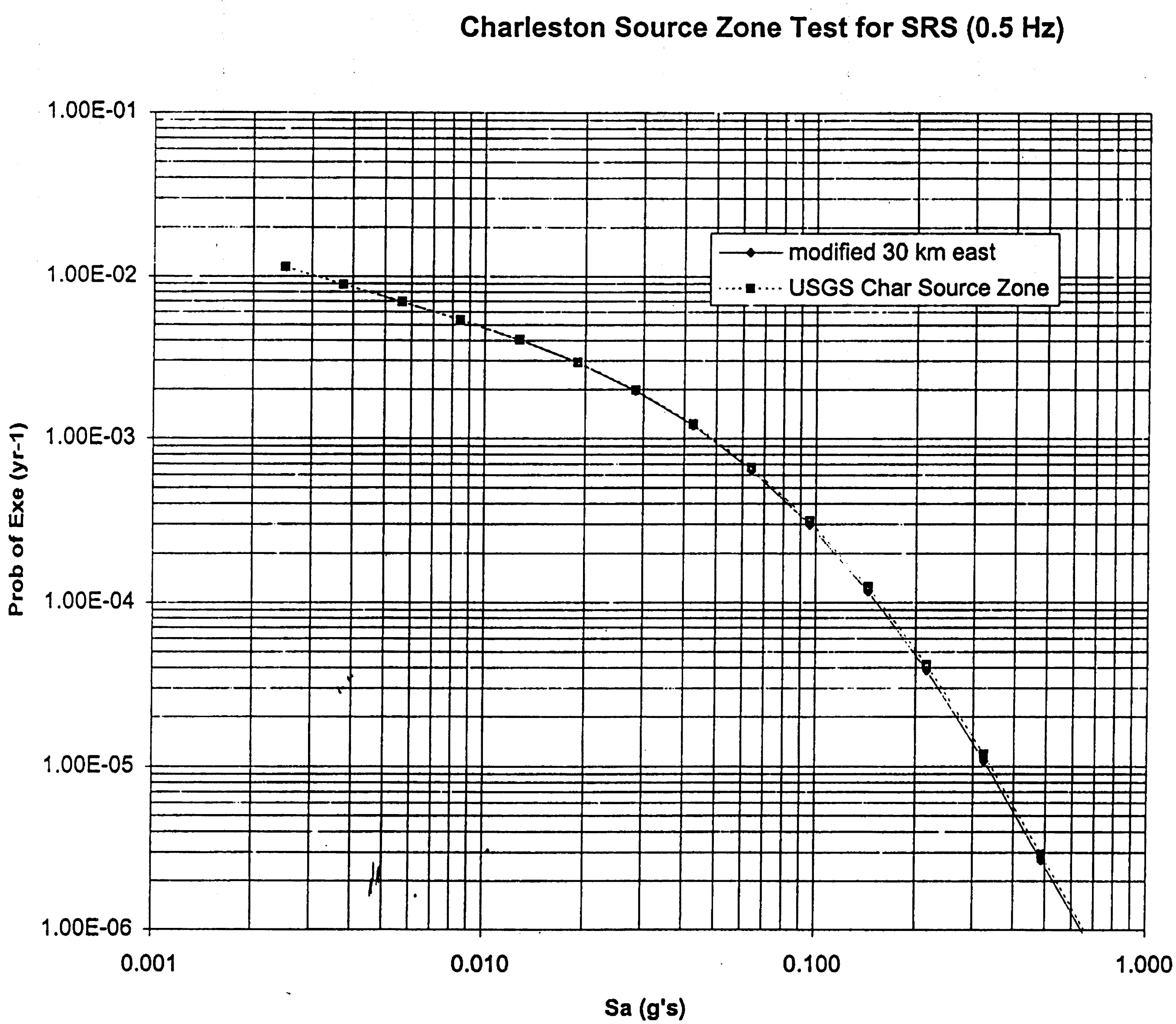

Figure 6a – Comparison of SRS bedrock 0.5-Hz hazard using USGS96 attenuation model and alternate Charleston source zones.

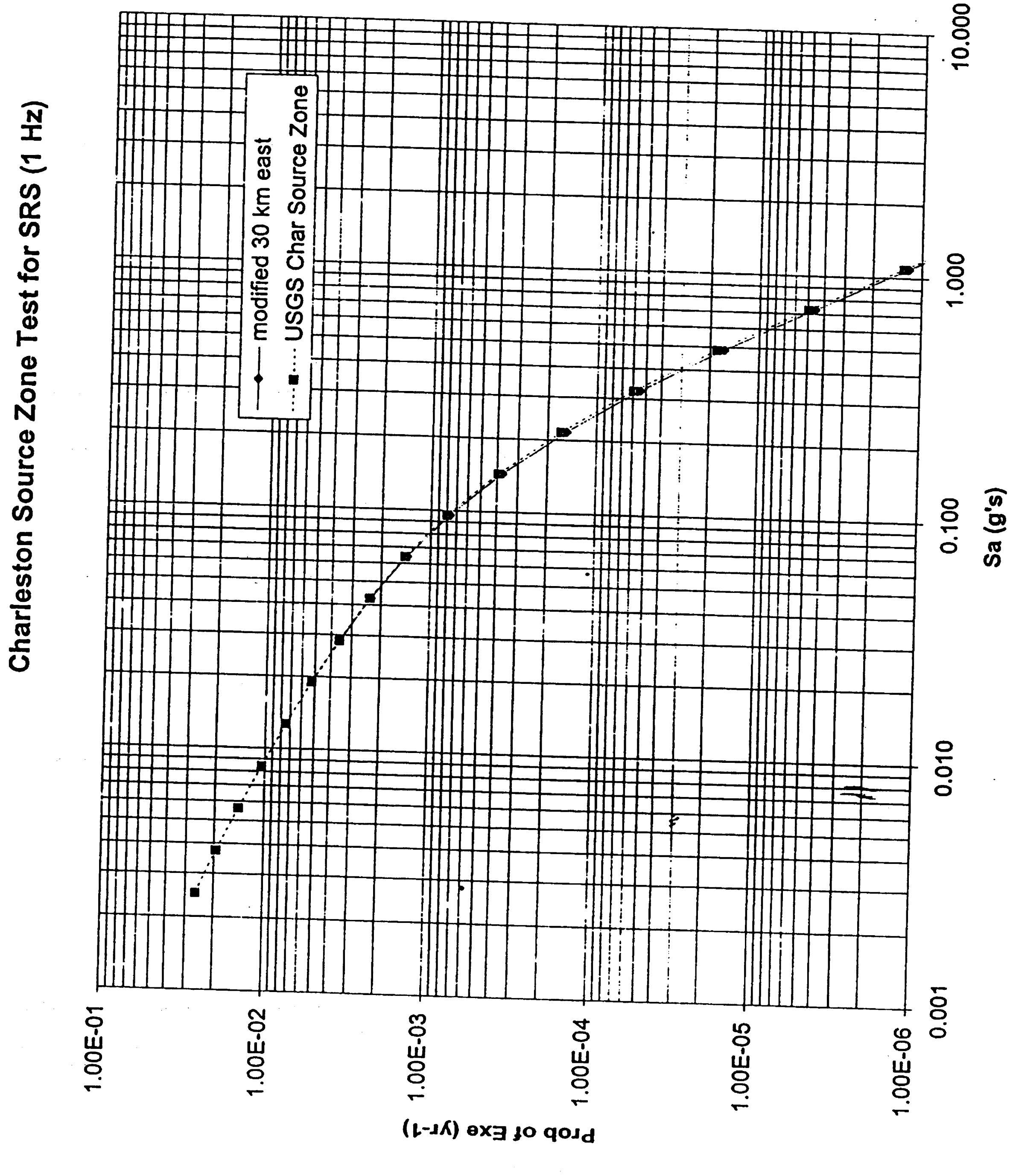

Figure 6b – Comparison of SRS bedrock 1-Hz hazard using USGS96 attenuation model and alternate Charleston source zones.

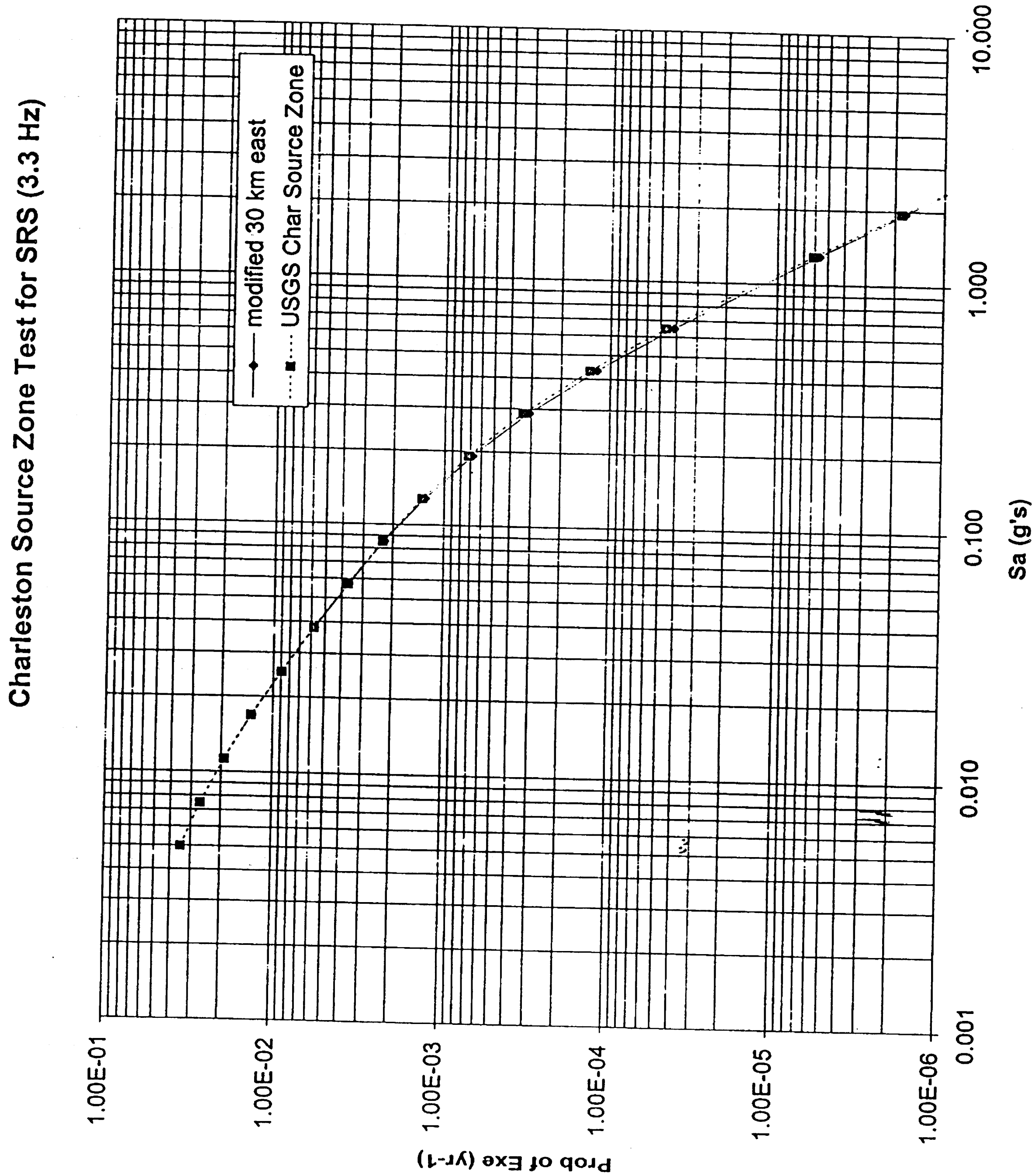

Figure 6c – Comparison of SRS bedrock 3.3 Hz hazard using USGS96 attenuation model and alternate Charleston source zones.

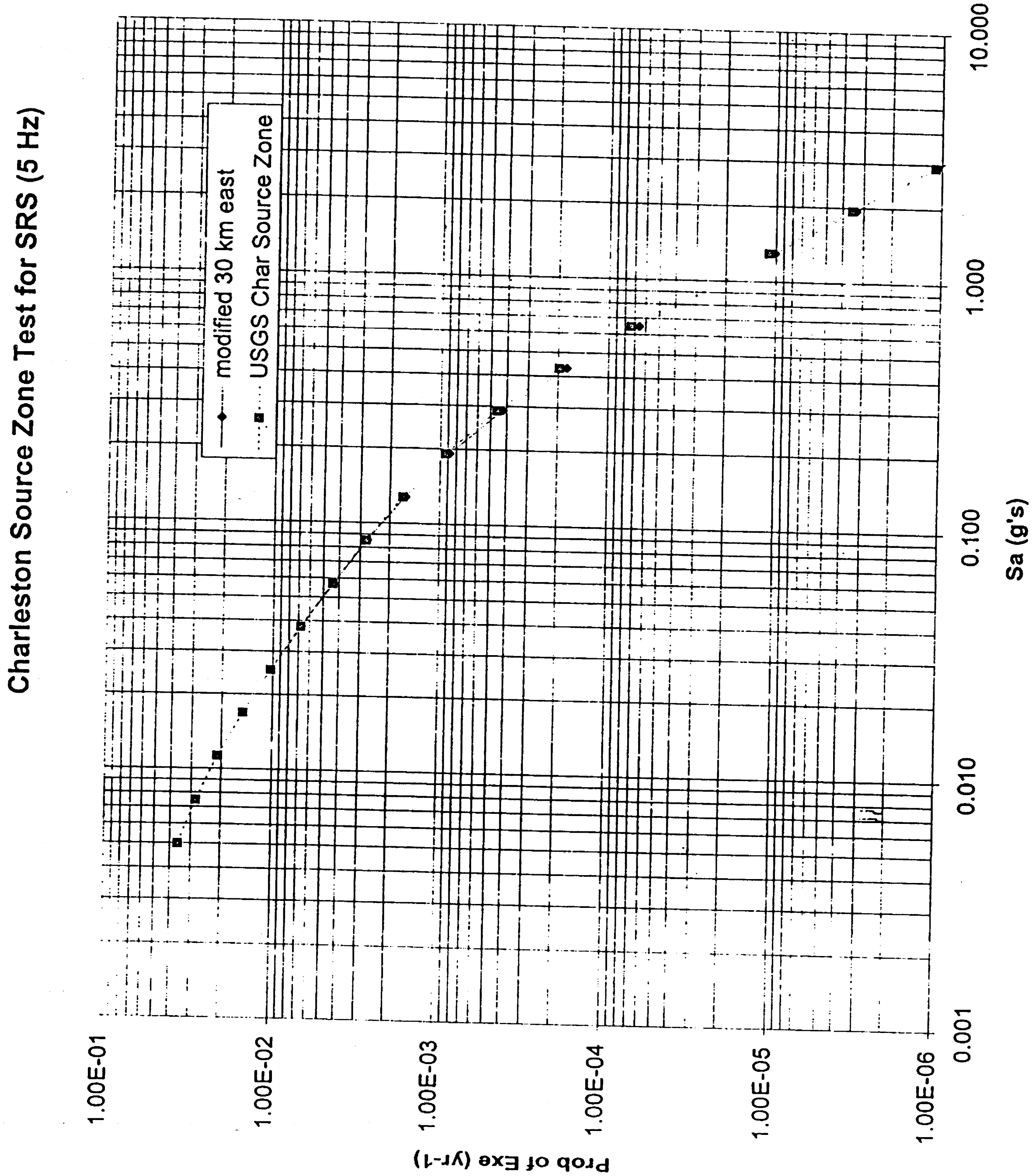

Figure 6d – Comparison of SRS bedrock 5 Hz hazard using USGS96 attenuation model and alternate Charleston source zones.

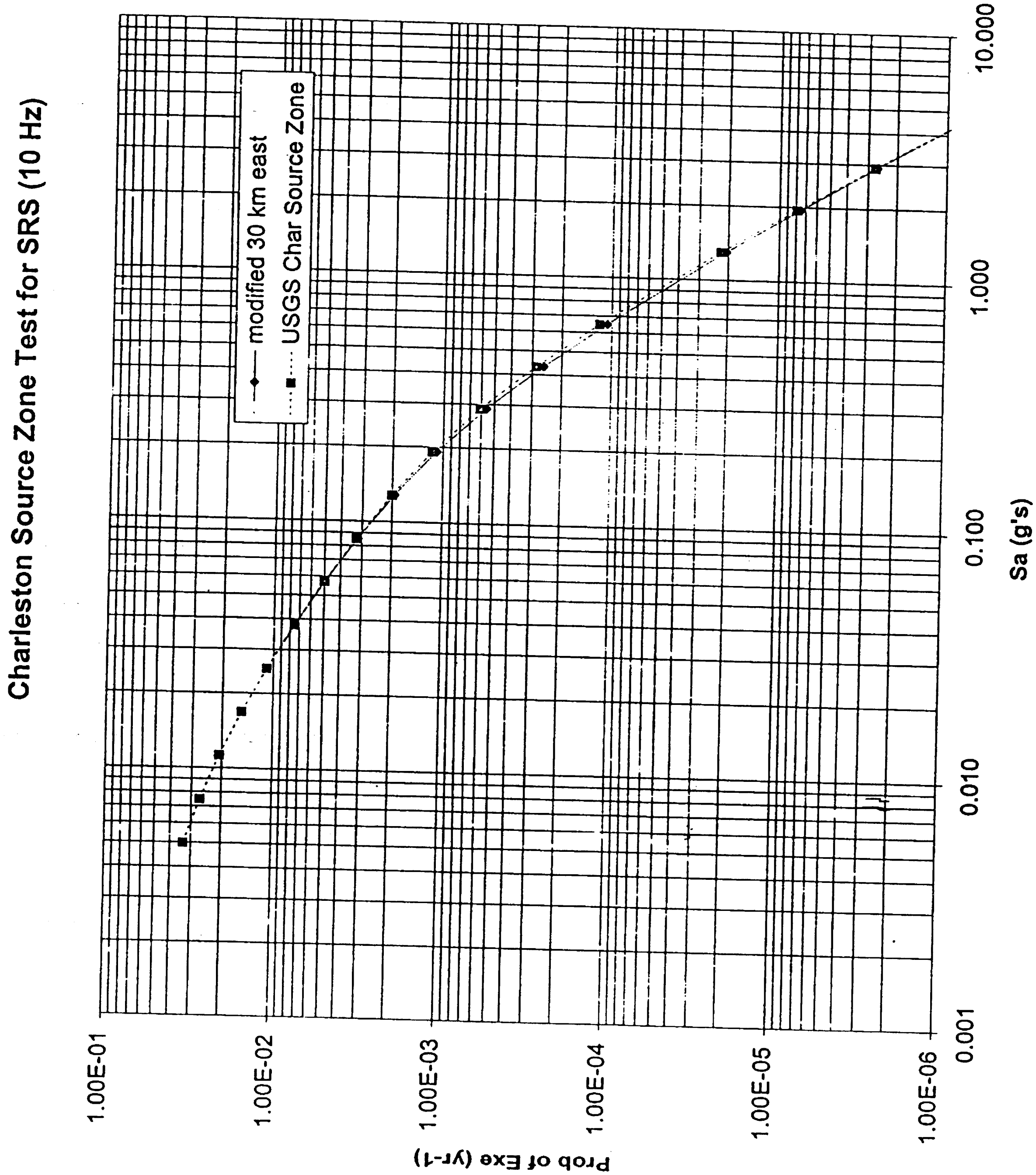

Figure 6e – Comparison of SRS bedrock 10 Hz hazard using USGS96 attenuation model and alternate Charleston source zones.

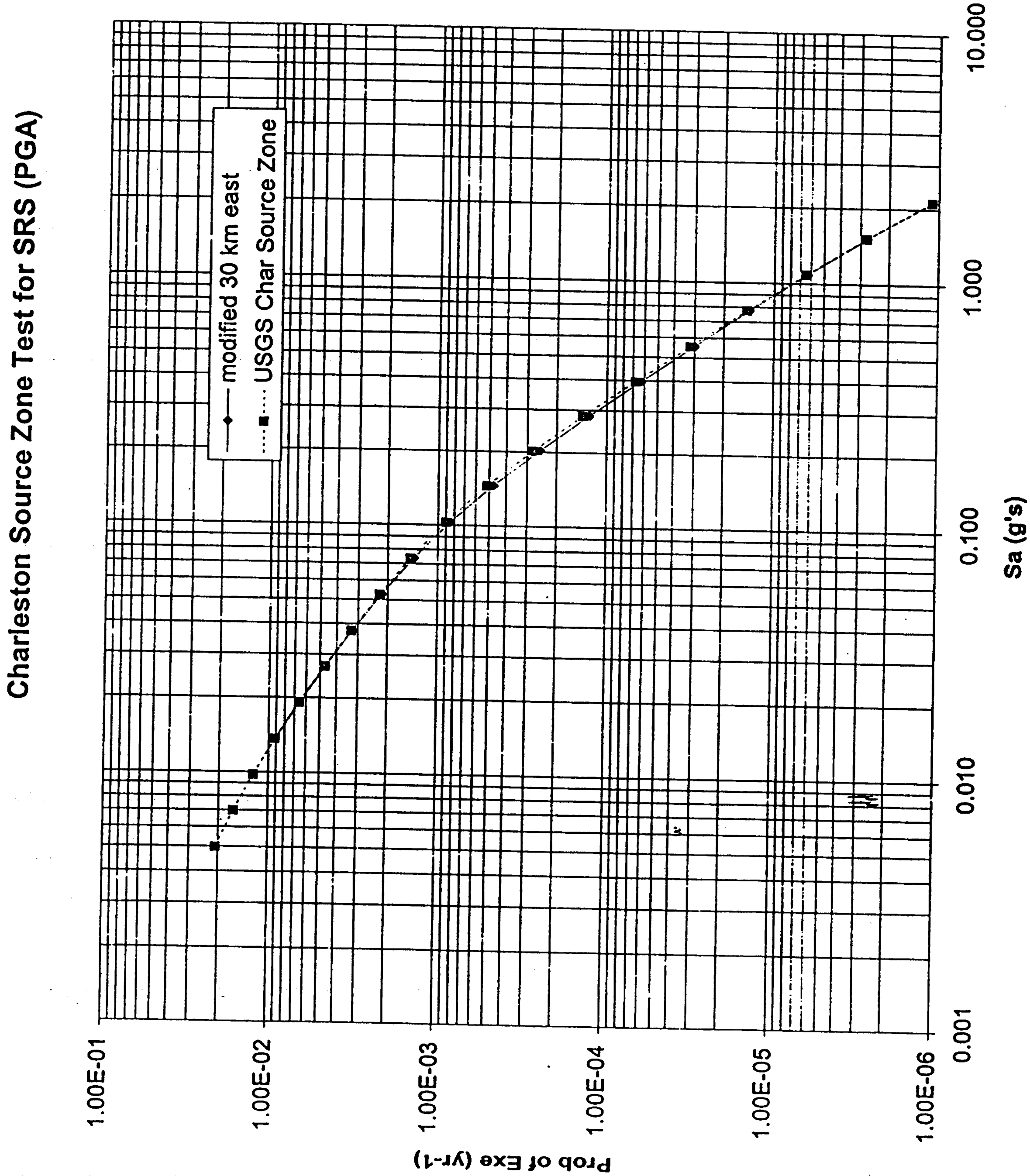

Figure 6f – Comparison of SRS bedrock PGA hazard using USGS96 attenuation model and alternate Charleston source zones.

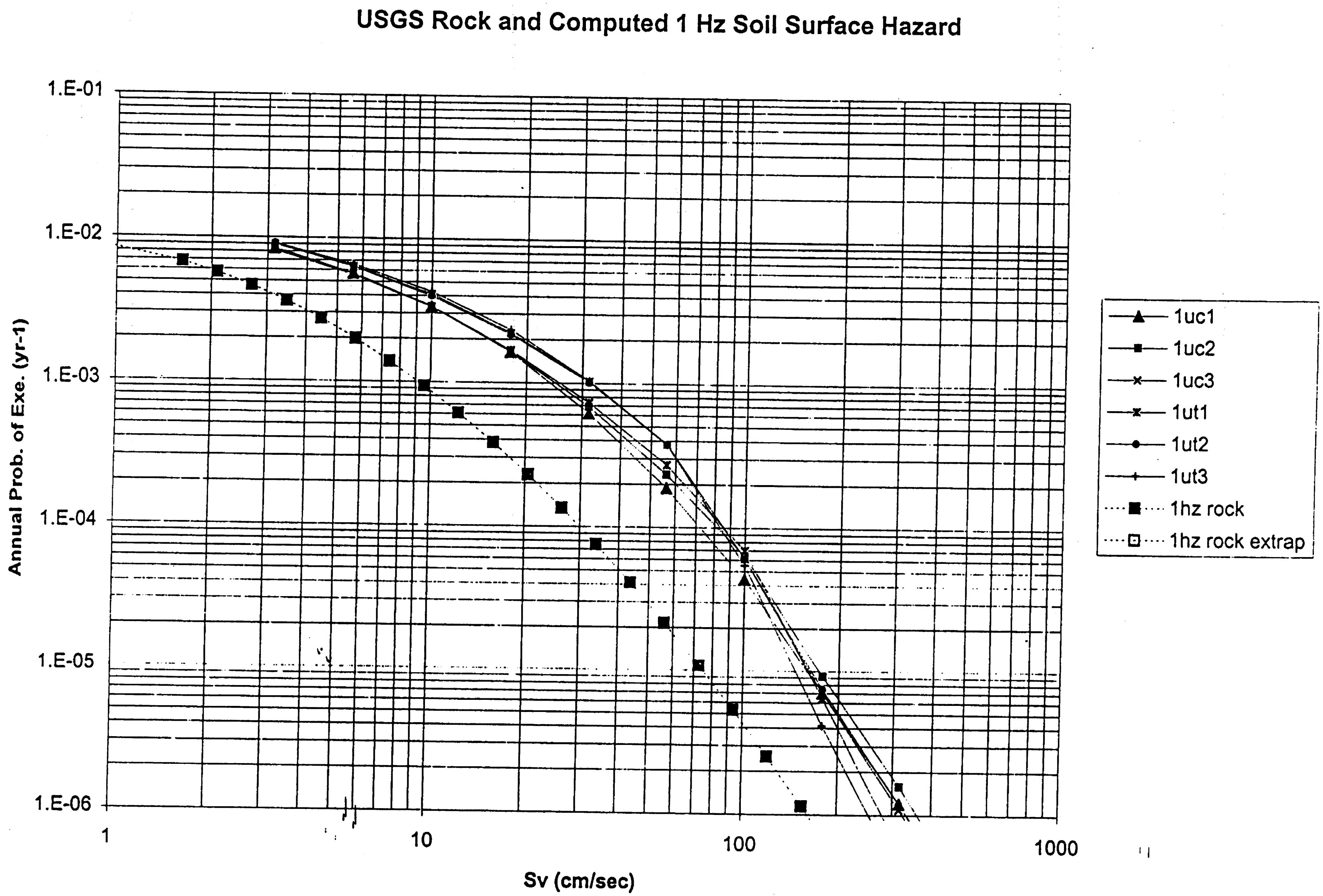

Figure 7a – Computed USGS 1-Hz soil surface hazard for six SRS site/bedrock conditions (solid lines). The letters "c" or "t" in the legend correspond to crystalline or Triassic bedrock respectively and the end numbers "1", "2", or "3" correspond to the soil column thickness category. USGS bedrock hazard shown by dotted line.

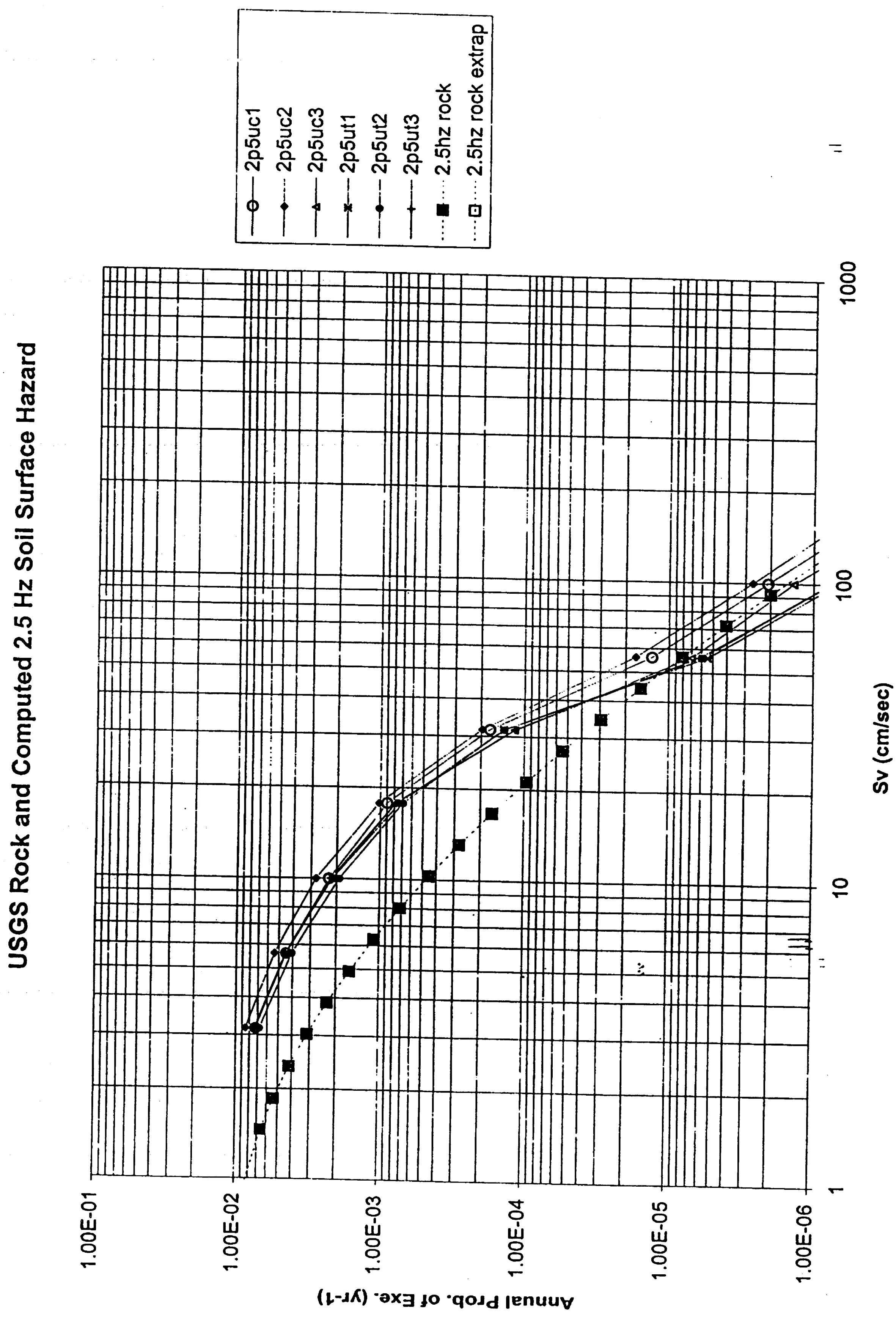

Figure 7b – Computed USGS 2.5-Hz soil surface hazard for six SRS site/bedrock conditions (solid lines). The letters "c" or "t" in the legend correspond to crystalline or Triassic bedrock respectively and the end numbers "1", "2", or "3" correspond to the soil column thickness category. USGS bedrock hazard shown by dotted line.

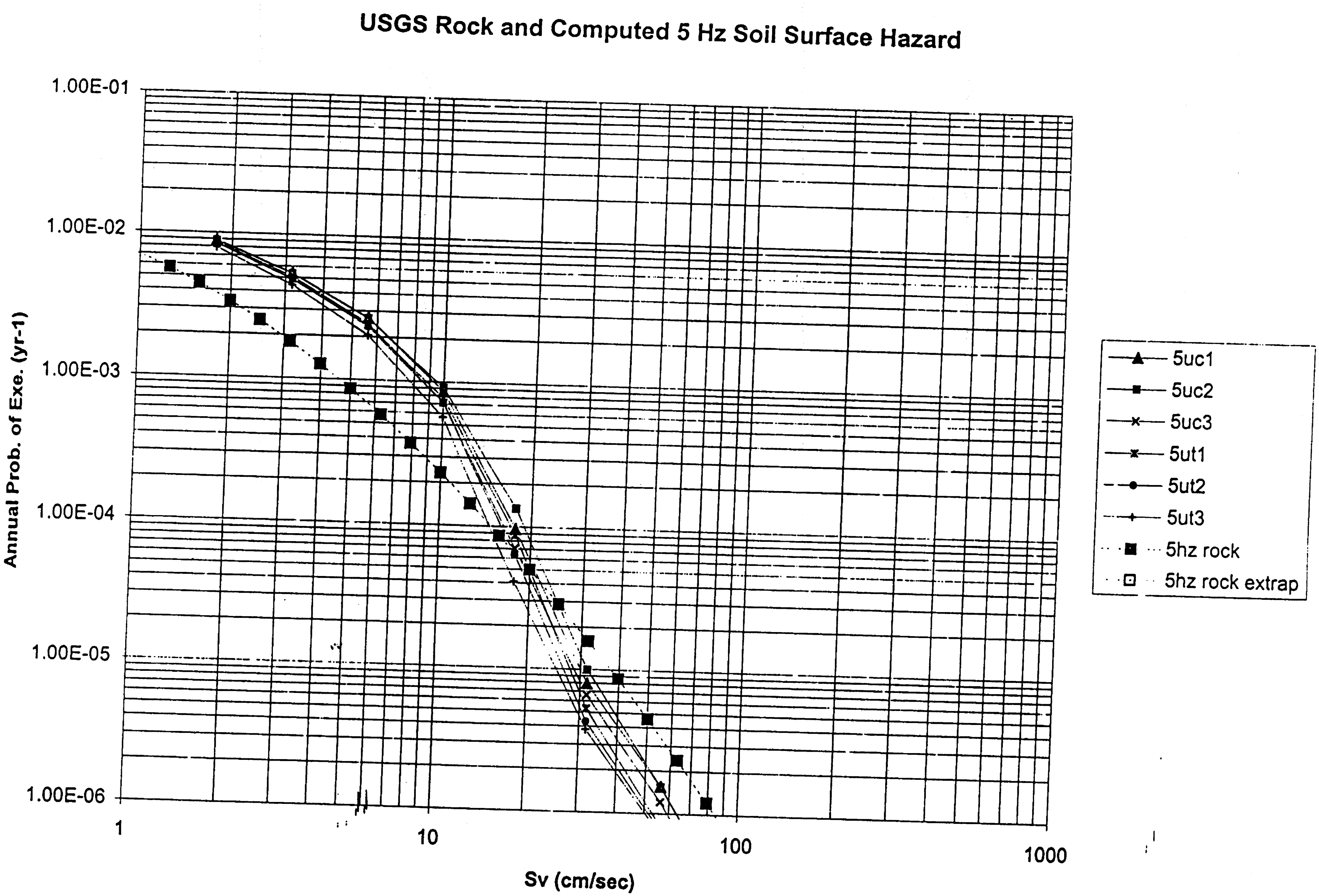

Figure 7c – Computed USGS 5-Hz soil surface hazard for six SRS site/bedrock conditions (solid lines). The letters "c" or "t" in the legend correspond to crystalline or Triassic bedrock respectively and the end numbers "1", "2", or "3" correspond to the soil column thickness category. USGS bedrock hazard shown by dotted line.

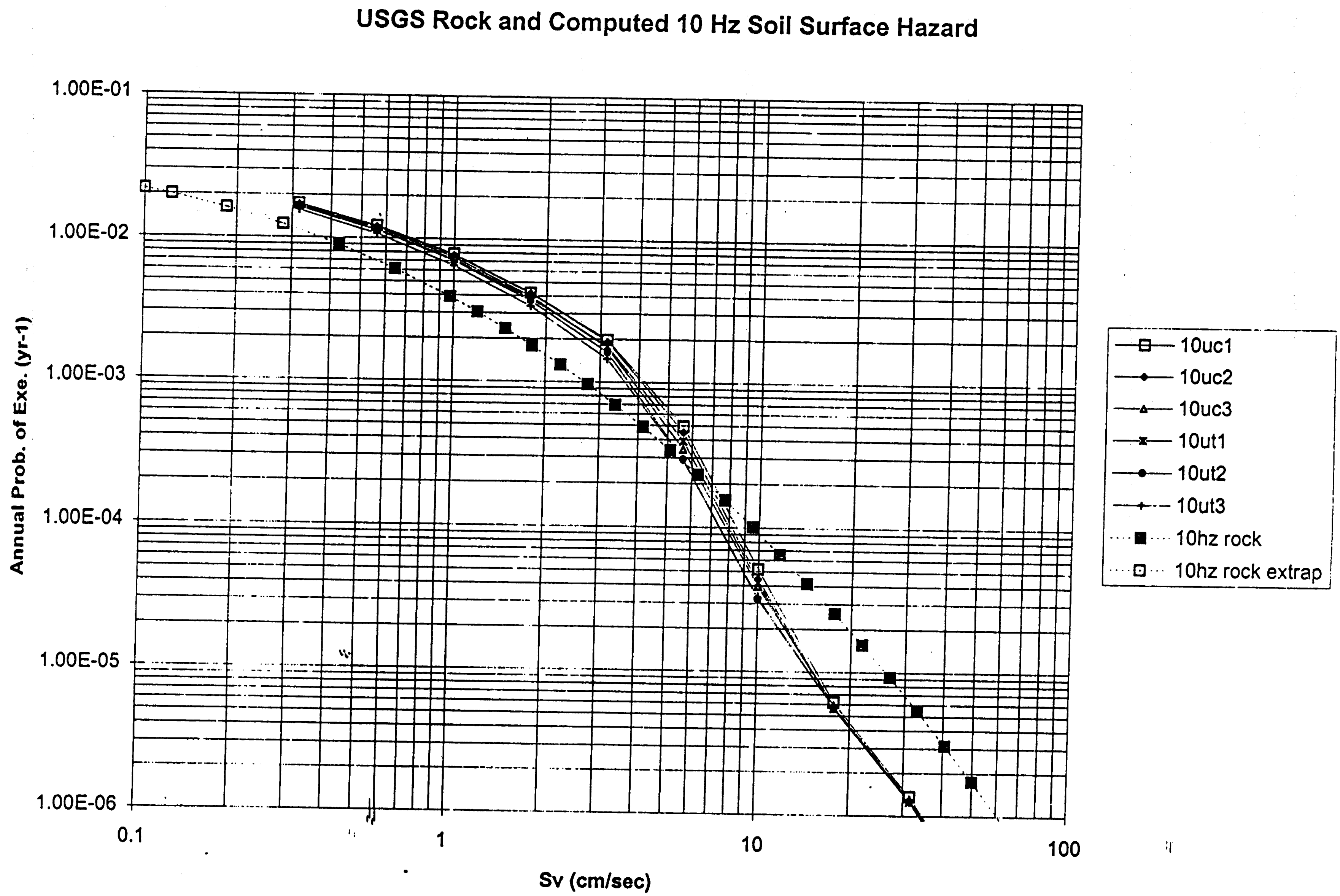

Figure 7d – Computed USGS.10-Hz soil surface hazard for six SRS site/bedrock conditions (solid lines). The letters "c" or "t" in the legend correspond to crystalline or Triassic bedrock respectively and the end numbers "1", "2", or "3" correspond to the soil column thickness category. USGS bedrock hazard shown by dotted line.

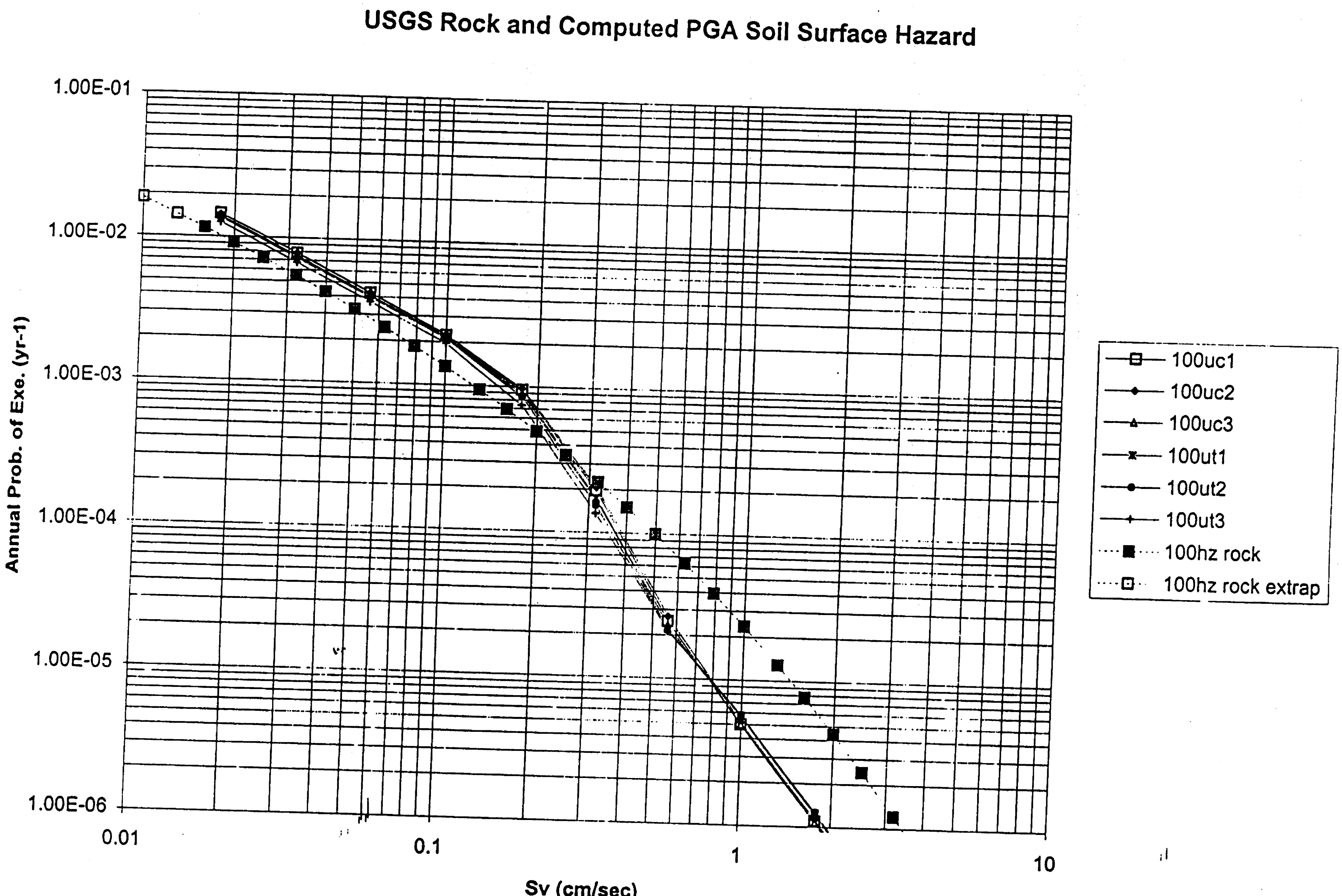

Figure 7e – Computed USGS PGA soil surface hazard for six SRS site/bedrock conditions (solid lines). The letters "c" or "t" in the legend correspond to crystalline or Triassic bedrock respectively and the end numbers "1", "2", or "3" correspond to the soil column thickness category. USGS bedrock hazard shown by dotted line.

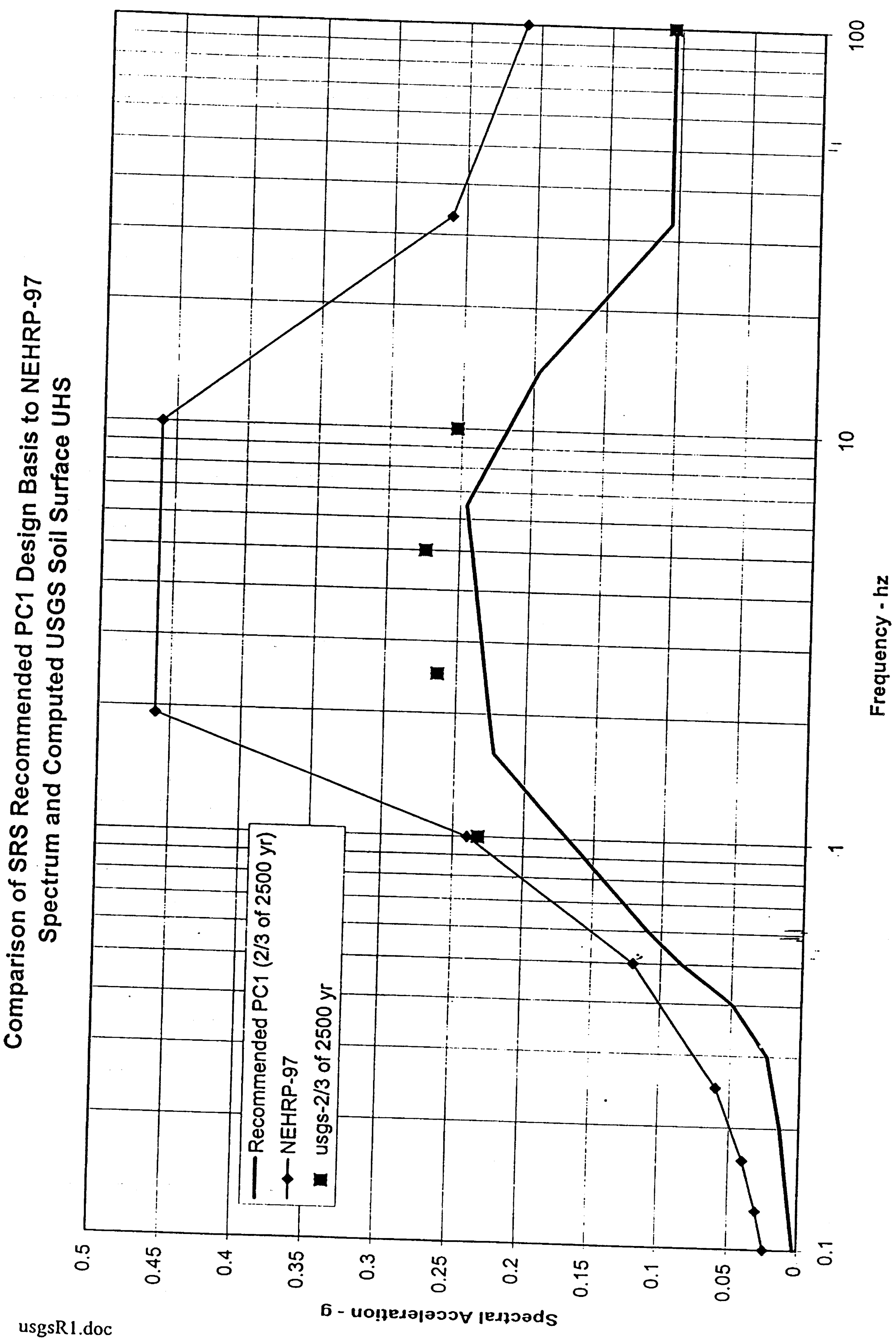

Figure 8 – Comparison of SRS PC1 spectrum to NEHRP-97 spectrum and USGS soil UHS for a criterion of 2/3 of the 2500-year return period.

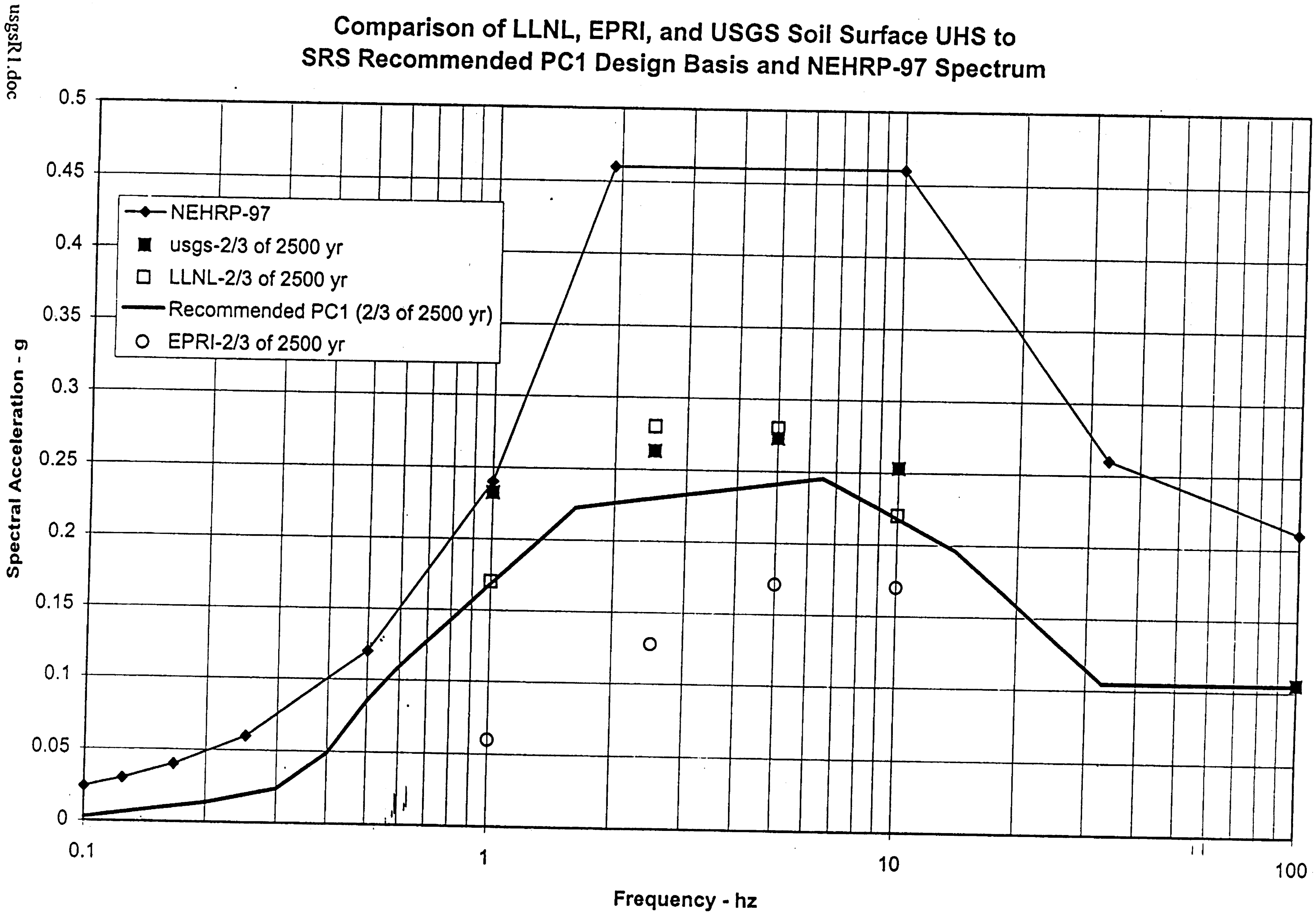

Figure 9a - Comparison of SRS site-specific soil UHS derived from USGS, LLNL and EPRI bedrock hazard evaluations and a criterion of 2/3 of the 2500 year return period. Also shown are the SRS PC1 and NEHRP-97 spectra.

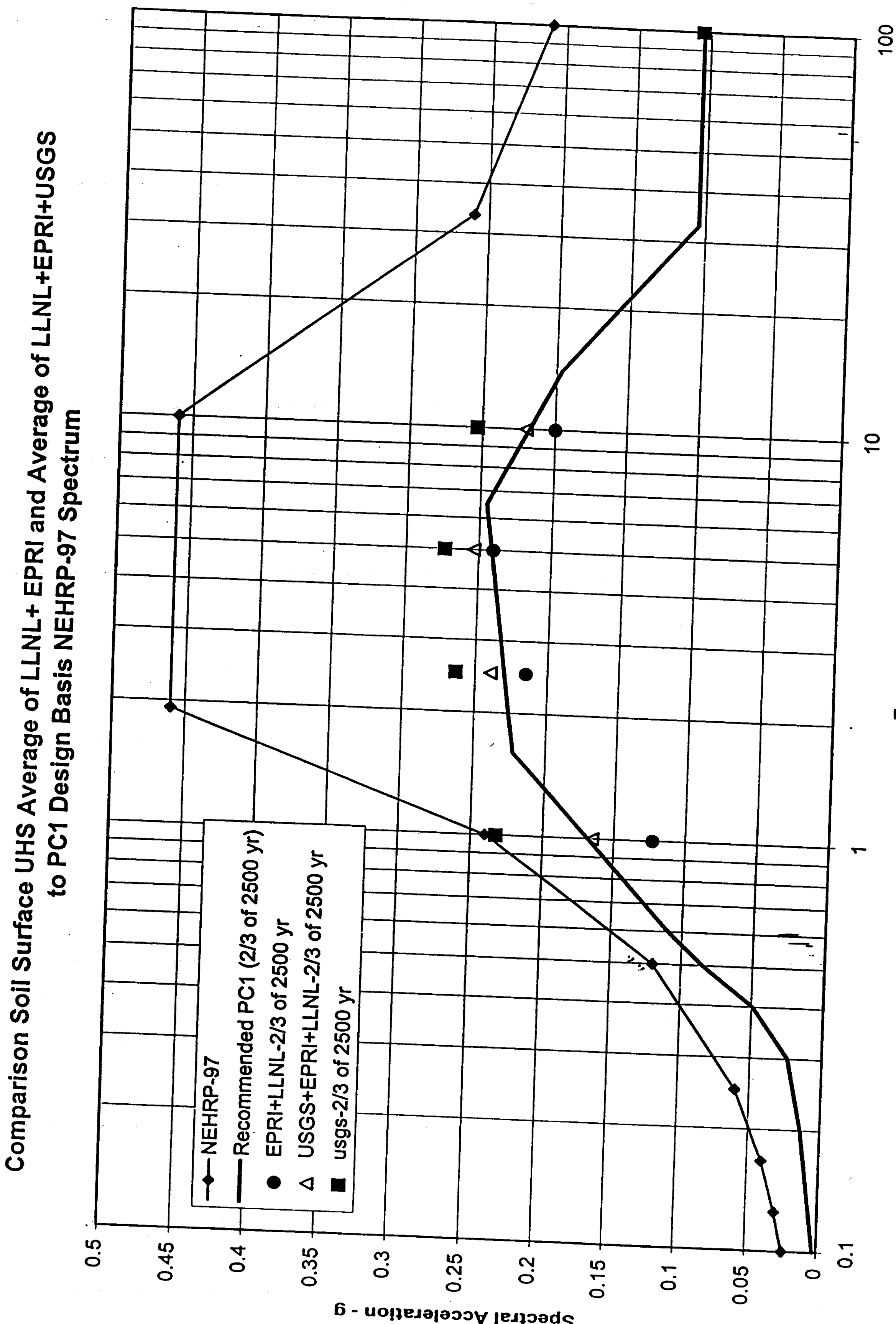

Figure 9b - Comparison of the average LLNL and EPRI soil hazard to the average LLNL, EPRI, and USGS soil hazard using a criterion of 2/3 of the 2500 year return period. Also shown are the SRS PC1, NEHRP-97 spectra and USGS soil UHS.

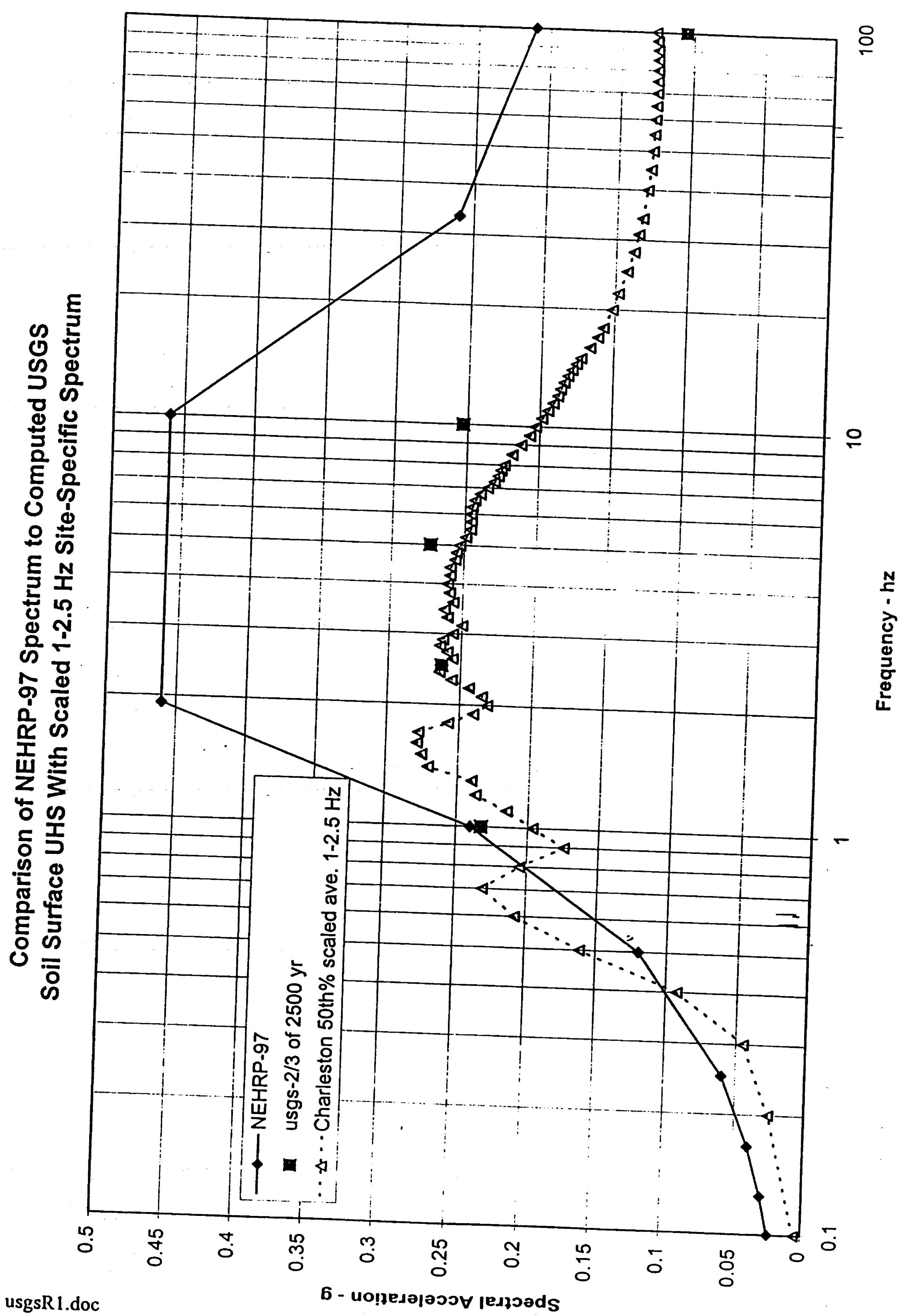

Figure 10 – Comparison of NEHRP-97 spectrum to USGS soil UHS with 1-2.5 Hz scaled Charleston 50th percentile spectrum for a criterion of 2/3 of the 2500-year return period.