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Review of Earthquake Hazard Assessments
of
Plant Sites at Paducah, Kentucky
and
Portsmouth, Ohio

by

U. S. Geological Survey

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Abstract

Members of the US Geological Survey staff in Golden, Colorado, have reviewed the submissions of Lawrence Livermore National Laboratory (LLNL) staff and of Risk Engineering, Inc. (REI) (Golden, Colorado) for seismic hazard estimates for Department of Energy facilities at Portsmouth, Ohio, and Paducah, Kentucky. We reviewed the historical seismicity and seismotectonics near the two sites, and general features of the LLNL and EPRI/SOG methodologies used by LLNL and Risk Engineering respectively, and also the separate Risk Engineering methodology used at Paducah. We discussed generic issues that affect the modeling of both sites, and performed alternative calculations to determine sensitivities of seismic hazard results to various

assumptions and models in an attempt to assign reasonable bounding values of the hazard.

In our studies we find that peak acceleration values of 0.08 g for Portsmouth and 0.32 g for Paducah represent central values of the ground motions obtained at 1000-year return periods. Peak accelerations obtained in the LLNL and Risk Engineering studies have medians near these values (results obtained using the EPRI/SOG methodology appear low at both sites), and we believe that these medians are appropriate values for use in the evaluation of systems, structures, and components for seismic structural integrity and for the seismic design of new and improved systems, structures, and components at Portsmouth and Paducah.

I. Executive Summary

• Introduction

Members of the US Geological Survey staff in Golden, Colorado, have reviewed the submissions of Lawrence Livermore National Laboratory (LLNL) staff and of Risk Engineering, Inc. (REI) (Golden, Colorado) for seismic hazard estimates for Department of Energy gaseous diffusion plant facilities at Portsmouth, Ohio, and Paducah, Kentucky. In this review we have incorporated seismic histories of the vicinities of the two sites, discussion of the tectonic issues, and a general overview of the characteristics of the LLNL and EPRI/SOG methodologies used by LLNL and Risk Engineering, respectively, and also the separate Risk Engineering methodology used at Paducah. We have discussed generic issues which affect the modeling of both sites and we have also performed alternative calculations of our own to determine sensitivities of seismic hazard results to various assumptions and models and to attempt to bound the levels of ground motion at the two sites in a reasonable way. The spectra generated by the various methodologies have been compared with each other and with spectra generated by the National Earthquake Hazards Reduction Program (NEHRP) recommended provisions and the methods of document UCRL-15910. Because issues of catalog magnitudes are important in assessing the applicability of current attenuation functions, we have included a review of the characteristics of various magnitude scales and their relationships in both the eastern and western United States. The various hazard studies at Paducah produce results in reasonable agreement, when adjustments are made to the methodologies to represent finite ruptures along the New Madrid fault zone. At Portsmouth, however, the probabilistic ground

motions differ by a factor of two from one another. We have investigated possible sources of this discrepancy, and have also attempted to assess which of the results is more likely given the historical intensities experienced in the vicinity of Portsmouth. (In this report, "intensity" refers to Modified Mercalli intensity.)

These investigations are described in detail in sections II through IX. Summaries of the respective results are found below.

• The setting of the two sites with respect to the occurrence of historical seismicity.

The seismicity of the Midwest region including Paducah and Portsmouth is dominated by the large earthquakes in the New Madrid seismic zone. The four great shocks that occurred there in 1811-1812 were each large enough to produce intensities of VIII in the vicinity of Paducah and VI and VII in the vicinity of Portsmouth. Although there are no specific reports available for either city from the 1811-1812 earthquakes, the estimated intensities for the two cities are high enough to cause minor damage (fallen plaster, broken windows) at Portsmouth and structural damage to ordinary unreinforced masonry construction at Paducah.

Six historical earthquakes not from this New Madrid sequence were found capable of producing intensities of VI (five earthquakes) to VIII (one earthquake) in the vicinity of Paducah. Three historical earthquakes not from the New Madrid sequence were found capable of producing intensity VI in the vicinity of Portsmouth.

- **Tectonic environment in the vicinity of the two sites.**

The source zones defined in the EPRI and LLNL seismic hazard methodologies represent a wide range of interpretations regarding possible future locations of earthquakes, their sizes, and frequencies of occurrence at and near the Paducah and Portsmouth sites. While the studies differ considerably in approach to defining seismic sources, both are limited by the large gaps in knowledge of the causes of earthquakes in the central and eastern United States. Considerably more detailed geologic information is available in the vicinity of the Paducah plant site than the Portsmouth site because of numerous field investigations related to the New Madrid earthquake region in the upper Mississippi embayment. Nonetheless, uncertainties remain regarding the characterization of seismic sources for both areas. We therefore expect a diversity of opinion concerning the relation of seismicity to geologic structure.

- **Sources of differences in hazard as a result of contrasting methodologies.**

Both the EPRI/SOG and LLNL seismic hazard estimation methodologies were designed to take into account and to represent the diversity of scientific opinion that exists regarding the probable locations of future earthquakes.

Differences in the EPRI/SOG and LLNL modeling procedures tend to produce several characteristic differences in the results of the two methodologies. (a) For the EPRI/SOG teams, source-zone sizes and choices tended to be constrained by meeting convened to discuss possible tectonic hypotheses and select candidate tectonic features which could be

considered for sources, while the LLNL experts had broader-scale zones and generally more varied delineation of source zones. Because of the use of multiple alternative scenarios, effectively there were more EPRI/SOG zones. (b) For the EPRI/SOG teams, the calculated likelihood of the existence of candidate source zones was strongly governed by the presence or absence of historical seismicity. At sites without prominent seismicity in the vicinity, the interaction of low likelihood of existence with low assessed zonal seismic rate often produced hazard estimates governed more by background zones than local features. (c) The EPRI/SOG seismicity rates were generally closer to the rates obtained from historical seismicity as compared to the LLNL rates. (d) Differences in the techniques used by LLNL and EPRI/SOG to select attenuation functions produced more variability in the LLNL ground motion attenuations (and probably one incorrect ground motion attenuation among them). (e) Differences in the methods of treating variability in model parameters produced more accurate assessment of the range of *variability* in hazard estimates using the LLNL methodology.

- **Generic modeling issues.**

We have investigated the role played in the hazard analysis of (1) point-rupture models vs various line-rupture models; (2) choice of depth of origin of strong ground motion; (3) choice of maximum magnitude; and (4) choice of which measure to use for "best estimate" of probabilistic ground motion value.

- **Point-rupture models.**

In general, point-source models are adequate for probabilistic ground motions that have annual exceedance probabilities of 2×10^{-3} to 1×10^{-3} or greater, for sources which are relatively inactive and for which maximum

magnitudes are not expected to produce ruptures more than about 10-20 km in length. For conventional equations relating magnitude and rupture length, these dimensions correspond to magnitudes of about 5.5 to 6.5 M_S . In the eastern United States, if earthquake ruptures are half of those values usually experienced in the western United States for strike-slip faults, and where source zones may be limited in length in the probable rupture direction, it is likely that point-source models are adequate up to magnitude 7.0 M_S , especially at exceedance probabilities which produce moderate to low ground motions (say, less than 0.3 g, peak horizontal acceleration).

On the other hand, for sources with maximum magnitudes above 6.5 M_S , for sites which are closer to the source than 60 km, and for return periods yielding moderate to large ground motions (say, greater than 0.3 g, peak horizontal acceleration), it is desirable to model the source with line-ruptures.

• Depth of origin of strong ground motion.

The effect of assumed depth of source of strong ground motion on the hazard estimate at the two sites is such that the effect of changing depths between a nominal 7 km and 3 or 10 km is often as great as the effect of changing the maximum magnitude by plus or minus 0.6 magnitude units, respectively.

Neither effect is very large, however. The sensitivity studies in this report suggest that for both sites, at ground motions having annual exceedance probabilities of 10^{-3} , the ground motions are low enough that the range in hazard owing to change in depth of earthquake source is small compared to the observed team-to-team or expert-to-expert range of alternative hazard estimates. In general, we expect that the contribution of the uncertainty in source depth to uncertainty in hazard is smaller than the contribution of the uncertainty in the

determination of source zone boundaries, seismicity parameters, or likelihood of zone existence.

• Maximum magnitude.

We have observed that the hazard result obtained by integrating over the uncertainty of symmetric maximum magnitude distributions is approximately that obtained by using the center magnitude of the uncertainty distribution. Our sensitivity studies, then, give a reasonable range with which to bound ground motion hazard estimates. The sensitivity studies suggest that for both the Paducah and Portsmouth sites, for ground motions having exceedance probabilities of 10^{-3} per year, the ground motions are low enough that the range of results obtained from a choice of maximum magnitude over a range of 6.1 (M_S) plus or minus 0.6 magnitude units is small compared to the observed range of alternative hazard estimates. In general, we expect that the choice of maximum magnitude may generally be a smaller source of uncertainty than the determination of source zone boundaries, seismicity parameters, or likelihood of zone existence.

• "Best" estimates: Median vs Mean.

Comparing the EPRI/SOG and LLNL studies at Portsmouth, the mean hazard values differ by a considerable amount. The LLNL values are higher, in part owing to the effect of ground motion expert 5. However, when the contribution of ground motion expert 5 is removed, the LLNL mean hazard value remains higher than the EPRI/SOG values, though by a lesser amount. This result occurs because of the generally larger variability of the LLNL estimates. (It may not be sufficiently appreciated that two hazard estimates with the same median value will have different mean

values, the larger mean corresponding to the hazard estimate with the greater variability.)

On the other hand, the median EPRI/SOG and LLNL values are quite similar, regardless of whether the opinion of ground motion expert 5 has been removed.

Ordinarily we would prefer a mean as a best estimate of hazard. The mean corresponds to a result which is an expected value under uncertainty. Furthermore the mean hazard is often similar to that obtained for sites close to source zones whose boundaries are based on clustering of historical seismicity. Finally, the mean hazard estimate of a long-tailed distribution of individual estimates is relatively conservative, corresponding to higher fractiles of that distribution. Nevertheless, it seems clear that the large difference in variability in the constituent estimates of the EPRI/SOG and LLNL studies has a large component due to the interaction of methodology and opinion, rather than variability inherent in the data or tectonic processes. *Thus there may be a methodological relative bias in mean LLNL and EPRI/SOG estimates.* On the other hand, the median estimates seem to be both resistant to extreme estimates as well as less sensitive to methodological differences, producing more stable results in these studies, and we think these reasons are sufficient for preferring medians in this study.

• Comparison studies.

Having investigated various model and parameter issues for generic sites in the central and eastern U. S., we have gone on (1) to test the sensitivity of standard models at the Portsmouth and Paducah to these generic issues, (2) to identify those modeling issues most critical to the site, and (3) to identify a range of values in which to expect site hazard values to lie.

• Portsmouth.

For the Portsmouth site, a 1000-yr probabilistic peak acceleration value of 0.082 g represents both the mean and median value of reasonable alternative values obtained in our studies. For the attenuation function used here, individual probabilistic ground motion values for various combinations of assumptions might be expected to range plus or minus 0.04 g about this median value, or about plus or minus 50 percent. In addition, at these ground motion levels, a variation of up to 50 percent might be expected owing to different choices of attenuation function. Our hazard curves lie in the higher fractiles of those curves given by the consultants, an effect that should be expected to be the case since the use of multiple alternative zonations should dilute the apparent hazard for sites in the vicinity of historical seismicity, compared to single zonations based on historical seismicity. We conclude therefore, that the median hazard estimates of the EPRI/SOG and LLNL methodologies, 0.025 to 0.045 g are in the low range of reasonable estimates for the Portsmouth site. An additional reason for the conclusion that both the EPRI/SOG and LLNL ground motions at Portsmouth are low is that they are not consistent with the historical shaking at this site.

• Paducah.

For Paducah, a reasonable range of 1000-yr peak accelerations from the USGS comparison studies has a median of 0.32 g and a mean of 0.38. The values range from about 0.26 g to 0.72 g, depending upon different assumptions about how closely rupture on the New Madrid fault zone can approach the site. The EPRI/SOG and LLNL median results fall in the lower part of this range. In the light of this comparison study and the fact that some of the EPRI/SOG and LLNL zonations place Paducah very near or within the New Madrid fault zone

(NMFZ), it is clear that the point-rupture assumption has had an important role in keeping these ground motions low. On the other hand, many of the zonations place the northern terminus of NMFZ source far from the site. For the farthest locations of this terminus, the point source assumption may not be greatly in error. Risk Engineering has modeled the NMFZ earthquakes as linear ruptures rather than point ruptures, obtaining a median 1000-year peak acceleration of 0.31 g, in good agreement with the USGS value. The Risk Engineering model differs from the USGS model in that strong ground motion is concentrated toward the interior of the rupture. *Even though a rupture may run several kilometers past the site, the portion of the rupture contributing strong ground motion may not be close to the site.* Accordingly, we asked that the Risk Engineering model be demonstrated for ruptures proceeding 40 or so kilometers beyond the site in order to confirm the contribution of strong shaking by the rupture. Nevertheless, the *median* Risk Engineering values are reasonable values to use for the evaluation of systems, structures, and components for seismic structural integrity and for the seismic design of new and improved systems, structures, and components for the Paducah site.

•Uniform Hazard Response Spectra for Ground Motion Exceedance Rate of 10^{-3} per year

Response spectra at the Paducah and Portsmouth sites obtained by various methodologies (EPRI/SOG, LLNL, combined EPRI/SOG-LLNL, REI rupture model, and U.S.G.S. models) were compared to spectra obtained using several approaches permitted by UCRL 15910 and some based on building code provisions. In general the spectra differ less at the short-period end than at the long period. At the long-period end, methods using a spectral

shape anchored by peak acceleration produce higher values than those methods for which the spectral ordinates have been calculated by the methods of seismic hazard analysis.

At longer periods, the spectral levels are very different between the values obtained by the EPRI/SOG methodology and those obtained by either the LLNL methodology or U.S.G.S. This effect can possibly be explained in terms of the influence of the maximum magnitude. In the EPRI/SOG methodology, if there is no known tectonic influence and the historical seismicity is low, low maximum magnitudes tend to be assigned to sources. Background-zone maximum magnitudes would be low for this reason. For the LLNL methodology, the experts have chosen maximum magnitudes for background zones which range from magnitude 5.0 to 7.5 (m_b), two-thirds of the values being from magnitude 5.0 to 6.0. The U.S.G.S. model uses a minimum central maximum magnitude of at least 6.1 (M_s) regardless of whether the zone is background or not. Accordingly, it would be expected that at longer periods the lowest spectral values would be those of the EPRI/SOG methodology, followed in turn by the combined EPRI/SOG-LLNL values, the LLNL values, and the U.S.G.S. values. In general, this is the case.

However, it can also be argued that the U.S.G.S. models yield higher values at short periods, and that the true comparison in spectral *shapes* ought to be made by forcing the short period ordinates to be the same. If this adjustment is made, it appears that the U.S.G.S. preferred spectra fall between the LLNL spectrum and that of the combined EPRI/SOG-LLNL result. This is, in part, due to the inclusion by LLNL of spectral attenuations derived from fixed spectral shapes anchored to peak accelerations.

Considering the sites individually, at the Paducah site the spectra for both soil and rock are bounded on the high side by the UCRL

spectra and on the low side by the EPRI/SOG spectra for rock. An ordinary building code spectrum, which is not site-specific, exceeded the EPRI/SOG, LLNL, and combined EPRI/SOG-LLNL spectra for periods around one second and the EPRI/SOG spectra for all periods. The spectra for the REI fault rupture model were similar in shape and amplitude to the U.S.G.S. spectra.

At the Portsmouth site it was also found that the spectra for both soil and rock were bounded on the high side by the UCRL spectrum and on the low side by the EPRI/SOG spectrum for rock. The ordinary building code spectrum, which is not site-specific, exceeded the other spectra for periods around one second and the EPRI/SOG spectrum for all periods. The U.S.G.S. spectrum was not significantly lower than the building code spectrum.

• Comparison of magnitude scales in eastern and western United States

In principle, the various magnitude scales in use by seismologists should give uniformity in earthquake size estimates for the eastern and western U. S.. However, because of the use of different seismic phases, frequencies, and seismographs in regions with markedly different attenuation properties, along with the variability in the definitions of magnitudes and the changes with time in their calculation, the requisite uniformity has not been achieved. A method of uniform size classification for intraplate eastern U.S. (EUS) earthquakes and interplate western U.S. (WUS) earthquakes was investigated. Comparison was made of the principal magnitude scales—body-wave magnitude, m_b , "Nuttli" magnitude, $m_b(Lg)$, local magnitude, M_L , surface-wave magnitude, M_S , and moment magnitude, M —using averages of multiple values as published by the International Seismological Centre. Moment

estimates were taken from a compilation by Stover and Coffman of the U.S. Geological Survey. These two data sets are judged to represent the most accurate size estimates that are presently available in catalog form.

Intercomparisons between the various scales indicate that (1) body wave magnitude, m_b , in the eastern U.S. is approximately equal to Nuttli magnitude, $m_b(Lg)$, in the eastern U.S., (2) local magnitude, M_L , in the western U.S. is approximately equal to body-wave magnitude, m_b , in the western U.S., (3) the relationship between surface wave magnitude, M_S , and body wave magnitude, m_b , appears to be the same in the eastern and western U.S. (though they are not equal to each other), (4) moment magnitude, M , is approximately the same as local magnitude, M_L , in the western U.S. over the range 4.5–7.0, and (5) moment magnitude, M , is less than Nuttli magnitude, $m_b(Lg)$, in the eastern U.S., the lower the magnitude the greater the difference. These relationships are expressed in equations, below:

$$m_b \text{ (EUS)} \approx m_b(Lg) \text{ (EUS)}$$

$$M_L \text{ (WUS)} \approx m_b \text{ (WUS)}$$

$$M_S = -3.23 + 1.57 m_b \text{ (EUS and WUS)}$$

$$M \approx M_L \text{ (WUS)} \quad (4.5 < M_L < 7.0)$$

$$M = -0.70 + 1.09 m_b(Lg) \text{ (EUS)}$$

It is recommended that the latter two equations be used when uniformity of earthquake size classification across the U.S. is required.

• **Assessment of differences in probabilistic ground motion estimates at Portsmouth.**

The range of median estimates at Portsmouth is large between assessors, the factor increase from EPRI/SOG to LLNL to USGS peak acceleration estimates being almost a factor of two at each step. We have reviewed various possibilities for accounting for these contrasts in probabilistic ground motion.

Attenuation function differences, exclusion of distant sources, and the combined use of low background maximum magnitudes with low values of source zone probabilities of existence (low p^A values) are found to be capable of accounting for the size and direction of the difference between EPRI/SOG and LLNL results at Portsmouth, but not the difference between the LLNL results and USGS results at Portsmouth.

The USGS use of epicentral intensity to guide magnitude conversion, a procedure designed to ensure near-field comparability in the eastern and western United States of ground motions associated with particular epicentral intensities, can account for the difference between USGS values at Portsmouth and those of EPRI/SOG and LLNL. This difference in probabilistic ground motion exists because there is a systematic difference between epicentral intensity and moment magnitude between the eastern and western United States, for those magnitudes between 4, 5, and 6 $m_b(Lg)$. This systematic difference could be the result of an lower site amplification for sites governing epicentral intensity values in the western U.S. than for sites governing epicentral intensity values in the eastern U.S. Minimum magnitudes for hazard analysis are often set to exclude the rates of non-damaging earthquakes from the analysis. A difference in overall site amplification should lead to a lowering of the

minimum magnitude used in a hazard analysis for the central and eastern U.S. compared to the western U.S. We estimate that the minimum magnitude should be lowered by about 0.5 magnitude units in the central and eastern U.S. compared to that in the west in order that historical earthquakes observed to be damaging are accounted for in the analysis.

Alternatively, the systematic difference between the eastern and western relationships between epicentral intensity and moment magnitude could be explained by a source difference in which eastern earthquakes have a higher stress drop for a given seismic moment. If so, moment magnitude attenuation functions constructed using random vibrations models in analogy with western United States sources may underestimate, by a factor of two or more, low-level high-frequency probabilistic ground motions in the eastern United States (but probably not the longer period ground motions). Similarly, attenuation functions in which $m_b(Lg)$ is the parameter, but which are based on such moment magnitude attenuations will also underestimate high-frequency probabilistic ground motions.

Comparison of the historical record of intensities experienced in the vicinity of Portsmouth and conversions of those historical intensities to both acceleration and velocity seem to indicate that the the probabilistic ground motions calculated by the USGS are more consistent with the seismic history.

Notice that these results obtained apply to the Portsmouth site situation, specifically, low probabilistic ground motions. Because the correspondence between epicentral intensity and moment magnitude for higher magnitudes in the east are similar to those of the western United States, the above conclusions probably do not hold for higher probabilistic ground motions, such as those calculated for Paducah, in which the role of larger-magnitude, near-site earthquakes dominate.

• Assessment of differences in probabilistic ground motion estimates at Portsmouth.

The range of median estimates at Portsmouth is large between assessors, the factor increase from EPRI/SOG to LLNL to USGS peak acceleration estimates being almost a factor of two at each step. We have reviewed various possibilities for accounting for these contrasts in probabilistic ground motion.

Attenuation function differences, exclusion of distant sources, and the combined use of low background maximum magnitudes with low values of source zone probabilities of existence (low p^A values) are found to be capable of accounting for the size and direction of the difference between EPRI/SOG and LLNL results at Portsmouth, but not the difference between the LLNL results and USGS results at Portsmouth.

The USGS use of epicentral intensity to guide magnitude conversion, a procedure designed to ensure near-field comparability in the eastern and western United States of ground motions associated with particular epicentral intensities, can account for the difference between USGS values at Portsmouth and those of EPRI/SOG and LLNL. This difference in probabilistic ground motion exists because there is a systematic difference between epicentral intensity and moment magnitude between the eastern and western United States, for those magnitudes between 4, 5, and 6 $m_b(Lg)$. This systematic difference could be the result of an lower site amplification for sites governing epicentral intensity values in the western U.S. than for sites governing epicentral intensity values in the eastern U.S. Minimum magnitudes for hazard analysis are often set to exclude the rates of non-damaging earthquakes from the analysis. A difference in overall site amplification should lead to a lowering of the

minimum magnitude used in a hazard analysis for the central and eastern U.S. compared to the western U.S. We estimate that the minimum magnitude should be lowered by about 0.5 magnitude units in the central and eastern U.S. compared to that in the west in order that historical earthquakes observed to be damaging are accounted for in the analysis.

Alternatively, the systematic difference between the eastern and western relationships between epicentral intensity and moment magnitude could be explained by a source difference in which eastern earthquakes have a higher stress drop for a given seismic moment. If so, moment magnitude attenuation functions constructed using random vibrations models in analogy with western United States sources may under-estimate, by a factor of two or more, low-level high-frequency probabilistic ground motions in the eastern United States (but probably not the longer period ground motions). Similarly, attenuation functions in which $m_b(Lg)$ is the parameter, but which are based on such moment magnitude attenuations will also underestimate high-frequency probabilistic ground motions.

Comparison of the historical record of intensities experienced in the vicinity of Portsmouth and conversions of those historical intensities to both acceleration and velocity seem to indicate that the the probabilistic ground motions calculated by the USGS are more consistent with the seismic history.

Notice that these results obtained apply to the Portsmouth site situation, specifically, low probabilistic ground motions. Because the correspondence between epicentral intensity and moment magnitude for higher magnitudes in the east are similar to those of the western United States, the above conclusions probably do not hold for higher probabilistic ground motions, such as those calculated for Paducah, in which the role of larger-magnitude, near-site earthquakes dominate.

Conclusion.

We find that peak acceleration values of 0.082 g and 0.32 g for Portsmouth and Paducah, respectively, represent central values of the ground motions obtained at 1000-year return periods in our alternative studies. Peak accelerations obtained in the LLNL and Risk Engineering Studies have medians near these values (results obtained using the EPRI/SOG methodology appear low at both sites), and we believe that these medians obtained are appropriate values for use in the evaluation of systems, structures, and components for seismic structural integrity and for the seismic design of new and improved systems, structures, and components at these sites.

II. Historical Seismicity and Significant Damaging Earthquakes Affecting Paducah, Kentucky, and Portsmouth, Ohio

by

Margaret G. Hopper

Summary

The seismicity of the Midwest region, including Paducah and Portsmouth, is dominated by the large earthquakes in the New Madrid seismic zone. The four great shocks that occurred there in 1811-1812 were each large enough to produce intensities of VIII in the vicinity of Paducah and VI or VII in the vicinity of Portsmouth. Although there are no specific reports available for either city from the 1811-1812 earthquakes, the estimated intensities for the two cities are high enough to cause minor damage (fallen plaster, broken

windows) at Portsmouth and structural damage to ordinary masonry construction (unreinforced) at Paducah.

Sixty-two earthquakes, obtained from the computer files of the National Earthquake Information Center, were examined for their possible effects in the Paducah area and 20 for the Portsmouth area. Those that were found to have actually caused damage in Paducah or Portsmouth, or for which Paducah or Portsmouth was within a damage-level isoseismal, are listed below.

Table II-1. Historical Earthquakes Capable of Damage-Level Intensities at Paducah or Portsmouth

The Modified Mercalli intensities given here are based on actual observed damage from historical reports except as noted by the word "isoseismal," which indicates that the site was within the given isoseismal but no specific damage information is available.

Paducah					Portsmouth				
Date	MMI _o	Km from Paducah	MMI at Paducah		Date	MMI _o	Km from Portsmouth	MMI at Portsmouth	
1811 Dec. 16 2am	XI	248	VIII isoseismal		1811 Dec. 16 2am	XI	756	VI isoseismal	
1811 Dec. 16 8am	XI	248	VIII isoseismal		1811 Dec. 16 8am	XI	756	VI isoseismal	
1812 Jan. 23	XI	125	VIII isoseismal		1812 Jan. 23	XI	644	VI isoseismal	
1812 Feb. 7	XI	111	VIII isoseismal		1812 Feb. 7	XI	634	VII isoseismal	
1843 Jan. 5	VIII	245	VI isoseismal		1895 Oct. 31	IX	596	VI isoseismal	
1883 Jan. 11	VI	54	VI		1901 May 17	VII	10	VII	
1891 Sept. 27	VII	129	VI		1980 July 27	VII	100	VI	
1895 Oct. 31	IX	72	VIII						
1905 Aug. 22	VI	63	V-VI						
1968 Nov. 9	VII	93	VI						

Introduction

Figure II-1 shows the patterns of the historical seismicity in the eastern United States and the Midwest and their relationships to Paducah and Portsmouth. This map shows all shocks having maximum Modified Mercalli intensities (MMI_o) greater than or equal to V. The larger earthquakes, $VIII \leq MMI_o \leq X$, capable of causing structural damage to ordinary masonry structures, and the great earthquakes ($MMI_o \geq XI$), are specifically identified in figure II-1. Most of the shocks shown on this map are either too small or too far away from Paducah and Portsmouth to cause damage at either of those places.

In order to determine which earthquakes might have an impact on Paducah or Portsmouth, intensity-attenuation relationships were developed (fig. II-2). They suggest that in the eastern United States intensities high enough to cause damage ($MMI \geq VI$) may occur out to an average distance of about 100 km for an $MMI_o = VII$ shock and out to about 300 km for an $MMI_o = IX$ shock. Great earthquakes such as the 1811-1812 New Madrid sequence can cause structural damage ($MMI \geq VIII$) out to an average distance of 200 km. These are "average" distances because the epicentral distance plotted in figure 2 is the radius of a circle with an area equal to the area of an isoseismal. Irregular isoseismals will extend beyond this distance in some areas and not reach it in others. Therefore, somewhat larger radii than given above must be chosen in order to insure that all earthquakes that might have an impact ($MMI \geq VI$) at Paducah or Portsmouth will be investigated. The chosen radii for all MMI_o 's and the earthquakes found within those radii are listed in tables II-2 and II-3. Where these large, conservatively chosen radii intersect a highly active area, such as the New Madrid seismic zone, many small shocks will

be included for investigation. Because of this there are approximately three times more earthquakes to be investigated for Paducah than for Portsmouth even though most are small and unlikely to seriously affect Paducah. It is nevertheless appropriate to investigate all of these shocks to determine if any of them actually did cause damage at the site.

II.A. Sources of Data

The earthquakes examined in this study were obtained from the computer files of the National Earthquake Information Center (NEIC). All earthquakes in the following categories were chosen from the files :

$MMI_o \geq VI$	within 200 km of Paducah or Portsmouth
$MMI_o \geq VII$	within 300 km of Paducah or Portsmouth
$MMI_o \geq VIII$	within 450 km of Paducah or Portsmouth
$MMI_o \geq IX$	within 650 km of Paducah or Portsmouth
$MMI_o \geq X$	within 950 km of Paducah or Portsmouth
$MMI_o \geq XI$	within 1400 km of Paducah or Portsmouth

The resulting lists of earthquakes for Paducah and Portsmouth are shown in Tables II-2 and II-3. The columns on the left of the two tables show the data obtained from the NEIC files: date, time, latitude, longitude, magnitude and magnitude reference, maximum intensity, and reference for those columns. (The reference is not simply NEIC, but rather the specific catalog among the NEIC files. It was necessary to search two catalogs in the NEIC files to get complete temporal coverage since the historical seismicity catalog searched currently ends with 1985). To find specific information about the effects at Paducah or Portsmouth for each

earthquake on the two lists, various sources were used. These included the series *United States Earthquakes*, studies by Street and Green (1984), and Docekal (1970), and other reports. These references and the information obtained from them are shown in the last four columns of Tables II-2 and II-3: state, location name, intensity and effects at Paducah or Portsmouth, and reference for those columns.

II.A.1. Paducah

Paducah is affected by two nearby seismic zones, the New Madrid on the southwest and the seismicity in southern Illinois and the Wabash Valley on the north. The New Madrid zone is by far the more important of the two for Paducah, but the southern Illinois earthquakes have also historically caused minor damage at Paducah. Table II-2 and figure II-3 show the historical earthquakes in the Paducah region.

Paducah probably experienced ground motion sufficient to cause structural damage ($MMI_o \geq VIII$) to ordinary masonry construction on at least five occasions in the historical record. Although no reports are given for Paducah in the 1811–1812 earthquakes (first settled in 1821 as “Pekin”, renamed “Paducah” in 1827 (Seltzer, 1962)), the present location of Paducah is within the VIII isoseismal for each of those shocks (figs. II-4–II-7). In addition, Paducah could have been within the damage area of many of the largest aftershocks of the 1811–1812 sequence (fig. II-8), although the data available are insufficient for drawing reliable isoseismals. In the 1895 earthquake (fig. II-9) many chimneys fell and walls were cracked in Paducah, giving the city a MMI of VII–VIII (Hopper and Algermissen, 1980).

Three other shocks in the New Madrid seismic zone caused minor damage ($MMI \geq VI$) at Paducah (1843, 1883, and 1891—figs. II-10–II-12 respectively). In addition, two shocks in the southern Illinois seismic zone north of Paducah have caused damage at Paducah—

1905 and 1968 (figs. II-13 and II-14) (Street and Green, 1984; Gordon and others, 1970). Paducah is also in an isolated outlying area of intensity VI due to the Charleston, South Carolina, earthquake of 1886 (fig. II-15), although the assigned intensity for the city for this shock is only V (Bollinger and Stover, 1976).

In addition to damage caused directly by earthquake vibrations, damage may also result from ground effects caused by the earthquake. Such effects include settling, slumping, landsliding, and liquefaction. An account of an 1811 liquefaction occurrence near Paducah is given in table II-2. Liquefaction may be expected in susceptible areas near Paducah (that is, areas of sandy, water-saturated soils, usually near rivers or streams) any time the local MMI reaches VIII or sometimes only VII.

II.A.2. Portsmouth

Portsmouth has probably had damage-level intensities ($MMI \geq VI$) from at least seven historical earthquakes (table II-3 and fig. II-16)—the four largest 1811–1812 shocks, the $MMI_o = IX$ shock in southeastern Missouri in 1895, a $MMI_o = VII$ shock centered near Portsmouth in 1901, and the northern Kentucky shock in 1980. There is no information about what happened at Portsmouth in the 1811–1812 or the 1895 shocks. However, the city lies within the VI isoseismal for three of these five earthquakes and within the VII isoseismal of the February, 1812, and 1901 earthquakes. Portsmouth may also have been within the damage area ($MMI \geq VI$) of two of the largest aftershocks of the 1811–1812 earthquake sequence (fig. II-8). Portsmouth was settled in 1803 (Seltzer, 1962), so it did exist at the times of all these earthquakes.

Data for the 1901 shock has recently been found. Old newspaper accounts describing the shock were collected by R.L. Street

(University of Kentucky) and sent to C.W. Stover (U.S. Geological Survey) who shared them with the author for the purpose of making the isoseismal map shown in figure II-17. Table II-4 lists all the information on which the 1901 isoseismal map (fig. II-17) is based. The little information previously available for this shock (fig. II-18) suggested that it had a maximum intensity of only V and was located at Wellston, Ohio (Docekal, 1970). It should be noted that the epicenter is now relocated near Portsmouth solely on the basis of the intensity assigned to the accounts from Portsmouth and Sciotovalle. Both Portsmouth and nearby Sciotovalle are assigned MMI VII on the basis of strong evidence, in both cases numerous damaged chimneys. The location of the highest intensity is only an estimator for the location of the actual epicenter in lieu of an instrumental epicenter. For example, the 1980 earthquake in northern Kentucky had its maximum intensity at Maysville, Ky., 50 km north of the instrumental epicenter (Stover and von Hake, 1982). The two most important reasons for this discrepancy were probably (1) that Maysville is situated in the Ohio River valley on alluvium, and (2) that Maysville is a large city with many people to feel the shock, many structures to be damaged, and newspapers to report the damage. Both of these items also apply to Portsmouth. Therefore, from the available intensity data, we can only say with assurance that the actual epicenter was probably within a 50-km radius of our chosen epicenter.

Other earthquakes in the list in table II-3 may also have been capable of causing damage in the Portsmouth area. However, little information is available for most of them. In particular, the $MMI_o = VII$ earthquake in 1926 just northeast of Portsmouth might have caused damage as far away as Portsmouth, although the short list of reports for this shock given by Docekal (1970) suggests that damage was confined to the epicentral area. More research is

needed to clarify the intensity distribution for this earthquake.

The 1980 earthquake in northern Kentucky ($MMI_o = VII$, fig. II-19) was located about the same distance from Portsmouth as the 1926 shock (but to the southwest). It generated an anomalous VI (that is surrounded by lower intensities) at Portsmouth (Stover and von Hake, 1982).

The $MMI_o = VIII$ earthquake in northwestern Ohio in the Anna area in 1937 (fig. II-20) apparently did not result in damage in the Portsmouth area (Docekal, 1970; Neumann, 1940).

II.B. Other Considerations

The maximum ground motion expected is not the only important consideration for judging earthquake damage at a site. For example, in the event of a major earthquake in the New Madrid seismic zone, landsliding and liquefaction will likely cause much damage to both buildings and lifelines. Another great danger, particularly in the Midwest, is the serious damage commonly caused to old unreinforced masonry structures even at intensity levels as low as VII. Moreover, low seismic wave attenuation in the eastern United States results in earthquakes with radii of perceptibility as much as 10 times larger than similar magnitude earthquakes in the western United States (Nuttli, 1973b).

Although the great shocks in the New Madrid seismic zone are estimated to have return periods of 500 to 600 or more years (Nuttli, 1974), smaller earthquakes of maximum intensity VIII or IX could do considerable damage in the more immediate future. Smaller shocks outside the New Madrid seismic zone may also affect both sites.

II.C. Conclusions

Paducah and Portsmouth have both been exposed to damage-level intensities during historical earthquakes, and Paducah has been exposed to structural-damage levels. In the Paducah area damage due to heavy vibration is not the sole consideration. Damage associated with liquefaction and landsliding is also possible in susceptible areas. Large earthquakes outside the New Madrid seismic zone may also cause significant damage at both sites, although historically such damages have never exceeded $MMI = VII$.

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Table II-2. Historical Earthquakes in the Paducah Region

Region included: $MMI_0 \geq VI$ within 200 km of Paducah
 $MMI_0 \geq VII$ within 300 km of Paducah

$MMI_0 \geq VIII$ within 450 km of Paducah
 $MMI_0 \geq IX$ within 650 km of Paducah

$MMI_0 \geq X$ within 950 km of Paducah
 $MMI_0 \geq XI$ within 1400 km of Paducah

Paducah is at $37.09^\circ N$, $88.60^\circ W$. Earthquakes in italics may have caused damage ($MMI \geq VI$) at Paducah. The earthquakes listed in this table are shown on the map, fig. II-3.

Date-Hour (GMT)	Lat $^\circ N$	Long $^\circ W$	M a g	R e f	M l o	R e f	Dist km	Epicentral location	MMI at Paducah	References ⁴
1811 12 16 08	35.400	90.400	7.20	FANU	11	SRA	248	AR New Madrid, Mo.	No intensity given for Paducah, but VII-VIII is assigned across the Ohio River at Fort Massac, Ill., where four of five chimneys fell and similar effects were reported from a 30-mile radius. Liquefaction: "About four miles above Paducah, on the Ohio river, on the Illinois side, on a post-oak flat, a large circular basin was formed, more than one hundred feet in diameter, by the sinking of the earth, how deep no one can tell, as the tall stately post-oaks sank below the tops of the tallest trees. The sink filled with water, and continues so to this time."	Street, 1981; Street, 1982; Street and Green, 1984
1811 12 16 14	35.400	90.400	7.00	FANU	11	SRA	248	AR New Madrid, Mo.	Paducah probably inside VIII isoseismal	Street, 1981; Street, 1982
1812 01 23 15	36.300	89.600	7.10	FANU	11	SRA	125	MO New Madrid, Mo.	Paducah probably inside VIII isoseismal	Street, 1981; Street, 1982
1812 02 07 09	36.500	89.600	7.30	FABAR	11	SRA	111	MO New Madrid, Mo.	Paducah probably inside VIII isoseismal	Street, 1981; Street, 1982
1812 11 09 22	36.500	89.600			6	SRA	111	MO Cape Girardeau	No information about this earthquake.	Docekal, 1970; Coffman and others, 1982
1827 07 05 11	38.000	87.500	5.00	FASG	6	SRA	140	IN New Harmony	Paducah inside IV and above area	Street and Green, 1984
1838 06 09 14	38.500	89.000			7	SRA	160	MO Saint Louis	Paducah inside IV and above area	Street and Green, 1984
1843 01 05 02	35.500	90.500	6.00	FABAR	8	SRA ⁵	245	AR Northeast Arkansas	Paducah inside VI isoseismal	Hopper, ed., 1985
1857 10 08 10	38.700	89.200	5.30	FABAR	7	SRA	186	IL Centralia	Paducah inside IV isoseismal	Street and Green, 1984
1858 09 21	36.500	89.200			6	SRA	85	KY Line Shore	No information about Paducah	Docekal, 1970
1865 08 17 15	36.000	89.500	5.30	FABAR	7	SRA	145	TN Memphis	Paducah inside the felt area	Street and Green, 1984
1876 09 25 06	38.500	87.800	4.70	FABAR	6	SRA	172	IL Friendsville	Paducah in I-III area	Docekal, 1970
1876 09 25 06	38.500	87.700	4.70	FABAR	7	SRA	175	IN Vincennes	Paducah outside IV isoseismal	Street and Green, 1984
1883 01 11 07	37.000	89.200	4.70	FASG	6	SRA	54	KY Paducah	VI. Severe; slightly cracked several brick walls and threw people from chairs	Street and Green, 1984
1883 04 12 08	37.000	89.200			6	SRA	54	IL Cairo	No information about Paducah	Coffman and others, 1982
1886 09 01 02	32.900	80.000	7.02	MwBOL	10	SRA	912	SC Charleston	V. (Paducah in an outlying VI area)	Bollinger and Stover, 1976; Bollinger, 1977
1887 08 02 18	37.200	88.500	5.20	FASG	6	SRA	15	IN Jasper, Russellville, Ky	V. Shook the town	Street and Green, 1984
1891 07 27 02	37.900	87.500	4.00	FASG	6	SRA	132	IN Evansville	Paducah outside felt area	Street and Green, 1984
1891 09 27 04	38.250	88.500	5.80	FASG	7	SRA	129	IL Mount Vernon	VI. People were driven into the streets	Street and Green, 1984
1895 10 31 11	37.000	89.400	6.20	FABAR	9	SRA	72	MO Charleston	VIII. A severe shock, felt all over town. Houses swayed to and fro. A number of chimneys fell and several walls were cracked	Hopper and Algermissen, 1980
1899 04 30 02	38.500	87.400	4.50	FASG	7	SRA	189	IN Greencastle, Princeton, Vincennes	Paducah outside felt area	Street and Green, 1984
1903 02 09 00	37.800	89.300	4.80	FABAR	7	SRA	100	IL Cartersville, Grand Towers, Murphysboro	V. Rattled buildings, windows, lights, some ran outdoors; a few instances of dishes shaken off tables	Street and Green, 1984
1903 11 04 18	36.500	89.500	4.40	FASG	6	SRA	104	MO New Madrid	Paducah inside I-III isoseismal	Street and Green, 1984
1903 11 04 19	36.500	89.800	4.80	FASG	7	SRA	126	MO New Madrid	IV-V. Walls and floors rocked and crockery rattled.	Street and Green, 1984

Table II-2
Paducah continued

Date-Hour (GMT)	Lat ON	Long OW	M a g ¹	R e f ¹	M M ₀ ²	R e f ³	Dist km	Epicentral location	MMI at Paducah	References ⁴
1905 08 22 05	37.200	89.300	4.80	FABAR	6	SRA	63	IL Cairo	V-VI. People aroused all over the city, broke dishes, overturned lumber piles	Street and Green, 1984
1909 09 27 09	39.500	87.400	4.80	FABAR	7	SRA	287	IN Covington, Princeton	V. Windows and doors rattled, nearly everyone was awakened	Street and Green, 1984
1916 12 19 05	36.600	89.200			6	SRA	76	KY Hickman	No information about Paducah	Docekal, 1970; Coffman and others, 1982
1917 04 09 20	38.100	90.200	5.00	FABAR	7	SRA	180	MO DeSoto	IV-V. Vibrated water pipes and tanks violently	Street and Green, 1984
1922 03 22 22	37.400	89.400	4.20	FASG	7	SRA	78	MO Ilmo	IV. Rattled windows and doors	Street and Green, 1984
1922 03 23 02	37.400	89.400	4.50	FASG	6	SRA	79	MO Ilmo	IV. Rattled windows and doors	Street and Green, 1984
1922 11 27 03	37.800	88.500	4.50	FABAR	7	SRA	79	IL El Dorado	IV. A distinct shock accompanied by a slight shaking of homes and the rattling of window panes	Street and Green, 1984
1923 10 28 17	35.500	90.400	4.50	FABAR	7	SRA	239	AR Marked Tree	Not reported at Paducah	Street and Green, 1984
1924 01 01 03	36.000	90.000	4.50	FASG	6	SRA	174	AR Osceola	Not reported at Paducah	Street and Green, 1984
1925 04 27 04	38.200	87.800	4.80	FABAR	6	SRA	142	IL Carmi	V. Toppled bric-a-brac from tables and mantles; aroused many people	Street and Green, 1984
1925 09 02 11	37.900	87.200	4.70	FASG	6	SRA	153	KY Henderson, Owensboro	V. Distinctly felt by hundreds, awakened many, but no damage	Street and Green, 1984
1934 08 20 00	37.000	89.200	4.30	FABAR	7	SRA	54	IL Southern Ill., Rodney, Mo.	I-III	Neumann, 1936
1940 11 23 21	38.200	90.100			6	SRA	181	IL Griggs, Illinois	No information about Paducah	Neumann, 1942; Docekal, 1970
1952 07 16 23	36.200	89.600			6	SRA	133	TN Dyersburg	No information about Paducah	Murphy and Cloud, 1954; Docekal, 1970
1955 01 25 07	36.073	89.827	4.50	FADG	6	SRA	157	TN Tenn.-Ark.-Mo. border	I-III	Murphy and Cloud, 1957
1955 03 29 09	36.000	89.500	4.00	FABAR	6	SRA	145	TN Finley	No reports from anywhere in Kentucky	Murphy and Cloud, 1957; Docekal, 1970
1955 04 09 13	38.232	89.785	4.30	FADG	6	SRA	164	IL West of Sparta	Paducah just inside I-IV isoseismal	Murphy and Cloud, 1957; Docekal, 1970
1956 01 29 04	35.756	89.803	4.00	FADG	6	SRA	183	TN Covington	Paducah just inside I-IV area on Docekal's map.	Docekal, 1970; Brazee and Cloud, 1958
1956 11 26 04	36.914	90.387	4.40	FADG	6	SRA	160	MO Wayne County	Paducah outside felt area	Brazee and Cloud, 1958
1958 11 08 02	38.436	88.008	4.40	FADG	6	SRA	158	IL Illinois-Indiana border	I-III	Brazee and Cloud, 1960
1962 02 02 06	36.374	89.511	4.15	MwSTT	6	SRA	114	MO New Madrid	I-III	Lander and Cloud, 1964
1962 07 23 06	36.044	89.399	3.38	MwSTT	6	SRA	136	TN Dyersburg	Paducah outside felt area	Docekal, 1970
1963 03 03 17	36.642	90.050	4.53	MwSTT	6	SRA	139	MO Southeastern Missouri	I-III	von Hake and Cloud, 1965
1965 08 14 13	37.226	89.307	3.44	MwSTT	7	SRA	65	IL Tamms	Paducah outside felt area	Nuttli and Zollweg, 1974
1967 07 21 09	37.440	90.443	3.92	MwSTT	6	SRA	168	MO Poplar Bluff	Paducah outside felt area	Nuttli and Zollweg, 1974
1968 11 09 17	37.911	88.373	5.27	MwHRN	7	SRA	93	IL South-central Illinois	VI. Few bricks fell from chimneys	Coffman and Cloud, 1970
1970 11 17 02	35.856	89.947	4.00	MwSTT	6	SRA	183	AR Northeastern Arkansas	Paducah outside felt area	Coffman and von Hake, 1972
1974 04 03 23	38.549	88.072	4.36	MwSTT	6	SRA	168	IL Southern Illinois	Paducah near outer limit of felt area	Coffman and Stover, 1976
1974 05 13 06	36.739	89.357	3.80	FADG	6	SRA	78	MO New Madrid region	Paducah outside felt area	Coffman and Stover, 1976
1975 06 13 22	36.543	89.682	4.73	MwHRN	6	SRA	114	MO New Madrid region	Paducah near limit of felt area	plotted from Coffman and Stover, 1977

Table II-2
Paducah continued

Date-Hour (GMT)	Lat ON	Long OW	M a g ¹	R e f ¹	M L _o ²	R e f ³	Dist km	Epicentral location	MMI at Paducah	References ⁴
1975 12 03 03	36.560	89.600	2.80	MnSLM	6	SRA	107	MO New Madrid region	No reports outside Missouri	Coffman and Stover, 1977
1977 01 03 22	37.583	89.714	3.40	MnSLM	6	SRA	112	MO Cape Girardeau	No reports outside Missouri and Illinois	Coffman and Stover, 1979
1980 12 02 08	36.175	89.429	3.80	MnSLM	6	SRA	126	TN Northwestern Tenn.	Paducah outside felt area	Stover and von Hake, 1982
1981 08 07 11	35.950	89.120	4.00	MnSLM	6	SRA	135	TN Western Tennessee	Paducah outside felt area	Stover, 1984
1984 06 29 07	37.700	88.470	4.10	MnGS	6	SRA	69	IL Southern Illinois	Paducah in I-III area	plotted from Stover, 1988
1987 06 10 23	38.713	87.954	4.60	MsBRK	6	PDE	189	IL Illinois	Paducah in II-IV area	U.S. Geological Survey, unpub. data, Aug., 1990
1989 04 27 16	36.006	89.768	4.70	MnBLA	6	PDE	159	MO Steele, Scott County	Not felt.	U.S. Geological Survey, unpub. data, Aug., 1990
1990 09 26 13	37.165	89.577	4.7	mb	6	PDE	87	MO Cape Girardeau region	IV. Rattled windows.	U.S. Geological Survey, unpub. data, Oct., 1990

¹Magnitude types and sources:

- FA Magnitude from felt area.
Mw Moment magnitude (N-m) by formula of Hanks and Kanamori (1979).
Mn M_n magnitude from Nuttli (1973b).
Ms. M_s magnitude from Bath (1966) or Gutenberg (1945).
mb m_b magnitude from Gutenberg and Richter (1956).
NU Computed according to Nuttli, 1973a.
BAR Computed according to Barstow and others, 1981.
SG Computed according to Street and Green, 1984.
BOL Computed according to Bollinger, 1986.
DG Computed according to Dewey and Gordon, 1984.
STT Computed according to Street and others, 1975.
HRN Computed according to Hermann, 1979.
SLM Computed according to Saint Louis University, Saint Louis, Mo.
GS Computed according to National Earthquake Information Center, U.S. Geological Survey (and predecessor agencies), Golden, Colo.
BRK Computed according to Seismological Station, University of California,

Berkeley, Calif.

BLA Computed according to Virginia Polytechnic Institute and State University, Blacksburg, Va.

²The intensity listed from the SRA and PDE catalogs is the maximum intensity reported *on land, in the United States*. In the central United States this is usually, but not always, the same as the maximum intensity, MMI_o , assigned for the earthquake.

³Reference for the information in all columns to the left of this column

SRA National Earthquake Information Center (NEIC), Earthquake Data Base System (EDBS), computer files of the State Seismicity File. The SRA catalog contains magnitudes ≥ 2.5 and is current through 1985.

PDE National Earthquake Information Center (NEIC), Earthquake Data Base System (EDBS), computer files of the Preliminary Determination of Epicenters listings published by the National Earthquake Information Service (NEIS). Searched from 1986 to present.

⁴Reference for the epicentral location and MMI at Paducah.

⁵SRA's maximum MMI_o of VII for the 1843 earthquake has been changed to VIII. See map, figure II-X.

Table II-3. Historical Earthquakes in the Portsmouth Region

Region Included:														MMI _o ≥ VI within 200 km of Portsmouth				MMI _o ≥ VII within 300 km of Portsmouth				MMI _o ≥ VIII within 450 km of Portsmouth				MMI _o ≥ IX within 650 km of Portsmouth				MMI _o ≥ X within 950 km of Portsmouth				MMI _o ≥ XI within 1400 km of Portsmouth			
Portsmouth is at 38.76°N, 83.00°W. Earthquakes in <i>italics</i> may have caused damage (MMI ≥ VI) at Portsmouth. The earthquakes listed in this table are shown on the map, fig. II-15.																																					
Date-Hour (GMT)	Lat °N	Long °W	M a _g ¹	R e _f ¹	M M _o ²	R e _f ³	Dist km	Epicentral location	MMI at Portsmouth	References ⁴																											
1776 14	39.600	81.900			6 SRA		133	OH Muskingum River	No information about Portsmouth	Docekal, 1970; Coffman, and others, 1982																											
1811 12 16 08	35.400	90.400	7.20	FANU	11 SRA		756	AR New Madrid, Mo.	Portsmouth probably inside VI isoseismal	Street, 1981 & 1982																											
1811 12 16 14	35.400	90.400	7.00	FANU	11 SRA		756	AR New Madrid, Mo.	Portsmouth probably inside VI isoseismal	Street, 1981 & 1982																											
1812 01 23 15	36.300	89.600	7.10	FANU	11 SRA		644	MO New Madrid, Mo.	Portsmouth probably inside VI isoseismal	Street, 1981 & 1982																											
1812 02 07 09	36.500	89.600	7.30	FABAR	11 SRA		634	MO New Madrid, Mo.	Portsmouth probably inside VII isoseismal	Street, 1981 & 1982																											
1875 06 18 12	40.200	84.000			7 SRA		182	OH Western Ohio, Urbana	Portsmouth outside felt area	Docekal, 1970																											
1886 09 01 02	32.900	80.000	7.02	MwBOL	10 SRA		704	SC Charleston	V	Bollinger and Stover, 1976; Bollinger, 1977																											
1895 10 31 11	37.000	89.400	6.20	FABAR	9 SRA		596	MO Charleston	Portsmouth inside VI isoseismal	Hopper and Algermissen, 1980																											
1897 05 03 17	37.100	80.700			7 SRA		274	VA Pulaski	Portsmouth outside felt area	Hopper and Bollinger, 1971																											
1897 05 31 18	37.300	80.700	5.80	FANUT	8 SRA		259	VA Giles County	Portsmouth inside I-IV isoseismal	Hopper and Bollinger, 1971																											
1901 05 17 07	38.745	82.955			7 SRA		10	OH Portsmouth	VII	Isoseismal map made for this report																											
1913 03 28 21	36.200	83.700			7 SRA		291	TN Knoxville	No information about Portsmouth	Docekal, 1970; Coffman and others, 1982																											
1926 11 05 14	39.100	82.100			7 SRA		87	OH Meigs County, Ohio	No information about Portsmouth	Docekal, 1970; Coffman and others, 1982																											
1930 09 30 20	40.300	84.300			7 SRA		204	OH Anna	No information about Portsmouth	Docekal, 1970; Neumann and Bodle, 1932																											
1931 09 20 23	40.429	84.270	4.50	FADG	7 SRA		215	OH Anna	Portsmouth just inside I-IV area.	Neumann, 1932																											
1937 03 02 14	40.488	84.273	4.70	FADG	7 SRA		221	OH Anna	Portsmouth on outer edge of felt area	Docekal, 1970; Neumann, 1940																											
1937 03 09 05	40.470	84.280	4.90	FADG	8 SRA		219	OH Anna	Portsmouth inside I-IV isoseismal	Docekal, 1970; Neumann, 1940																											
1952 06 20 09	39.640	82.023	4.10	FADG	6 SRA		129	OH Southeastern Ohio	Portsmouth outside felt area	Docekal, 1970; Murphy and Cloud, 1954																											
1980 07 27 18	38.193	83.891	5.03	MwHRR	7 SRA		100	KY Northern Kentucky	VI	Stover and von Hake, 1982																											
1988 09 07 02	38.143	83.878	4.60	MnBLA	6 PDE		103	KY Near Sharpsburg	IV	U.S. Geological Survey, unpub. data, Oct., 1990																											

¹Magnitude types and sources:

- FA Magnitude from felt area.
Mw Moment magnitude (N-m) by formula of Hanks and Kanamori (1979).
Mn M_n magnitude from Nuttli (1973b).
NU Computed according to Nuttli, 1973a.
BAR Computed according to Barstow and others, 1981.
BOL Computed according to Bollinger, 1986.
NUT Computed according to Nuttli and others, 1979.
DG Computed according to Dewey and Gordon, 1984.
HRR Computed according to Herrmann and others, 1982.
BLA Computed according to Virginia Polytechnic Institute and State University, Blacksburg, Va.

²The intensity listed from the SRA and PDE catalogs is the maximum intensity reported on land, in the United States. In the central United States this is usually, but not always, the same as the maximum intensity, MMI_o, assigned for the earthquake.³Reference for the information in all columns to the left of this column

SRA National Earthquake Information Center (NEIC), Earthquake Data Base System, computer files of the State Seismicity File. The SRA catalog contains magnitudes ≥ 2.5 and is current through 1985.

PDE National Earthquake Information Center (NEIC), Earthquake Data Base System (EDBS), computer files of the Preliminary Determination of Epicenters listings published by the National Earthquake Information Service (NEIS). Searched from 1986 to present.

⁴Reference for the epicentral location and MMI at Portsmouth

Table II-4. Earthquake of May 17, 1901, Portsmouth-Sciotoiville, Ohio

Location	MMI	Lat °N	Lon °W	Description
Ky. Ashland	5	38.48	82.64	Severe, houses rocked. People awakened, some thinking an explosion. Many articles displaced, dishes rattled. Roaring. Three shocks, duration 20 seconds, south to north.
Ky. Beattyville	4	37.57	83.71	People awakened. Lamp oil seen splashing.
Ky. Catlettsburg	3	38.40	82.60	Felt.
Ky. Greenup	6	38.57	82.83	Windows, dishes broken. Nearly everyone awakened. Explosion then quaking.
Ky. Lexington	0	38.05	84.50	Not reported in local newspapers.
Ky. Louisville	0	38.25	85.76	Not reported in local newspaper.
Ky. Maysville	5	38.64	83.74	Chinaware, everything loose broken. Whole town awakened. Windows, doors rattled. Rumbling, then cannon crack, then shaking. Duration 10-15 seconds, north to south.
Ky. Paris	0	38.21	84.25	Not reported in local newspapers.
Ky. S. Portsmouth	4	38.72	83.01	People awakened.
Ky. Vanceburg	4	38.60	83.32	Many awakened. Loud roar. Duration 10 seconds, north to south.
Oh. Aberdeen	5	38.66	83.76	Dishes broken.
Oh. Buena Vista	4	38.63	83.26	Almost entire village awakened. Houses shook, dishes, windows rattled. A loud report. Many badly frightened. Gas well exploded same day as earthquake [caused by earthquake?]. [3 "Buena Vista's" in Ohio. Assumed the one west of Portsmouth.]
Oh. Chillicothe	5	39.33	82.98	Severe. People rushed from bed presuming an explosion. No damage, 30 seconds.
Oh. Cincinnati	0	39.16	84.46	Not felt.
Oh. Circleville	0	39.60	82.95	Not felt.
Oh. Gallipolis	5	38.81	82.20	Plaster shaken loose in a house. People awakened. Dishes rattled. Like distant thunder. Wavy motion.
Oh. Hillsboro	4	39.20	83.61	Doors, windows rattled. Low rumbling like distant thunder.
Oh. Ironton	5	38.54	82.68	Many awakened, some nauseated. A succession of violent undulations. 30 seconds, west to east.
Oh. Jackson	5	39.05	82.64	Largest buildings shaken until feared walls would be unsafe.
Oh. Lucasville	5	38.88	83.00	Many rushed into streets. Dishes, windows rattled. Rocking chairs moved. No serious damage. Some presumed intruders. Rumbling like thunder.
Oh. Manchester	4	38.69	83.61	People awakened. A few clocks stopped. No damage, duration several seconds, south to north.
Oh. Marietta	3	39.42	81.46	Felt.
Oh. New Boston	5	38.75	82.94	Houses swayed. People badly frightened.
Oh. Piketon	4	39.07	83.01	General alarm.
Oh. Portsmouth	7	38.73	83.00	The severest earthquake in the history of the city. Many chimneys damaged, often tops fell, or a few bricks on roof. Many West Front Street house windows shattered. Canned goods fell in groceries, vases from mantles. Nearly everyone awakened, hundreds rushed into streets, great alarm. Many presumed explosion in nearby gas fields. Police presumed bank robbery. Rumbling. Two sharp shocks, first heavier, duration 10 seconds, west to east.
Oh. Sciotoiville	7	38.76	82.89	Rocked violently. Many chimneys fell. People awakened, almost a panic. Windows rattled, many dishes broken.
Oh. Taylorsville	6	39.08	83.73	Beds moved .6 m, furniture overturned. People awakened, alarmed. Loud roar like thunder. [2 "Taylorsville's". Assumed one nearer Portsmouth.]
Oh. Washington	0	39.54	83.44	Not reported in local newspaper. [Assumed "Washington Court House."]
Oh. Wellston	5	39.12	82.53	Severe. Felt most in west and north parts of city. Displaced furniture. Many awakened, ran into streets, much alarm. Dishes rattled. 3 shocks.
Oh. West Union	5	38.79	83.55	Violent. People awakened. Lighted lamp nearly fell off table.
Oh. Wheelersburg	5	38.73	82.86	A battery and glass jars fell. People thrown out of bed, some thought burglars.
Oh. Zanesville	4	39.94	82.01	Many awakened, general alarm. No serious damage, duration half a minute.
W.Va. Charleston	4	38.34	81.63	No damage. Many presumed a mine explosion.
W.Va. Huntington	4	38.42	82.45	Severe. No damage. One shock.
W.Va. Kenova	5	38.40	82.58	Man almost thrown off a lunch counter stool. Pen flew across table. Rumbling. People badly frightened.
W.Va. Williams-town	4	39.37	81.50	Inkstand overturned. Rumbling. Duration 8 seconds.

Figure II-1. Important historical earthquakes in the eastern United States. Epicenters were obtained from the National Earthquake Information Center's computer data base. Only shocks with maximum Modified Mercalli intensities $MMI_0 \geq V$ were selected.

Figure II-2. Intensity attenuation for four large earthquakes in the Midwest. From this graph it may be seen that damage intensities ($MMI \geq VI$) in this region commonly occur out to distances of approximately 300 km from the epicenter of an $MMI_o = IX$ shock, and out to a little over 100 km from an $MMI_o = VII$ shock. The epicentral distance shown here is the radius of a circle with area equal to the area of the isoseismal; however, most isoseismals are irregular in shape, having protrusions and reentrants. Therefore shocks at slightly greater distances from the sites than the intensity-VI radii shown here must be investigated for possible damage at Paducah and Portsmouth.

Figure II-3. Important historical earthquakes in the region around Paducah, Ky. Epicenters were obtained from the National Earthquake Information Center's computer data base. Shocks with maximum intensities $MMI_0 \geq VI$ were selected within 200 km of Paducah; $\geq VII$ within 300 km of Paducah; $\geq VIII$ within 450 km of Paducah; $\geq IX$ within 650 km of Paducah; $\geq X$ within 950 km of Paducah; and $\geq XI$ within 1400 km of Paducah. These distance- MMI_0 combinations were chosen based on the intensity-attenuation curve (Fig. II-2). Although many of the earthquakes within these radii did not in fact cause damage at Paducah, every shock having any potential to cause such damage is shown in this figure and listed in table II-2.

Figure II-4. Isoseismal map for the earthquake in the New Madrid seismic zone on December 16, 1811 (02:15). The map is from Street (1981) and a possible set of isoseismals have been added by Margaret Hopper for this report.

Figure II-5. Isoseismal map for the earthquake in the New Madrid seismic zone on December 16, 1811 (08:15). The map is from Street (1981) and a possible set of isoseismals have been added by Margaret Hopper for this report.

Figure II-6. Isoseismal map for the earthquake in the New Madrid seismic zone on January 23, 1812. The map is from Street (1981) and a possible set of isoseismals have been added by Margaret Hopper for this report.

Figure II-7. Isoseismal map for the earthquake in the New Madrid seismic zone on February 7, 1812. The map is from Street (1981) and a possible set of isoseismals have been added by Margaret Hopper for this report.

Figure II-8. Principal aftershocks of the 1811–1812 New Madrid earthquake sequence. Date and time of the aftershock are shown on each map. Squares indicate locations reporting the aftershock. Data are from Street and Nuttli (1981). Because no Modified Mercalli intensities are assigned to the reporting locations, no isoseismals have been drawn on the maps. However, if it is assumed that reporting localities experienced at least MMI IV–V, then Paducah and Portsmouth are probably within the felt areas of all these aftershocks. Portsmouth might be within the damage area (MMI $\geq$ VI) for two of the aftershocks (Dec. 17 and Feb. 7 (22:40)), and Paducah might be within the damage area of almost all of the aftershocks.

Figure II-8. (Continued).

Figure II-9. Iseismal map for the earthquake near Charleston, Missouri, on October 31, 1895. The map is from Hopper and Algermissen (1980).

Figure II-10. Isoseismal map for the earthquake in northeastern Arkansas on January 5, 1843. The map is from Hopper (1985).

Figure II-11. Isoseismal map for the earthquake near Cairo, Illinois on January 11, 1883. The map is from Street and Green (1984).

Figure II-12. Isoseismal map for the earthquake near Cairo, Illinois on September 27, 1891. The map is from Street and Green (1984).

Figure II-13. Iseismal map for the earthquake in southeastern Missouri on August 22, 1905. The map is from Street and Green (1984).

Figure II-14. Isoseismal map for the earthquake in south-central Illinois on November 9, 1968. The map is from Gordon and others (1970).

Figure II-15. Isoseismal map for the earthquake near Charleston, South Carolina, on September 1, 1886. The map is from Bollinger (1977).

Figure II-16. Important historical earthquakes in the region around Portsmouth, Ohio. Epicenters were obtained from the National Earthquake Information Center's computer data base. Shocks with maximum intensities $MMI_0 \geq VI$ were selected within 200 km of Portsmouth; $\geq VII$ within 300 km of Portsmouth; $\geq VIII$ within 450 km of Portsmouth; $\geq IX$ within 650 km of Portsmouth; $\geq X$ within 950 km of Portsmouth; and $\geq XI$ within 1400 km of Portsmouth. These distance- MMI_0 combinations were chosen based on the intensity-attenuation curve (Fig. II-2). Although many of the earthquakes within these radii did not in fact cause damage at Portsmouth, every shock having any potential to cause such damage is shown in this figure and listed in table II-3.

Figure II-17. Isoseismal map of the earthquake near Portsmouth, Ohio, on May 17, 1901. The data were collected by R.L. Street of the University of Kentucky. The intensities were assigned and the isoseismals drawn by Margaret Hopper and Carl Stover for this report.

Figure II-18. Earlier version of the isoseismal map of the earthquake of May 17, 1901. The shock had been listed as a $MMI_o = V$ earthquake with epicenter near Wellston, Ohio. The additional data shown on figure II-17 made possible a much more detailed map and showed a maximum intensity of VII. This map is from Docekal (1970). The dots show the locations reporting the shock (felt and not felt), and the circle shows the limit of the felt area.

Figure II-19. Isoseismal map of the earthquake in northern Kentucky on July 27, 1980. The map is from Stover and von Hake (1982).

Figure II-20. Isoseismal map of the earthquake near Anna, Ohio, on March 9, 1937. The map is from Docekal (1970). The dots show the locations reporting the shock (felt and not felt). Docekal's map of a similar, but slightly smaller shock on March 2, 1937, shows Portsmouth outside the boundary of the felt area.

III. Tectonic Summary of the Site Vicinities

by

Paul C. Thenhaus

Summary

The potential for strong earthquake ground motion at the Paducah Gaseous Diffusion Plant site is dominated by the seismic sources of the Reelfoot Rift and geologically related structures in the midcontinent region. Interpretations of recently collected deep-crustal seismic reflection profiles have questioned previous interpretations regarding the geographic extent of the inferred, Precambrian, New Madrid Rift Complex. Seismic source zones and maximum magnitude distributions based on the previously suggested extent of the rift complex are considered conservative when compared to recent tectonic interpretations and are adequate for the required probabilistic ground-motion hazard analysis. Seismic sources in the the eastern United States that affect the Portsmouth plant site represent a wide range of interpretations regarding source zone geometries and adequately represent the generally poor understanding of seismogenic features in this region.

Introduction

Delineating seismic sources in the eastern United States for the purpose of estimating ground motion hazard from earthquakes involves considerable scientific judgment to bridge large gaps in knowledge regarding earthquake processes and potentially seismogenic geologic structure (Thenhaus, 1983). The source zones defined in the Electric Power Research Institute (EPRI) and Lawrence Livermore National Laboratories (LLNL) seismic hazard studies represent a wide range of interpretations regarding possible future locations of earthquakes, their sizes, and frequency of occurrence at and near the

Paducah, Kentucky and Portsmouth, Ohio gaseous diffusion plant sites. The studies differ in approach to defining seismic sources. Most LLNL seismicity experts generally followed a traditional approach to source zone definition in the eastern U.S. in which relatively large, homogeneous zones of activity were defined primarily on the geographic distribution of historical seismicity and implied associations with regional geologic structure. The EPRI approach, by design, allows identification of individual geologic features and subjective assessments of their probability of being active or capable of producing earthquakes. However, both approaches are limited by the poor understanding of causes of earthquakes in the eastern United States. Hence, although the EPRI seismic source zones show considerably more detail than the LLNL sources, the probabilities of activity assigned to many of the identified features are low because the hypotheses relating seismicity to these features are speculative. Most commonly, the spatial association of a feature with historic seismicity was used as the primary criterion that a feature may be potentially active because the physical properties of the features are so poorly known and the relationship of earthquakes to specific physical characteristics so uncertain. In light of these uncertainties, we expect diverse opinions concerning the relation of seismicity to known or inferred geologic structure. The EPRI and LLNL source zone methodologies attempt to represent this range of opinion regarding the future distribution of earthquakes in the eastern United States. However, new geologic data and interpretations are continually being developed and professional opinion can be expected to change in time as more data are brought to bear on controversial issues. We

believe, nonetheless, that for reasons explained in the following sections, the representations of seismic sources in the two studies remain adequate at present to derive the required probabilistic ground-motion hazard estimates at the Paducah and Portsmouth plant sites.

III.A. Paducah Gaseous Diffusion Plant Site

The Paducah site, 10 km west of Paducah, Kentucky, is located within a complex junction of northeast-, northwest-, and east-trending Precambrian structural trends at the northern terminus of the Mississippi embayment (Fig. 1). The dominant source of strong ground motion at the Paducah site is seismicity associated with the Reelfoot rift because of the large earthquakes that occurred there historically, the continuing relatively high rate of low-magnitude earthquake activity associated with the New Madrid Seismic Zone (NMSZ), and proximity of the site location to these features (Fig. 1).

A residual aeromagnetic map of the upper Mississippi embayment images the Reelfoot rift as a northeast-trending zone of subdued magnetic expression 50-70 km wide (Fig. 2; Hildenbrand and others, 1982). The rift is interpreted as a down-dropped crustal block bounded by faults with an average structural relief on the crystalline basement of about 2 km. High-amplitude circular and subcircular anomalies along boundary fault zones and central to the rift are interpreted as mafic intrusives emplaced during episodes of extensional reactivation throughout the geologic history of the rift (see Fig. 1). While the Reelfoot rift originated and was reactivated during periods of extensional tectonism in late Precambrian through Mesozoic time, the present crustal stress regime of the eastern United States is dominated by northeast- to east-west-trending maximum compressive

horizontal stress. The New Madrid Seismic Zone in the Reelfoot rift is therefore interpreted as being caused by compressional reactivation of rift faults that originally formed in an ancient extensional tectonic environment (Fig. 3; Hamilton and Zoback, 1982; Russ, 1982). However, details of such faults such as length, location and possible segmentation remain mostly unknown.

Seismic reflection profiles across the NMSZ between Caruthersville, Missouri and Marked Tree, Arkansas reveal disruption of the top of magnetic basement as well as antiformal doming and structural disruption of Paleozoic sedimentary layers (Crone and others, 1985). The deformed axial zone as well as the NMSZ terminate 25 km southwest of Marked Tree, Arkansas although the rift structure continues considerably farther southwest. North of Caruthersville, Missouri, the deformed zone probably merges with the northwest-trending Dyersberg-New Madrid seismicity trend of the NMSZ (Crone and others, 1985). Focal mechanisms of small earthquakes along the Dyersberg-New Madrid trend have a significant thrust component in contrast to the pure dextral-slip motion exhibited in the northeasterly trends of the NMSZ (Stauder, 1982; Nicholson and others, 1984). Surface deformation along the Dyersberg-New Madrid trend is manifested by the Lake County uplift, an elongate dome of Quaternary age that is about 50 km long, 23 km wide and displaces the Mississippi River valley as much as 10 meters (Russ, 1982). Thrust components of motion along the northwest trend associated with the Quaternary uplift and pure dextral-slip on northeast trends are consistent with a model of a left-stepping restraining bend causing localized compression within a dextral-slip fault zone (Fig. 3; Russ, 1982; Stauder, 1982).

The subdued aeromagnetic expression of the rift in northeastern Arkansas continues northeasterly through western Kentucky (Hildenbrand and others, 1982) and perhaps

into southern Indiana (Braile and others, 1982; 1985). However, in western Kentucky, a strong overprint of northwest-trending aeromagnetic signatures is evident (crustal domain IV of Hildenbrand and others, 1982; Fig. 2). The correlation of the northwest-trending magnetic lineaments with major fault zones suggests that the faults are fundamental basement structures related to Precambrian structural trends (Lidiak and Zietz, 1976) and alternating magnetic highs and lows across the northwest trend may reflect block faulting (Hildenbrand and others, 1982). Lineament s'-s correlates with the Rough Creek fault zone through western Kentucky (Hildenbrand and others, 1982; Braile and others, 1982). Between s'-s and p'-p, a depressed magnetic basement reflects the Moorman syncline of western Kentucky (Fig. 1) which itself contains northwest-trending magnetic highs bounded by lineaments q-q' and r-r'. Faults of the New Madrid system near the southeast margin of the Reelfoot rift (B-B') curve easterly into the Moorman Syncline (Fig. 1). Lineaments o'-o and p'-p bound an inferred upthrown crustal block that contains the site location (Fig. 1) and perhaps are subsurface strands of the St. Genevieve fault zone that extends to the northwest into Missouri where the fault is mapped at the surface (Hildenbrand and others, 1982). The St. Genevieve fault is one of a family of steeply dipping, northwest-trending, left-lateral fault zones through southeast Missouri (Fig. 1) that share a complex geologic history of strike-slip and reverse reactivations (Clendenin and others, 1989). The faults probably served as transfer faults, normal to the Reelfoot rift, that accommodated differential separation of the crust along the rift in late Precambrian and Mesozoic rifting episodes. Although Quaternary movement on these faults is not known, Clendenin and others (1989) suggest that the faults are responsible for seismicity northwest of the Reelfoot rift and at

intersections of transfer faults with extensional rift faults.

Many northeast-trending faults have been mapped as part of the New Madrid fault system at the head of the Mississippi Embayment in southeastern Illinois and extreme western Kentucky (Fig. 1). The abundance of mapped faults in this area is a consequence of detailed geologic mapping related to mineral exploration in the Illinois-Kentucky fluorspar mining district (Heyl and McKeown, 1978). The paucity of faults mapped in southwestern Illinois, south of the Cottage Grove fault zone (Fig. 1), is very likely not an accurate portrayal of existing faults but, rather, reflects a lack of detailed geologic mapping in that area (Heyl and McKeown, 1978). It is not known to what extent the intense faulting along northeast trends at the head of the embayment reflects a fault system that is at depth to the south beneath the Cretaceous-Tertiary fill of the embayment. Faults of the fluorspar mining district may be more closely related to the uplift and collapse of Hicks dome, a late Paleozoic structural high (similar to the present Ozark dome in southeast Missouri) that collapsed by late Cretaceous time. In this case, the faults might be shallow extension features typically associated with crests of domes and anticlines and not of deep crustal origin (Heyl and McKeown, 1978). Notably, a wedge-shaped area containing the site location and roughly bounded on the north by the Cottage Grove-Rough Creek fault system and on the southwest by the St. Genevieve fault is uniquely characterized by very little seismic activity compared to the Wabash Valley area to the north and the Reelfoot rift and Ozark dome to the south and west, respectively (McKeown and others, 1983).

The Cottage Grove-Rough Creek fault system through southern Illinois and western Kentucky (Fig. 1) is a deep, fundamental crustal structure as inferred from its significant length, its expression in geophysical studies

and the presence of mantle-derived intrusives emplaced within the fault system (Heyl, 1972; Heyl and McKeown, 1978). The fault system is composed of steeply-dipping anastomosing strike-slip faults within which normal and reverse separations interchange across the fault zone. Numerous short northwest-striking echelon normal faults cross the braided strike-slip faults. The overall structure of the zone indicates a late-Paleozoic wrench fault origin with right-lateral displacement (Nelson and Krause, 1981; Harding and others, 1985). Strikes of faults in the Illinois fluorspar district south of the fault system trend 10-20 degrees clockwise of fault trends in the Wabash Valley fault zone to the north. There is no evidence that faults in Paleozoic rocks of the fluorspar district to the south and the Wabash Valley fault zone to the north cross the Cottage Grove-Rough Creek fault system (Bristol and Treworgy, 1979). Although Quaternary displacements are not known in the fault system, Heyl (1972) and Heyl and McKeown (1978) suggest that some parts of the system might be presently active because of the close proximity of a small number of low intensity earthquakes.

The Wabash Valley fault zone of southeastern Illinois and extreme southwestern Indiana is a system of north-northeast-trending normal faults extending some 100 km north of the Rough Creek fault zone (Fig. 1). Individual faults range from about 5 to 80 km in length and are characterized by small offsets (up to about 150 meters) of post-Pennsylvanian and pre-Pleistocene age (Bristol and Treworgy, 1979). Quaternary displacements are not known to exist. Sexton and others (1986) interpreted seismic reflection profiles collected in the Wabash River valley as showing that the small-offset Wabash Valley faults project downward to older, large-offset (up to 500 meters) basement (?) faults suggesting post-Pennsylvanian reactivation of a basement rift system. However, COCORP (Consortium for

Continental Reflection Profiling) profiles 20 km north of Sexton's lines did not image a distinct graben system in the basement nor a characteristic thickening of lower Paleozoic strata as observed in the Reelfoot rift to the south (Pratt and others, 1989). Based on Sexton and others (1986) profiles and other proprietary reflection data, Nelson (1990) suggests that the Wabash Valley faults die out at depth. Nelson (1990) and Pratt and others (1990) argue that rifting associated with the Reelfoot rift did not extend north of the Rough Creek fault zone in western Kentucky.

Nuttli (1979) proposed the existence of a Wabash Valley seismic zone in the vicinity of the Wabash Valley fault system that encompassed 5 earthquakes since 1899 with magnitudes of at least m_b 5.0. An m_b 5.2 earthquake occurred in the seismic zone on 10 June 1987 (Langer and Bollinger, 1990). However, no earthquakes to date have been demonstrably associated with faults of the Wabash Valley fault system. Hamburger and Rupp (1989) argue against the existence of the Wabash Valley seismic zone noting the diffuse nature of seismicity throughout southern Illinois and Indiana, the poor location quality of the historic earthquakes and the lack of evidence of Quaternary surface rupture on Wabash Valley faults. Nonetheless, widespread, late Holocene liquefaction features are known to exist in the Wabash River valley and their geological attributes suggest they were produced by strong shaking (Obermeier, written commun., 1990; Obermeier and others, 1991).

For nearly a decade, the most commonly referenced regional tectonic model for the central interior region has been that of the New Madrid Rift Complex. Based on interpretations of geophysical data, Braile and others (1982) proposed the existence of the New Madrid Rift Complex in which terminal arms of the Reelfoot rift extend to the northwest to include St. Louis, Missouri, to the northeast into

southern Indiana and eastward into Kentucky (Fig. 4). However, recent COCORP seismic reflection lines that traverse a central part of the inferred St. Louis arm and cross all of the southern Indiana arm revealed no rift features in the deep crust (Pratt and others, 1989, 1990; Nelson, 1990). Nelson (1990) maintains that only the Kentucky arm of Braile and others' (1982) "New Madrid Rift Complex" exists and occupies the Rough Creek graben (Fig. 5).

III.B. Adequacy of Source Zone Models at Paducah

The question of whether a part of the midcontinent is underlain by an extensive ancient rift complex bears most directly on the assessment of maximum magnitudes in the region. A rift is characterized generally by crustal-penetrating faults, which, if unhealed and suitably oriented in the prevailing stress field, are capable of releasing strain energy to cause large earthquakes. Hence, the lack of an extensive rift complex north of the Mississippi embayment (Nelson, 1990) might imply that maximum magnitudes of potential earthquakes outside the Reelfoot-Rough Creek graben is no higher than typical intraplate background seismicity. Braile and others' (1982) model of the New Madrid Rift Complex influenced 5 of the 6 source zone models in the EPRI study; representation of the "St. Louis arm" and "southern Indiana arm" of the complex are explicitly represented with median maximum magnitudes ranging between 5.9 and 7.4. Probabilities that these zones are active (p^A 's) are relatively high among the Tectonic Evaluation Committees' (TECs') assessments and reasonable in light of the historical activity in the region. Partial representations of the terminating arms of the rift complex are given by three LLNL seismicity experts (experts number 1, 10 and 13). The remaining experts chose to represent seismicity outside the NMSZ

by more general, subjectively defined source configurations.

Regardless of the relation of deep crustal structure to seismic potential, sand blows and liquefaction features provide empirical evidence of prehistoric earthquakes in the Wabash Valley (Obermeier, written communication, 1990; Obermeier and others, 1991). Presently uncertain is whether all of the liquefaction features were produced by a single earthquake. If so, the paleoseismic event might have been as large as m_b 6.6 (Obermeier, written communication, 1990). The weakest historical earthquake in the NMSZ known to have caused liquefaction was the magnitude m_b 6.2, 1895 Charleston, Missouri earthquake (Obermeier, written communication, 1990). Thus, maximum magnitudes of at least m_b 6.2–6.6 seem appropriate for Nuttli's (1979) Wabash Valley seismic zone as well as the broader region north of the Mississippi embayment if this region is interpreted as not having seismicity clusters or alignments indicative of "zones" (Hamburger and Rupp, 1988). Maximum magnitudes central to a range defined by each of the EPRI TEC's and each of LLNL's experts for this region are between 6.2–6.8 and 6.0–7.3, respectively. Thus, the majority of maximum magnitudes assigned in the EPRI and LLNL studies are suitable and adequate in light of the more recent paleoseismicity investigations. Some minor percentage of these evaluations (the lower-magnitude tails of some maximum magnitude distributions) are perhaps too low to be reasonable in light of the recent paleoseismic information. However, because ground motion hazard at the site vicinity is dominated by the NMSZ, the effects of such a deficiency would be inconsequential at the site location.

It is fair to point out that, although faults such as the Cottage Grove (Heyl, 1972; Heyl and McKeown, 1978) and the St. Genevieve (Clendenin and others, 1989) have been suggested in the literature to be seismogenic

based on spatial associations with small magnitude earthquakes, such associations are highly speculative, particularly when based on small magnitude earthquake locations in the midcontinent area. Mislocations of some small-magnitude earthquakes in the region since 1971 have been found to be greater than 50 km (Gordon, 1988). Moreover, nearly 50 percent of recently relocated earthquakes in the region had new locations in which the 95-percent-confidence location ellipses did not even contain the previously accepted epicenter (Gordon, 1988). The point is, that without detailed seismological investigation, identifying seismically active faults in the region on the basis of spatial associations with historical, low-magnitude seismicity is a highly conjectural exercise. The Bechtel team chose to represent the Cottage Grove ($p^A = 0.15$), Rough Creek ($p^A = 0.20$) and St. Genevieve ($p^A = 0.40$) faults as specific tectonic features in their assessment. The low probabilities of these faults being active seem reasonable lacking any evidence of fault activity other than spatial associations with low-magnitude earthquakes previously discussed. It is not surprising, however, that most teams chose not to explicitly represent such features because of the lack of evidence of activity. In the region surrounding the NMSZ, LLNL seismicity experts did not attempt to define individual faults as seismic sources.

With respect to the plant site, the northeastern extent of the New Madrid seismic zone within the Reelfoot rift is important to the estimation of ground motion hazard at the site. Commonly, that part of the Reelfoot rift associated with the NMSZ is terminated on the northeast along aeromagnetic lineament o'-o (see Fig. 2) (McKeown and others, 1983). The distinct northwest structural trends and low level of seismic activity northeast of this boundary (see Fig. 4) contrast with structural style and seismic activity to the southwest. Together, these attributes are typically taken as

evidence of a fundamental change in seismotectonic setting. Nonetheless, subdued geophysical expression of the Reelfoot rift extends into this area (Hildenbrand and others, 1982; Hinze and others, 1982) and contributes to the location uncertainty of a northern boundary to the NMSZ. Characterization of seismic sources in the site vicinity among the TEC's in the EPRI study, viewed as a whole, represent a range of interpretations regarding the northeastern termination of the NMSZ. For example, the Bechtel team locates this boundary at the Paducah site and the Woodward-Clyde team locates this boundary about 90 km southwest of the site. The remaining TECs' boundaries lie between these extremes. All models have maximum magnitudes for this zone as large as the 1811-12 New Madrid earthquakes (m_b 7.2-7.5). The TEC interpretations appear to adequately account for uncertainty in the location of the northern boundary of the NMSZ as that zone has been expressed by the historical and instrumental record of earthquakes. Similar comparisons for LLNL source zone boundaries are precluded by the lack of a geographic coordinate system for referencing source zone boundaries to the site on the seismic zonation base maps.

III.C. Portsmouth Gaseous Diffusion Plant

The Portsmouth plant site is located on the western flank of the Appalachian basin. Crystalline basement is in excess of 10,000 ft. below sea level to the east in West Virginia and rises to less than 2,000 ft. below sea level west of the site in Ohio along the Cincinnati arch and the Indiana-Ohio platform (Fig. 6; Lucious and von Frese, 1988). Earthquake activity in this region is diffuse and specific seismogenic features or faults are not known. An ancient rift structure about 1.3-1.0 billion years old (Keweenawan age) is inferred in the basement

rocks of western Ohio from geophysical studies, extending from northeastern Indiana southward into central Tennessee (Fig. 6; Keller and others, 1982; Lucious and von Frese, 1988). The fact that the Anna, Ohio earthquakes (March 2, 1937, m_b 5.3; March 9, 1937, m_b 5.3; Nuttli, 1979) and the Sharpsburg, Kentucky earthquake (July 10, 1980, m_b 5.2) occurred in close proximity to the boundaries of this inferred rift and that such rifts may be characterized by persistent zones of weakness in the continental crust (Hamilton, 1981), provide circumstantial evidence for the rift being a seismogenic source. Mauk and others (1979) noted a spatial relation between earthquakes in the Anna area relocated by Dewey and Gordon (1984) and the Anna-Champaign fault. The strike of the fault parallels the general trend of the inferred rift to the northwest although the specific relation of the fault to the rift is not known. Alternatively, seismicity has been noted to concentrate along the Cincinnati arch in the eastern midcontinent (Barstow and others, 1981) and may be related to shallow basement structure rather than the rift feature.

Drill hole and seismic reflection investigations have tentatively identified a half-graben of Precambrian age in northern Warren County, Ohio (Wolfe and others, 1989) (Fig. III.6). However, the geographic extent of this feature is not known and no seismicity is presently known to be associated with the structure. An east-west COCORP transect through the state of Ohio imaged opposing sets of dipping reflectors through midcrustal to deep crustal levels. Reflectors dipping 25° to 30° eastward dominate a 40-50 km-wide zone beneath west-central Ohio whereas a zone greater than 80 km wide through eastern Ohio is underlain by west-dipping (<40°) reflectors (Pratt and others, 1989). These reflectors are thought to mark a major boundary between blocks in the ancient Grenville crust of the eastern midcontinent area. Other seismic reflection data

to the north in Canada and to the south in northern Alabama suggest that each of the dipping crustal features may be continuous for more than 500 km (Pratt and others, 1989). A relation between the dipping features in the deep crust and seismicity in the region is not known.

The spatial coincidence of suspected rift features and a major boundary in the deep crust with the Cincinnati arch in a region of dispersed moderate- to low-magnitude earthquakes contributes a high degree of uncertainty concerning the geologic bases for seismic source zones in this region.

III.D. Adequacy of Source Zone Models at Portsmouth

Two EPRI source zone models (Law team and Woodward-Clyde team) entertain the possibility that the rift of Keweenaw age is seismogenic although both models give generally low probabilities to this hypothesis. The rift extends farther to the east in the TEC's source zone models than shown in figure 6 and include the site location. Other TEC's source zones model the Cincinnati arch as an active source as well as consider alternate zonations for the Anna, Ohio earthquake area and various geophysical anomalies that occur within or transect the state of Ohio. Median maximum magnitudes designated among the TEC's range between m_b 5.1-6.8 for the site vicinity.

Several source zone models of the LLNL study interpret the high-basement features of the region as seismogenic sources. Mostly, however, source zones take on a variety of shapes reflecting primarily personal preferences on grouping historical earthquakes for recurrence calculations. Median maximum magnitudes designated among LLNL's seismicity experts vary between m_b 5.2-7.3.

Relating seismicity to any specific geologic feature in this region is a highly speculative exercise. Low probabilities assigned to such associations are appropriate. Traditionally, source zones of this region correspond to regional basement structures or interpretations based on the regional distribution of historic seismicity and most source zones of the EPRI and LLNL studies retain this approach. Together, the seismic sources and corresponding maximum magnitudes represent a wide range of interpretations regarding source zone geometries and earthquake potential and adequately represent the generally poor understanding of seismogenic features in the region.

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Figure III-1. Map showing seismicity (1974-1977), geologic and inferred magnetic structures in the northern Mississippi embayment and vicinity. Modified from Hildenbrand and others (1982). Faults in southeastern Missouri taken from Clendenin and others (1989).

Figure III-2. Aeromagnetic map showing interpreted lineaments indicating structural or lithologic boundaries in the northern Mississippi embayment and vicinity (from Hildenbrand and others, 1982).

Figure III-3. Hypothetical tectonic model for area of compression and uplift along the Dyersberg-New Madrid seismicity trend. The left step-over in the right-lateral strike-slip system causes compression in the vicinity of the step-over due to convergent movement of blocks A and B (modified from Russ, 1982).

Figure III-4. Extent of the New Madrid Rift Complex as proposed by Braile and others (1982).

Figure III-5. Extent of the Reelfoot Rift — Rough Creek Graben as proposed by Nelson (1990).

Figure III-6. Generalized basement structures of Ohio (modified from Lucious and von Frese, 1988). Warren County is shaded.

IV. A Description and Comparison of the EPRI/SOG and LLNL Seismic Hazard Methodologies

by

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Summary

Both the EPRI/SOG and LLNL seismic hazard methodologies were designed to take into account and to represent the diversity of scientific opinion that exists regarding the probable locations of future earthquakes. We investigated six aspects of the two methodologies in an attempt to determine how each aspect might affect the relative levels and range of ground motion exceedance estimates at a site calculated using each methodology. We examined the two methodologies in regard to: (1) the elicitation of expert opinion; (2) the formalism used for defining source zones; (3) the formalism for determining values of the seismicity parameters for the source zones; (4) the choice of ground motion attenuation functions; (5) the means by which alternative source zone scenarios, values of the seismicity parameters, and attenuation functions were combined to obtain a range of hazard estimates; and (6) the means by which a single "best" estimate was obtained from the ensemble of estimates.

With regard to (1), (2) and (3), one might expect more variability in the hazard estimates obtained at a site using the LLNL methodology than in those obtained using the EPRI/SOG methodology. This follows because each individual LLNL seismicity expert developed source zones and estimated earthquake rates in any manner and using whatever data base he or she desired, whereas, the EPRI/SOG teams used a well-defined formalism and a common data base for estimating rates and defining source zones based on possibly active tectonic features. In addition, EPRI/SOG team members exchanged ideas at numerous meetings and consensus within teams

(but not between teams) was required, whereas, there was very little formal interaction between the LLNL experts and no attempt to reach a consensus. (A possible exception that might suggest greater variability for EPRI/SOG than for LLNL hazard estimates occurs with regard to (2); a single EPRI/SOG team tended to propose more alternative scenarios than did an LLNL expert, suggesting more variability per team resulting from scenarios in the EPRI/SOG methodology. However, the use of eleven LLNL seismicity experts compared with six EPRI/SOG teams reduced the difference in the the total number of scenarios for LLNL compared with EPRI/SOG.)

Each of five LLNL ground motion experts selected (and assigned weights to) as many as six attenuation relationships for use in the hazard analysis, whereas the EPRI/SOG organizers (rather than individual teams) selected a total of three attenuation relationships. Thus, with regard to (4), the use by LLNL of a greater range of attenuation relationships further suggests we might expect more variability in the LLNL estimates than in the EPRI/SOG estimates. In addition, one of the LLNL attenuation relationships predicted considerably higher ground motions than did the others; this attenuation relationship so increased the range of results and so significantly affected the statistics, that LLNL tended to present separately hazard estimates calculated including and not including this relationship.

With regard to (5) and (6), EPRI/SOG used a "logic tree" formalism to evaluate ground motions for all combinations of source zones, values of seismicity parameters and attenuation relationships, whereas LLNL used a Monte Carlo technique to evaluate combinations of inputs randomly selected in

accordance with the probabilities assigned to each combination. The Monte Carlo technique allowed LLNL experts to assign continuous distributions to the values of the seismicity parameters, whereas the logic tree approach allowed the EPRI/SOG teams to propose only a small number of alternative earthquake rates, *b*-values and maximum magnitudes. The EPRI/SOG methodology assigned weights to each team based on the consistency of that team's hazard estimates with the estimates of the other teams, whereas LLNL methodology allowed the experts to "self-weight" themselves. Given the two evaluation approaches and weighting schemes, we might expect lower variability in the EPRI/SOG weighted results.

We concluded that aspects (1)–(5) suggest one might obtain a greater range of hazard estimates when using the LLNL methodology than when using the EPRI/SOG methodology. We also concluded that higher mean probabilistic ground motions will likely result for a site in an LLNL hazard analysis if an attenuation relationship (which predicts unusually high ground motions) proposed by one LLNL ground motion expert is included. On the other hand, the ground motion exceedances calculated at a site for any scenario (and a given attenuation function) depend primarily on the rate of earthquakes assigned to sources in the vicinity of the site. Higher levels of ground shaking will be calculated for a site in scenarios in which the site is in the vicinity of a high rate source than in scenarios in which the site is encompassed by a low rate background source. The calculated ground motion exceedances may depend strongly on the distance of the site from the boundary of a high rate source which includes the site or is near the site. The average or median level (and percentile curves) depend on the actual site location relative to source boundaries, the rates assigned to each source in various scenarios, and on the weights assigned to alternative scenarios. For a specific site and a given attenuation relationship, either methodology might tend to give higher or lower ground shaking estimates. Hence, we could

not conclude that systematic differences in the source or seismicity inputs will cause either LLNL or EPRI/SOG to predict consistently higher mean or median probabilistic ground motions for a given attenuation function.

Introduction

In order to perform a probabilistic seismic hazard analysis, locations of seismic source zones, average annual rates and magnitudes of earthquakes within these zones and one or more attenuation functions (relationships between ground shaking, earthquake magnitude and distance) must be provided as inputs. Traditionally, values of the numerical input parameters have been derived primarily from an analysis of historic seismicity. However, particularly in the central and eastern United States, earthquake data are inadequate, incomplete, and subject to interpretation, with the consequence that different individuals, regarded as being equally knowledgeable, may provide significantly different values for the input parameters. These different input values may, in turn, result in considerably different estimates of seismic hazard at any given site. The United States Nuclear Regulatory Commission (NRC) and also the Electric Power Research Institute together with a group of 42 utilities (EPRI/SOG) funded the development of seismic hazard methodologies that would elicit and take into account the diversity of scientific opinion in estimating hazard at sites of critical facilities (e.g., nuclear weapons facilities and/or nuclear power plants) sited in the central and eastern U.S.

The NRC study, performed at Lawrence Livermore National Laboratory, was begun in 1982, completed in 1985, and the results presented in a series of documents (Bernreuter and others, 1984, Bernreuter and others, 1985, Savy and others, 1986). The research program sponsored by EPRI/SOG was begun in 1983,

completed in 1986, and the results reported in a ten volume report to the Nuclear Regulatory Commission "Seismic Hazard Methodology for the Central and Eastern United States" (EPRI/SOG, 1986a-1986j).

After the methodologies were developed, annual ground-motion exceedance rates were calculated at nine sites using the EPRI/SOG and LLNL methodologies, and the results were compared (Bernreuter and others, 1987). For four of the nine sites, the median exceedance rates were practically equal. For the remaining sites, the median exceedance ranged from a factor of two to a factor of five higher in the LLNL study than in the EPRI/SOG study. The 85th percentile curve ranged from a factor of two to a factor of ten higher at most ground motions at most sites for the LLNL study than for the EPRI/SOG study. However, when hazard was calculated using identical inputs, the LLNL and EPRI/SOG computer programs gave the same results (Bernreuter and others, 1987, p.140).

The LLNL methodology was later updated (Bernreuter and others, 1989a-1989g), and both the EPRI/SOG and LLNL methodologies were applied to estimating hazard at 69 sites east of the Rocky Mountains.

The USGS staff reviewed the EPRI/SOG methodology rather extensively (Perkins and others, 1988). Below, we more briefly describe and compare both methodologies.

IV.A. Summary of Methodologies

Seismic hazard estimates obtained by EPRI/SOG are based on complicated interactions between the methodological "ground rules" and individual interpretations of the available data. The EPRI/SOG methodology required that each of the six teams of consultants taking part in the program (1) identify physical criteria or characteristics that

might be associated with the occurrence of earthquakes, (2) estimate probabilities that a hypothetical tectonic "feature" having various combinations of these characteristics is active or capable of producing earthquakes in the future, (3) identify tectonic features in the Eastern and Central United States, (4) estimate the probability that each of the identified features has each of the characteristics, (5) document the basis for the estimates of the probabilities in (4). (In the end the presence or absence of historic seismicity became the principal basis for estimating whether a feature could produce earthquakes.) In this methodology, hazard estimates are made using various combinations of "background" zones and seismic source zones based on individual features. The probability assigned to a combination of sources is determined by the (estimated) probability that each feature is active and by the probability that various features are dependent or independent.

After collecting and evaluating the available information, the EPRI/SOG teams agreed to use a common data base including an earthquake catalog in which earthquakes had a "uniform" magnitude and in which foreshocks, aftershocks, and earthquake swarms had been deleted. In identifying features, assessing probabilities, defining source zones, etc., consensus within a team was required, but individual teams were encouraged to act independently of one another. (However, the teams interacted at a number of meetings and this interaction might be expected to result in some convergence of viewpoints.)

The project organizers (rather than individual teams) provided and weighted the (three) attenuation functions to be used in the hazard analyses. The organizers (rather than the teams) also fit earthquake rates and b -values for small gridded areas ($1^\circ \times 1^\circ$ or $1/2^\circ \times 1/2^\circ$) based on earthquakes in the EPRI catalog, in accordance with specifications of individual teams regarding the amount of spatial smoothing of

the fitted values, the prior estimate of b , weights on magnitude intervals, etc. (A team might specify different amount of smoothing, different prior on b , etc. to obtain an alternative (a,b) pair for an area.)

To do a hazard analysis at a site, EPRI/SOG did the hazard calculations for each alternative source zone scenario and each alternative (a,b) and maximum magnitude for each team, using each attenuation function. A distribution of hazard estimates for a site for each team was obtained by weighting each estimate in accordance with the probability assigned by a team to the corresponding scenario and the weight assigned by EPRI/SOG to the attenuation function that was used. The overall distribution of estimates was based on an iterative procedure that weighted a team's results according to the consistency of that team's estimates with the average of the other teams' estimates.

On the other hand, the LLNL formalism was based on developing a set of questions and then using detailed questionnaires to elicit opinions of 11 individual seismicity experts regarding seismicity and source zonation and of 5 ground motion experts regarding ground motion models (attenuation relationships). The experts used their own data bases, although a standard LLNL earthquake catalog was eventually made available. Each seismicity expert provided boundaries of source zones on a "base map" and possibly some alternate zonations. Each seismicity expert also provided for each source a "best estimate" a -value, b -value, and maximum magnitude, plus upper and lower limits for each quantity, assuming a triangular distribution. Each ground motion expert selected and assigned weights to a set of attenuation relationships.

Some feedback meetings were held during which results of hazard analyses using inputs of various experts were presented and compared. After the meetings, experts were

permitted to adjust their inputs. However, experts were encouraged to retain their own viewpoints, and consensus among experts was not sought.

A Monte Carlo procedure was used to perform the final hazard analysis at each site (i.e., typically obtaining 2750 hazard estimates resulting from 50 hazard analysis for each of 11 seismicity experts paired with each of 5 ground motion experts). Each hazard analysis was based on a source zone scenario and seismicity parameters selected at random from the distribution specified by a seismicity expert and a ground motion model selected at random from the models specified by a ground motion expert. A self-weighting scheme was used to assign weights to the results of the various experts.

In this section, we describe and compare the LLNL and EPRI/SOG methodologies and note some of the differences in the methodologies that might lead to differences in inputs and hence to differences in results.

IV.B. Structure: Teams (EPRI/SOG) vs Individual Experts (LLNL)

Implementation of the EPRI/SOG methodology was achieved by assembling six teams of scientists, including in each team academic and consultant specialists such that different members of each team represented different disciplines and brought expertise in a variety of areas. Each team was asked to develop tectonic interpretations, source specifications, and seismicity parameter inputs for the hazard analysis. (The teams were referred to as Tectonic Evaluation Committees, or TEC's, and bore contractor titles -- Bechtel, Dames and Moore, Law Engineering, Rondout, Weston Geophysical and Woodward-Clyde.) Consensus within teams was required. The EPRI/SOG program managers (rather than the

teams) selected three attenuation functions (equations relating ground motion at a site to earthquake magnitude and distance from the site to the earthquake) to be weighted and used in the analysis.

By contrast, the LLNL study elected to seek the opinions of a number of individuals regarded as experts in the seismicity and tectonics of the Eastern and Central United States, and of other individuals regarded as expert in ground motion modeling. (See Appendix for a listing of these experts.) Panels were formed such that experts in zonation and seismicity constituted one panel; experts in ground motion modeling the other panel. Each ground motion expert selected (and assigned weights to) a set of up to six of attenuation functions.

IV.B.1. Comments

(1) EPRI/SOG's use of a smaller number of attenuation relationships might be expected to decrease the variability in the hazard estimates obtained by EPRI/SOG compared with those obtained by LLNL.

(2) Requiring consensus within teams might tend to decrease variability between teams as compared to between individual experts.

IV.C. Formalism: Defining Seismic Source Zones

IV.C.1. Source Zones—EPRI/SOG

The EPRI/SOG program participants began by making a major effort to obtain, assimilate and evaluate all available scientific information, hypotheses and conjectures regarding the tectonic processes and stresses operative in the eastern and central United States. This effort included compilation of geo-science data sets and an in-depth assessment of the historic record, resulting in a common geoscience data

base (including an earthquake catalog; gravity and magnetic anomaly maps, geophysical maps, topographic maps, and maps depicting locations of various stress orientation data) that was provided to all of the teams.

As part of the project, the teams attempted to identify all tectonic features in the eastern and central United States, a tectonic feature being defined as "a large scale geologic structure or element of the earth's crust, perhaps manifested only as a geophysical anomaly. A tectonic feature has a distinct geographical location, but may also be a member of a class of features that have similar characteristics or genetic history. Examples of tectonic features are the midcontinent geophysical anomaly and the Brevard fault zone." (EPRI/SOG, 1986a, p. 3-1.) (The words "large scale" in the definition of a feature might imply the existence of a relatively small number of tectonic features, but in fact, the teams identified numerous features, e.g., the Woodward Clyde team identified and assessed 96 features, which are listed in EPRI/SOG, 1986h, p. A167-A169).

After each of the six teams was given the data base, a series of meetings was held at which the members of the various teams discussed, investigated and attempted to evaluate the relevance to earthquakes of such physical characteristics as spatial association of a *hypothetical* feature with seismicity, observation of recent strain and paleoseismicity, scale or vertical extent of a feature within the crust, fault orientation and allowable slip within a stress field, geologic evidence of brittle slip, and spatial or temporal changes in strength. Having evaluated the available information, each team selected a few (usually three) characteristics that it regarded as most highly correlated with the ability of a tectonic feature to generate earthquakes. The team then estimated the probability that a *hypothetical* feature having any given combination (present or absent) of the selected

characteristics is "active". (Throughout most of the program, a feature was defined as active if it were considered to be capable of generating moderate-to-large earthquakes, i.e., $m_b \geq 5.0$ in the current stress regime; the corresponding probability of activity was designated p^* . During the latter part of the program, the definition of activity was changed to mean the ability of a feature to generate earthquakes of any magnitude; the corresponding probability of activity was then designated p^A .) The estimated probability of activity for a feature having each possible combination of characteristics was entered into a "feature characteristic matrix" as illustrated in figure IV-1.

All teams concluded that the presence or absence of "spatial association with seismicity" by a feature is the most important characteristic to use in estimating the probability that a feature is active. (Each team initially included the question "has the feature been spatially associated with moderate-to-large earthquakes," "associated with small earthquakes only," or "not spatially associated with seismicity." However, because of the change in the definition of activity late in the program, some teams modified the matrices to include only "spatial association with seismicity" and "no spatial association with seismicity.") Having reached a consensus that earthquake sources are features responding to region-wide compression, all teams chose geometry relative to the stress field (orientation and/or sense of slip) being "favorable" or "unfavorable" as a second characteristic. Five of the six teams chose deep crustal expression being present near intersections of geologic structures (or present with a barrier), present but not near intersections (or present without a barrier), or not present, as the third characteristic. The team that did not ask the question concerning deep crustal expression included instead a question regarding most

recent age of brittle slip on a feature (EPRI/SOG, 1986i, p. 5-3).

Given the feature characteristic matrix that they had constructed, members of a team then examined each tectonic feature previously identified, and attempted to estimate the probability that each of the characteristics in the feature characteristic matrix was "present" or "absent" at the feature. This was done by filling out a "feature assessment form" for each feature (figure IV-2). The probability that a specific feature was active then was taken to be the probability given in an entry in the feature characteristic matrix multiplied by the probability in the corresponding entry in the feature assessment form, summed over all entries. (A team could override this computation and assign its own probability of activity to a feature if it were dissatisfied with the result—however, usually teams accepted the calculated probabilities.)

After probabilities of activity had been assigned to the various features, source zone scenarios were constructed containing various combinations of active features and background or default zones. The total weight or probability of all scenarios containing a feature was equal to the total probability that the feature was active (e.g., if a feature had a forty per cent probability of being active, it appeared or was active in forty per cent of the weighted scenarios). Usually the probabilities of various scenarios were obtained by assuming the features were independent and multiplying the probabilities of activity. For example, assuming two independent features A and B, with respective probabilities of activity, $P(A) = 0.3$, $P(B) = 0.4$, four source zone scenarios are possible with probabilities

$$P(AB) = 0.12 \text{ (both A and B active);}$$

$$P(A\bar{B}) = 0.18 \text{ (A active, B not);}$$

$$P(\overline{A}B) = 0.28 \text{ (} B \text{ active, } A \text{ not);}$$

$$P(\overline{A}\overline{B}) = 0.42 \text{ (neither } A \text{ nor } B \text{ active).}$$

Features could also be regarded as dependent or mutually exclusive—e.g., alternative hypothesis could lead to one feature or the other being active, but not both active simultaneously. In the preceding example, if A and B were mutually exclusive, only three source zone scenarios would be possible; the assigned probabilities would be

$$P(A) = 0.3 \text{ (} A \text{ active);}$$

$$P(B) = 0.4 \text{ (} B \text{ active);}$$

$$P(\overline{A}\overline{B}) = 0.3 \text{ (neither } A \text{ nor } B \text{ active).}$$

Each feature is assigned one or more alternative rates, b -values and maximum magnitudes in those scenarios in which it is active. If a feature is not active in a given scenario, the seismicity that is associated with the feature when it is active is instead distributed to a background or default source. (Thus, if no feature is active, all earthquakes are assigned to a background or default source.)

IV.C.2. Source Zones—LLNL

Rather than employing a number of teams, holding numerous group meetings and using a common data base as in the EPRI/SOG approach, the LLNL study constructed panels consisting of individual experts, held few meetings, and allowed each expert to select his/her own source of data (e.g., choose the earthquake catalog(s) to use). Basic information was elicited from each LLNL panel member by means of detailed questionnaires. The seismicity-tectonic panelists answered questions regarding the specification of source zones and seismicity parameters; the ground-motion panelists answered questions regarding

the specification of ground motion as a function of magnitude (or intensity) and distance from an earthquake. Inconsistencies in an expert's answers were resolved through personal communications with the coordinators. Follow-up discussions in which the experts interacted and feedback meetings were held for each panel, during which the results of a hazard analysis using each expert's inputs were shown, compared and discussed. The responses of each panel member, possibly revised after the feedback meetings, were then used in a separate hazard analysis and the results were then combined with those of other experts. An additional feedback loop was then performed to allow the experts to revise and finalize their input data.

In the LLNL study, a source zone was defined as a region which has homogeneous seismic characteristics in terms of rate of activity, magnitude distribution and upper magnitude cutoff. Each seismicity-zonation expert in the LLNL study was asked to provide maps of the source zones that he/she identified, including a map with the "best estimate" of the boundaries of the zones, and maps containing alternative boundaries of individual zones and clusters of zones. Each expert was also asked to specify his/her level of confidence regarding the existence or non-existence of individual zones or clusters of zones, and to record the region that would contain a zone (or cluster) in the event that the given zone (or cluster) did not exist. Answers were to be based on an analysis of earthquake catalogs (recognizing incompleteness of the catalogs, etc.), general experience in the region, geologic and tectonic considerations, similarities of the Eastern U.S. with other regions, and all other available data.

IV.C.3. Comments

IV.C.3.a. Tendency to consensus

EPRI/SOG ground rules required consensus within teams (e.g., a team must construct a single characteristic matrix, etc.), but the teams were encouraged to be independent of each other. However, the availability of a common data base, discussions and interactions at group meetings may have contributed to some consensus between teams (e.g., the choice by all teams of approximately the same two or three questions to use in their feature characteristic matrices). Thus, interactions between teams and the EPRI/SOG matrix formalism might, in fact, be expected to decrease the extent to which the hazard estimates of different teams are independent, and also to decrease the variability in these estimates from team-to-team compared with variability from expert-to-expert in the LLNL study.

IV.C.3.b. EPRI/SOG: Documentation

The EPRI/SOG study emphasized documentation and trackability, (e.g., each team was required to summarize the relevant geologic, tectonic, and seismic information that team used to evaluate the probability it assigned in the feature assessment form that each real feature it considered had or did not have each characteristic listed in the feature characteristic matrix.)

IV.C.3.c. LLNL: Documentation not required

The LLNL experts in providing maps of source areas were not required to justify their decisions nor to adhere to a particular formalism. "This study was designed as an expert opinion sampler. It is conceptually different from other current studies, such as the one sponsored by the Electric Power Research

Institute, whose goals are to reach a consensus of opinion at some levels in the analysis." (Bernreuter and others, 1985a, p. 2-3)

IV.C.3.d. EPRI/SOG Team struggle with characteristic matrix

The characteristic matrix *formalism* of the EPRI/SOG study required that the teams identify characteristics related to feature activity and then make estimates of the probability that a *hypothetical* feature with each combination of characteristics is active. The development of observable tectonic criteria useful for identifying seismogenic tectonic features proved difficult. Comments made by individual teams reflect frustration in identifying such features. A few of these comments follow.

Rondout:

"Try as I will, to find what relates potential field data, crustal thickness, geology, refraction and reflection discontinuities to the seismicity, I am almost invariably stumped...Not only is the time scale too short, but also the spatial scale is also probably too large..." (EPRI/SOG, Vol.10, 1986, p. A-206).

Woodward Clyde:

"...about 50 percent of the features evaluated are believed to have no more than a probability of 0.25 of being active. This represents fairly the consensus of the team that the true tectonic explanations for observed seismicity have yet to be formulated." (EPRI/SOG, Vol. 8, 1986, p.4-15.)

Bechtel:

"...[W]e found it very difficult to generalize activity to "similar" historically inactive features (those not associated historically with moderate-to-large earthquakes), and viewed background zones not as a circumvention of the proper association of

future earthquakes with historically aseismic structures but rather as the logical repository of our uncertainty about the proper association of past earthquakes with recognized tectonic features." (EPRI/SOG, Vol. 9, 1986, p. 5-3)

IV.C.3.e. Role of seismicity in characteristic matrix

For all teams, the seismicity characteristic in the feature characteristic matrix dominated the tectonic characteristics. For example, each team assigned a higher probability of activity to a feature that has had spatial association with seismicity but has unfavorable geometry, than to a feature that has had no spatial association with seismicity but does have favorable geometry. One consequence is that a feature that has no spatial association with seismicity is assigned a low probability of being active, regardless of the presence or absence of other "characteristics." The selection of "spatial association with seismicity" as the principal criterion means that historic earthquakes rather than physical criteria become the primary basis for estimating the probability of feature activity. This suggests that a tectonic basis for "generalizing" seismicity from features that have had earthquakes to "tectonically similar" features that have not had earthquakes was, in fact, not established, and features that have not been spatially associated with earthquakes in the past are assigned a very low probability of having earthquakes in the future.

IV.C.3.f. Meaningfulness of characteristics

If the selected characteristics are not highly related to earthquake occurrences, probabilities of feature activity based on the presence or absence of these characteristics at a feature are not very meaningful. However, these estimated probabilities became the basis for constructing (and assigning probabilities to) scenarios in which various combinations of features are

active. Thus, the EPRI/SOG formalism contains well-defined (if not verifiably correct) procedures creating and assigning probabilities to a range of scenarios.

IV.C.3.g. Benefit of EPRI/SOG formalism

In the EPRI/SOG methodology, earthquakes that have been recorded in the vicinity of a feature are generally used to estimate future earthquake rates and *b*-values for the feature, i.e., a source zone is defined by the geographic location and extent of a feature, and the rate of earthquakes in this zone in the scenarios in which the zone (feature) is active is determined from the historic earthquakes that occurred within the boundaries of the zone. Thus, the EPRI/SOG formalism provides a rationale for defining source zones and determining rates, etc., in the vicinity of identified features.

IV.C.3.h. Leverage of historical seismicity

If few or no earthquakes have been recorded in the vicinity, a feature will define a source zone that has a low probability of being active and a low rate of seismicity when it is active. On the other hand, if historic earthquakes have occurred in the vicinity of a feature, the estimated rate of earthquakes for the feature-source when it is active will be higher, but the probability that the feature-source is active may, nevertheless, be low. (Recall the probability that a feature is active is based on the probability that a hypothetical feature with given combinations of characteristics is active multiplied by the probability that the specific feature has each combination of characteristics.) A low probability of activity is illustrated in the feature characteristic matrix in Figure IV-1 (A), where if "moderate to large earthquakes" have been "spatially associated with the feature" but other conditions are "unfavorable", the probability that the feature is active is 0.20, and if only small earthquakes

have been observed, the probability is 0.05. Furthermore, even if earthquakes have been observed in the vicinity of the feature, a probability p_s must be assigned that the earthquakes are "spatially associated" with the feature, and frequently the "informational uncertainty" results in a probability p_s much less than 1.0 (e.g., both the locations of the earthquakes and spatial extent of the feature may be inexactly known, or the feature may have a north-south orientation and the earthquakes an east-west trend, making it difficult to assess spatial association.)

IV.C.3.I. Interaction of number of features with historical seismicity

Each EPRI/SOG team defined a large number ($\approx 65-85$) of feature-based source zones, many of which represented features with low probabilities of activity; these low-probability source zones were active in various combinations in many alternative "source zone scenarios," each of which had a low probability assigned of being the correct scenario. Earthquakes that are associated with features when they are active are redistributed into the background in scenarios in which the features are not active. These earthquakes may be "spread" over a large area or a small area, depending, for example, on whether "high," "medium" or "low" smoothing of a -values is requested (see following section on seismicity parameters). Restated, earthquake rates and b -values are recalculated for each scenario for those cells ($1^\circ \times 1^\circ$ or $1/2^\circ \times 1/2^\circ$) that are in background sources for that scenario, and the a and b values for any cell may (or may not) be significantly different for different scenarios. This suggests that the large number of alternative scenarios for an EPRI/SOG teams could possibly lead to a wide range of hazard estimates at a site for that team.

IV.C.3.J. Interaction with smoothing

If a feature-source has a relatively high rate of earthquakes, higher probabilistic ground motions will be calculated for sites near the feature when the feature is active than when the feature is not active, if the seismicity that was associated with the feature is diffused into a large background zone ("moderate" or "high" smoothing on a) in the latter case. However, if no or "low" smoothing of a -values is requested (rate estimates for a cell are based primarily on earthquakes in the cell or the cell and a few nearby cells) one might expect approximately the same a -values for cells containing the feature regardless of whether or not the feature is active, and similar hazard estimates in both cases.

If one averages over various scenarios, any "spreading out" of seismicity in some scenarios in EPRI/SOG methodology may tend to cause lower probabilistic ground motions to be calculated for sites in seismically active areas than one might expect based on the historic record.

On the other hand, if a feature has a sufficiently low rate of seismicity when it is active, a site in the source zone defined by the feature may have a lower calculated hazard in scenarios in which the feature is active than in scenarios in which the feature is not active. This is obvious if we recall that a background source is exclusive of other sources, i.e., the background may surround (but not overlap) feature sources, and hence the background may contain "holes" where there are active features. If high (or possibly moderate) smoothing of a -values over the cells in the background is requested, the smoothed earthquake rates in the cells in the "hole" in the background may be higher than the rates obtained for these cells alone. Thus, if the rate for the feature is based on historic earthquakes, the hazard may be higher when the feature is not active and (highly) smoothed background rates are used in

the cells that "fill in" the hole. The assignment of seismicity to features based on historic earthquakes seems to negate any attempt to extrapolate hazard from historically active features to "similar" features that have been historically inactive.

IV.C.3.k. Relative stability of LLNL process

Perhaps because the LLNL experts did not attempt to place seismicity on individual features, the LLNL experts tended to have fewer zones and fewer alternative scenarios, i.e., zones drawn on the base map of an LLNL expert generally had high probabilities, and any alternative zonations had relatively low probabilities. This means that a - and b -values for an area for an LLNL expert might remain more stable than the values for an EPRI/SOG team during a hazard analysis. This suggests there may be less variability resulting from alternative source zone scenarios in hazard estimates for an LLNL expert than in estimates for an EPRI/SOG team.

IV.D. Formalism: Seismicity Parameters

Both the EPRI/SOG and LLNL studies make the assumption usually made in hazard analysis that earthquake occurrences are Poissonian, i.e., earthquakes are regarded as independent events that occur randomly in space and time.

IV.D.1. Seismicity Parameters—EPRI/SOG

The EPRI/SOG model assumes that earthquakes within some magnitude range $m_{\min} \leq m \leq m_{\max}$ occur in accordance with a truncated Gutenberg-Richter magnitude-frequency relationship. A single catalog (called the EPRI catalog) is used as the basis for estimating rates and b -values for an area.

In developing the EPRI catalog a "uniform magnitude" m_b^* value was determined for every earthquake in order that "equivalent rates for magnitudes converted from various magnitude scales and intensities" could be obtained. The m_b^* value for an earthquake was derived by "converting" sizes provided by various size measures to an m_b value (using assumed linear relationships between m_b and intensity and/or m_b and other magnitude scales) and then adjusting the converted m_b value for uncertainties in the original size measures. Earthquakes that were determined (by a computer algorithm) to be aftershocks were flagged.

The EPRI/SOG formalism allows earthquake rates, b -values, and maximum magnitudes to be specified for each cell in a latitude-longitude grid, that is, cell-by-cell (e.g., $1^\circ \times 1^\circ$ or $1/2^\circ \times 1/2^\circ$) spatial variation of seismicity within a source zone is allowed. A penalized maximum likelihood technique is used to simultaneously estimate a - and b -values for earthquakes in each cell included within a source zone. The algorithm permits spatial smoothing of the a - and b -values estimated for each cell and permits estimation and smoothing of the probabilities of having detected random earthquakes of given magnitudes at given times in given areas. For each source, a team could specify several (usually teams selected one or two) alternatives for the degree of smoothing (high, medium or low) for the a - and b -values, and they could provide a prior estimate of b together with the "strength" of that prior. For example, a team might select "high smoothing of a , medium smoothing of b , weak prior of $b=1.0$ " as one alternative, and "weak smoothing of a , strong smoothing of b , no prior of b " as a second alternative. (Thus EPRI/SOG computer programs, rather than the teams, provided the final numerical values of a and b .) The smoothing options ranged from attempting to reproduce historic cell-by-cell seismicity exactly to, in effect, "spreading" the observed

historical seismicity uniformly over a large area.

IV.D.2. Seismicity Parameters-LLNL

The LLNL methodology optionally allowed earthquake occurrences to be modeled with a negative exponential magnitude-frequency relationship within the entire magnitude range $m_{\min} \leq m \leq m_{\max}$, or to be modeled with a negative exponential magnitude-frequency relationship within some smaller range $m_1 \leq m \leq m_u$, and with a different relationship in the range $m_{\min} \leq m \leq m_1$ and $m_u \leq m \leq m_{\max}$. The latter model had the effect that the number of earthquakes in the interval $m_u \leq m \leq m_{\max}$ might be larger than the number in the interval $m_u - \Delta m \leq m \leq m_u + \Delta m$, which cannot happen if the negative exponential model is assumed throughout. The LLNL model is discussed in more detail in Appendix B.

In the LLNL study, the experts themselves were asked to estimate a - and b -values for their source zones using whatever catalogs and whatever techniques they deemed appropriate. They were also asked to decide on the type of correction to apply for catalog incompleteness and aftershocks. For comparison with an expert's estimate of a and b for an area (and for comparison with EPRI/SOG results) LLNL provided estimates of a and b -values derived using a "uniform method" which took into account incompleteness in the data. The uniform estimates were based either on an LLNL catalog or EPRI catalog, as specified by the individual expert, and on values of the completeness time parameters that were supplied by the expert. (The experts were provided the uniform estimates for informational purposes, and were not encouraged to use these estimates in place of their own values.)

In addition to providing a best estimate of a and b for a source, each expert specified upper and lower bounds (a_l, a_u) on a and (b_l, b_u) on b

such that these bounds represented a 95 per cent confidence interval for each quantity, assuming a and b have triangular distributions within the specified bounds.

IV.D.3. Comments

IV.D.3.a. EPRI/SOG methodology for uniform magnitude

The EPRI/SOG algorithm for obtaining the uniform magnitude m_b^* values in the EPRI catalog was based on the assumption that errors in the magnitudes (e.g., m_b , M_L , etc.) and intensity I_o reported for an earthquake are normally distributed, and that earthquake magnitudes have a negative exponential distribution. The m_b^* values that resulted do not have a simple relationship with m_b values that might be presented for various earthquakes, e.g., if an m_b value (and no other measure of size) was provided for an earthquake, the m_b^* value is less than the m_b value; but if an I_o value was also given, the m_b^* may be greater than (or smaller than) the corresponding m_b value (see Table 3.4.2 in Bernreuter and others, 1987). This could affect the $\hat{b}$ -values that are fitted using m_b^* values as contrasted with $\hat{b}$ -values fitted using m_b values, for example, and could lead to differences between $\hat{b}$ -values obtained by LLNL experts and EPRI/SOG. In addition, the number of earthquakes with $m_b^* > m_o$ is not likely to equal the number of earthquakes with $m_b > m_o$ (for some minimum magnitude m_o) when magnitudes for the same set of earthquakes are converted to m_b using some other fitting technique.

Other results that seem surprising include: (a) An example by Veneziano and Van Dyck (1985, p. A-71) in which both an I_o value and M_{L1} value were provided for an earthquake. Using both the I_o and M_{L1} values gave an m_b^* value that was larger than the m_b^* that would have been obtained if only I_o or M_{L1} had been

used; (b) Table 3.4.2, Bernreuter and others, (1987), which shows 150 of the largest earthquakes in the EPRI catalog, gives the value $m_b^* = 5.39$ for 15 earthquakes with $I_o = VII$ and having m_b values $m_b = 4.0, 4.8, \text{ or } 5.1$ (or with m_b not shown); on the other hand, $m_b^* = 4.98$ for three earthquakes with $I_o = VII$ and $m_b = 5.1$.

IV.D.3.b. Contrast in rates between EPRI/SOG and LLNL

It is difficult to predict how estimates of earthquake rates and b -values derived using the m_b^* magnitudes in the EPRI catalog for main shocks will compare with estimates of rates and b -values that are derived using earthquake sizes as recorded in some other catalog, and in which different earthquakes (or no earthquakes) may have been identified as aftershocks and clusters. *LLNL analysts concluded that "if the (LLNL) experts only relied on the EPRI catalog, their a -values would be the same or smaller;" and "differences between the LLNL and EPRI catalog lead to about 30 per cent differences between hazard curves based on either the LLNL or EPRI catalogs with the LLNL catalog leading to the higher hazard curves."* (Bernreuter and others, 1987, p. 69)

IV.D.3.c. Role of I_o coefficient in magnitude conversion

In converting between I_o and m_b or m_b^* , EPRI/SOG assumed an increase of ≈ 0.6 magnitude units (m_b or m_b^*) corresponds to an increase of one unit in I_o (e.g., Veneziano and Van Dyck, 1985, p. A-65); LLNL assumed an increase of 0.5 units in m_b corresponds to an increase of one unit in I_o (Bernreuter and others, 1987, p. 84). Differences in assumptions such as these are likely to affect the b -values that are fitted to earthquakes in the LLNL and EPRI catalogs, even if the same fitting technique is used in both cases.

IV.D.3.d. Expected hazard contrasts

In hazard calculations performed by LLNL at four sites using the experts' "best estimate" a - and b -values and then repeated using a - and b -values fitted by LLNL, the hazard curves calculated using the best estimate a - and b -values were approximately a factor of two higher than the curves calculated using the LLNL fitted values. (Bernreuter and others, 1987, p.120-123.)] Furthermore, hazard curves obtained by LLNL using a - and b -values fitted to the LLNL catalog were approximately 30 per cent higher than hazard curves obtained using a - and b -values fitted to the EPRI catalog. These results imply that if EPRI/SOG used the same zonations as LLNL and used the LLNL method for fitting a - and b -values, for a given attenuation function, hazard curves calculated for the EPRI/SOG teams would be expected to be at least a factor of two lower than the comparable LLNL curves.

IV.D.3.e. EPRI/SOG use of cell seismicity

EPRI/SOG fits a - and b -values for small areas (e.g. $1^\circ \times 1^\circ$ cells) and allows smoothing of results, which even in the case of "high smoothing of a and b " may not converge to the estimates $\hat{a}$ and $\hat{b}$ that would be obtained if the earthquakes in the small areas were combined and the a - and b -values were fitted for the larger area. (We regard this as a flaw in the algorithm.)

Estimates $\hat{a}$ and $\hat{b}$ must often be made for cells which contain zero (or one) earthquakes; in this case (and even in those cases in which a cell contains several earthquakes), there is simply too little data to make meaningful estimates for individual cells using the historic earthquakes in the cell. Nevertheless, EPRI/SOG begins by estimating a - and b -values for each individual cell in a set of cells and then "smooths" the estimated values for each cell (in an iterative

procedure). The final estimates depend heavily on the prior on b , the type of smoothing (high, moderate or low) on the $\hat{a}$ and $\hat{b}$ values estimated for each cell and on assumptions that are made regarding completeness, etc. We found that the consequences of selecting various combinations of strengths of smoothing for $\hat{a}$ and $\hat{b}$ estimates and choosing various strengths of the prior estimate of b were not always predictable, e.g., in an example provided by EPRI/SOG, the estimated $\hat{b}$ for a cell obtained using "moderate" spatial smoothing of the $\hat{a}$ and $\hat{b}$ values did not lie between those obtained using "low" smoothing and those obtained using "high" smoothing.

A second demonstrable problem with the EPRI/SOG algorithm is that if $\hat{a}$ values are spatially smoothed, the $\hat{b}$ values for individual cells are altered. We regarded this behavior as incorrect, as illustrated by the following hypothetical example, in which we pretend that 9, 3, and 1 earthquakes in successive magnitude intervals (e.g., $3.3 \leq m < 3.0$, $3.9 \leq m < 4.5$ and $4.5 \leq m \leq 5.1$) have been observed in one cell, and 18, 6, and 2 earthquakes have been observed in the same intervals in a second cell. We would obtain the same $\hat{b}$ for both cells, if we estimate b separately for the two cells. We would also obtain the same $\hat{b}$ if we estimated b for the combined set of earthquakes (27, 9 and 3 earthquakes in the three magnitude intervals). However, using the EPRI/SOG algorithm, the estimates $\hat{b}$ would be altered when estimates of a -values were smoothed.

In practice, selecting strong priors on b and/or high smoothing on $\hat{b}$ -values seems to produce reasonable results, and most of the EPRI/SOG teams generally selected from among these options. However, as noted, the methodology also permits choices which yield results that are

counterintuitive, and a naive user might select such alternatives.

IV.D.3.f. LLNL complementary zone vs. EPRI/SOG background zone

LLNL notes a difference between their "complementary" zone and EPRI/SOG's "background zone" and notes that at some sites it is very important how this "default" zone is modeled (Bernreuter and others, 1987, p.190). LLNL states that it *requires* that there may be no areas of zero seismicity and some earthquakes must be assigned to all areas that are not specifically included in listed source zones. These areas are then defined to be the complementary zone. In the EPRI/SOG study, all the seismicity for an area may be assigned to specific features, with no seismicity assigned to an areal background zone [e.g., LLNL in analyzing results for the Limerick site, observed that the team with the lowest median ground-motion estimate had no background zone containing Limerick. (Bernreuter and others, 1987, p. 36)]. In addition, in the LLNL approach, the complementary zone may have a high maximum magnitude, whereas in the EPRI/SOG study, lower maximum magnitudes are generally assigned to background zones.

IV.D.3.g. Ranges of hazard estimates

In hazard calculations at nine sites (done using the Nuttli, 1984, attenuation function, a minimum magnitude $m_o = 5.0$ and no site correction), (see Bernreuter and others, 1987a, p.12-20), the 85th percentile curve obtained by LLNL using the source and seismicity inputs provided by the LLNL experts was significantly higher for all sites than the 85th percentile curve obtained by EPRI/SOG using source and seismicity inputs provided by the EPRI/SOG teams. However, at four sites the median hazard estimates for the two groups were similar, suggesting that differences in the range of estimates at these sites resulted from either a wider range of scenarios or a wider

range of values of the seismicity parameters in the LLNL analysis.

IV.D.3.g.1. Differences in experts' best estimates

Different LLNL experts may propose significantly different source zone scenarios and widely varying rates and b -values. We observed that at a site (Limerick) at which LLNL provided a "best estimate" hazard curve for each of the eleven seismicity experts, the three highest curves were very close together and about a factor of six to eight higher than the median "best estimate" hazard curve (Bernreuter and others, 1987, p.40). The median best estimate hazard curve and the three highest best estimate curves are almost identical to the the median and the 85th percentile curves shown for the same site when the calculations were (apparently) done for alternative source zone scenarios and a distribution of values of the seismicity parameters (Bernreuter and others, 1987, p. 13). Thus, it appears at this site at least that differences between various experts' best estimate scenarios, rather than the range of scenarios for each expert, can account for the variability in the results. (Limerick is the only site for which best estimate hazard curves are shown for individual experts and the 15th, 50th and 85th cumulative percentile curves combined over all scenarios for all experts are presented for the same set of conditions, i.e., for a specific single attenuation function, a minimum magnitude $m_o = 5.0$, and no site correction applied.)

IV.D.3.g.2. Hazard ranges due to differing methods of modeling uncertainty

Greater variability between the median and 85th percentile estimates in an LLNL hazard analysis compared to an EPRI/SOG analysis could result from the different treatments of variability in the seismicity parameters in the two methodologies, as discussed below. An

LLNL expert provides a best estimate and upper and lower bounds on a , b and m_{max} for a source, assuming a triangular distribution for each of these parameters within the specified bounds. The assumption of a triangular distribution on a (the logarithm of the rate of earthquakes in a source with magnitude $m > 0$) could result in a wide range of possible rates. For example, $1 \leq a \leq 3$ implies rates r in the range $10 \leq r \leq 1000$, and a "best estimate" value $a = 2$ corresponds to $r = 100$. This means that in 50 percent of the scenarios for this source $10 \leq r \leq 100$ and in the remaining 50 percent, $100 < r \leq 1000$. In this case, the 85th percentile curve for the rate will correspond to $r \approx 300$, or a factor ≈ 3 higher than the median. In many cases, variability of b is regarded as independent of variability of a , and variability of b coupled with variability of a could result in a wide range of hazard estimates for a single source zone scenario (see Appendix B).

On the other hand, an EPRI/SOG team typically uses two alternative values of a and b for each ($1^\circ \times 1^\circ$) or ($1/2^\circ \times 1/2^\circ$) square. A hazard estimate is obtained corresponding to each (a,b) pair; if two pairs of (a,b) -values (with weights) are used, the distribution of hazard estimates for one source zone scenario consists of two points, which might (or might not) be close together.

IV.D.3.g.3. Methodological differences in estimation of seismicity parameters

Individual EPRI/SOG teams did not estimate a - and b -values, but rather specified the type of smoothing, prior on b and strength of that prior, magnitude weighting, etc. The program managers used a single catalog and computer program to estimate a - and b -values for each source for each team, subject to the team's specifications. One might expect less variability from team-to-team in this case than if the teams calculated their own values using various different techniques or if they were totally

unrestricted in selecting their values, as were the LLNL experts.

IV.D.3.h. Range of hazard in background and complementary zones

Calculated hazard levels are often dominated by ground motions from earthquakes in the vicinity of a site. An EPRI/SOG team's earthquake rates in adjacent cells may be quite different (because a - and b -values are estimated on a cell-by-cell basis), and two sites in the same background zone several cells apart might have a significantly different calculated hazard. On the other hand, for an LLNL expert, the seismicity that is assigned to a background (or complementary) zone is uniform throughout the zone, with the effect that if two sites are nearby in the same complementary zone, the calculated hazard is likely to be similar at the two sites.

IV.D.3.i. Maximum magnitude in background and complementary zone

The LLNL experts tended to assign higher maximum magnitudes to their complementary zones than the EPRI/SOG teams assigned to their background zones, thus tending to increase the hazard calculated at a site in the background (complementary) zone by LLNL compared with that calculated by EPRI/SOG. The use of the "LLNL model" for assigning earthquake rates to magnitude intervals also might cause more earthquakes to be assigned to a higher magnitude interval than are assigned by EPRI/SOG using the negative exponential model, further increasing the relative hazard calculated by LLNL compared with that calculated by EPRI/SOG.

IV.D.3.j. Role of minimum magnitude

Initially LLNL used a minimum magnitude $m_o = 3.75$ whereas EPRI/SOG used $m_o = 5.0$. The choice of a lower value of m_o would tend to suggest that more exceedances of some ground motion levels would be calculated by LLNL than by EPRI/SOG. However, in later

work, LLNL presented results using $m_o = 5.0$. The effects of changing minimum magnitude m_o from $m_o = 3.75$ to $m_o = 5.0$ are easy to isolate, and we do not regard the choice of minimum magnitude as intrinsic to the methodology.

IV.D.3.k. Role of different catalogs, conversions, etc.

Considerable variability in LLNL hazard estimates may have come about because individual experts in estimating a - and b -values used different conversions between magnitude scales, different catalogs, made different assumptions regarding catalog completeness, etc., used different techniques (e.g., least squares, maximum likelihood) for fitting magnitude data, or derived estimates in some manner not based solely on historic earthquakes.

To investigate variability in estimates of a - and b -values, LLNL calculated hazard curves for Limerick and for Braidwood for each of the 11 LLNL experts using a single attenuation function and the experts' "best estimate" source zone scenario and "best estimate" values of a and b for each active source. LLNL then repeated the calculations for each expert using a - and b -values for each source that were fitted by the LLNL "uniform" method to earthquakes in the LLNL catalog. At Braidwood ground motion (PHA) exceedance probabilities calculated using the experts best estimate a - and b -values varied by about a factor of 400 at 400 cm/sec². For the "uniform" values, at Braidwood exceedance probabilities for the highest expert were about a factor 3.5 lower, and the probabilities for the lowest expert were about a factor of 3.5 higher than values calculated using the experts' own rates, decreasing the overall variability from the lowest curve to the highest curve to about a factor of 30. At Limerick, ground motion exceedance probabilities calculated using the experts' a - and b - values varied by a factor of

50–100 (depending on ground motion level) from the highest to the lowest expert. Using LLNL uniform values, the overall variability decreased to a factor of 10–30, but at Limerick the expert who had the lowest curve when his rates and b -values were used had the fourth lowest curve when the uniform rates and b -values were used.

IV.E. Attenuation Relationships

A major uncertainty in hazard analysis is the ground shaking expected from earthquakes at various distances from a site. A variety of attenuation relationships has been proposed to represent ground shaking as a function of earthquake magnitude (and/or intensity) and distance. These relationships may predict considerably different ground motions, and using different relationships may result in significantly different hazard estimates.

IV.E.1. EPRI/SOG method

In the EPRI/SOG study, individual teams did not select the attenuation relationships to use; three relationships were selected and assigned weights by the organizers of the study.

IV.E.2. LLNL method

On the other hand, the LLNL ground motions experts were presented with a large number of possible relationships, e.g., 59 for peak ground acceleration. (However, in practice, many of these were never selected.) The relationships for peak acceleration, for example, were divided into seven categories ("intensity models" with (1) no weighting, with (2) distance weighting, with (3) magnitude weighting, with (4) magnitude and distance weighting, and (5) semi empirical models; "direct models" of two types). The experts were asked to select a "best estimate" model, plus one relationship from each category, and

then weight the relationships such that the weights summed to 1.0. (Any category could have zero weight.) The experts were similarly asked to select models for peak ground velocity and for response spectra.

The LLNL experts were also provided with alternatives for making adjustments for soil site conditions. Local soil conditions could be characterized in one of two ways: (a) The soil site conditions are one of three: rock, deep soil, or intermediate; (b) The soil site conditions are one of eight: rock, deep soil, shallow soil, till-like (with three different depths) or shallow soil sand-like (with three different depths.) An LLNL expert could select (give weights to) one or more of three possible correction approaches for local soil conditions: (a) Apply no correction (b) Apply a simple correction (a constant factor, selected by the expert) for the given soil site condition; (c) Apply a categorical correction (a median factor and standard deviation determined by LLNL) for the given soil site condition. (For details, see discussion in Bernreuter and others, 1989a, p.58–65).

The LLNL experts were asked to provide estimates of attenuation variability, i.e., the variability in log ground motion at a site resulting from different earthquakes of the same magnitude at the same distance from the site. The experts could specify a maximum ground motion or a cutoff at some number of σ if desired to avoid very high ground motions being calculated for an earthquake. (The EPRI/SOG organizers selected the σ to be used for an attenuation function, with no cutoff options.)

In the various attenuation models, earthquakes were treated as point sources, the site-to-source distance for some attenuation models being a function of the surface distance of the site from a source as well as the depth of the earthquake hypocenter. Therefore, the seismicity experts in the LLNL study were asked to specify their best estimates of the depths of earthquakes as

well as a range of depths, and provide a relationship (if any) between depth and magnitude.

IV.E.3. Comments

IV.E.3.a. Role of site intensity

In the LLNL approach, attenuation equations based on site intensity I_s require specifying a relationship between site intensity and epicentral intensity I_o and equations based on M_L require a relationship between M_L and m_b . The ground-motion experts select these relationships. Thus, analyses done for different experts who choose the same ground motion relationship but select different relationships between I_o and I_s and between M_L and m_b will result in different ground motion values.

IV.E.3.b. Role of assumed depths

Calculated ground-motion exceedance probabilities at a site, particularly at the higher ground-motion levels, are highly dependent on ground motions from nearby earthquakes (e.g., within 15 km). When site-to-source distance includes earthquake depth, a shallow earthquake will produce considerably higher ground motions than will a deeper earthquake, and a wide range of median ground motions for a given magnitude and distance can result using different assumed depths. For example, in an attenuation of the form

$$\log a = c_1 + c_2 m - \log \sqrt{R^2 + d^2}$$

where (a = ground motion, m = magnitude, R = surface distance, d = depth), at $R = 5$ km., setting depth $d = 3$ results in a ground-motion level approximately twice as high as does using $d = 10$, and 50 percent higher than obtained using $d = 6$. Allowing different seismicity experts to specify different depths increases the variability in the results for a given attenuation function.

IV.E.3.c. Role of truncation of attenuation variability

Truncating the ground motions at different factors of σ might cause a range of results to be obtained for a single source zone scenario when a single attenuation function is used. EPRI/SOG, by not truncating the ground motions, would be expected to obtain higher ground-motion exceedance probabilities than are obtained by LLNL who either truncated the ground motions at some number of σ or set a limit on ground-motion values (Bender, 1984, illustrates some effects of truncation.)

IV.E.3.d. Influence of one expert

If the attenuation relationships used by EPRI/SOG represent a cross section of the available relationships, the fact that LLNL used a much larger number of attenuation relationships than did EPRI/SOG should not in itself result in higher or lower mean calculated ground-motion exceedance probabilities. However, one LLNL ground-motion expert (Expert 5) selected only one attenuation function, and this resulted in considerably higher calculated ground-motion exceedance probabilities than did the attenuation functions selected by the other experts. Thus, Expert 5's attenuation significantly increased the mean estimates. To deal with this, LLNL presented some "results with and without Expert 5."

IV.E.3.e. Role of numbers of different attenuation functions

As the number of attenuation functions increases, one might expect the range of hazard estimates to increase, i.e., as more attenuation functions are selected, functions that give extreme results are more likely to be included. Hence, one might expect, for example, a greater range of exceedance probabilities of a ground-motion level to be calculated by LLNL than by EPRI/SOG for the same site.

IV.E.3.f. Different site adjustment methods

EPRI/SOG did not make any adjustment for soil-site conditions during their original study. [However, EPRI/SOG did present "soil amplification factors" in later work (e.g., EPRI/SOG, 1989)]. Inasmuch as LLNL experts could use and weight several options for adjusting for soil conditions, it is not easy to delete the effect of the soil correction on hazard estimates made by LLNL in comparing LLNL results with those obtained by EPRI/SOG.

IV.F. Monte Carlo versus Logic Tree Approach

IV.F.1. EPRI/SOG method

Given alternative source zone scenarios, a set of rates, b -values and maximum magnitudes for each active source, and several (three) attenuation relationships, EPRI/SOG laboriously evaluated every combination of inputs for each team, and assigned a weight to the results in each case (the logic tree approach).

IV.F.2. LLNL method

On the other hand, LLNL developed the input for a hazard calculation by selecting at random from among the possible source-zone scenarios and then selecting a rate, b -value and maximum magnitude for each source zone in accordance with the distribution of these parameters proposed by a given seismicity expert. LLNL then randomly selected an attenuation function for a given ground-motion expert in accordance with the weights assigned to the attenuation functions for that expert. A hazard calculation was then done using the selected source-zone, ground-motion inputs for the pair of seismicity

and ground-motion experts. The process was typically repeated 50 times for a pair of experts, and then repeated for all possible pairs of experts. By repeating the process many times [typically fifty simulations for each pair of 11 seismicity experts and 5 ground-motion experts (Bernreuter and others 1989a, p. 13) LLNL obtained a distribution of results (2750 per site) (the Monte Carlo approach).

IV.F.3. Comments

As we have noted, the EPRI/SOG analysis used one or two alternative a - and b - values for earthquakes within each of the cells of a source. If one regards the alternative (a,b) pairs as the only possible values of a and b , then the logic tree approach can give an accurate representation of the distribution of ground motions. On the other hand, if the selected (a,b) pairs are regarded as one or two points from a distribution of a and b values, (e.g., if a has some probability of being larger than the largest or smaller than the smallest of the a -values selected), then the logic tree approach cannot give an accurate representation of the true distribution. Assuming a continuous distribution of a - and b -values, the Monte Carlo approach can better sample the tails of the distribution.

IV.G. Combining Results

Given a distribution of the ground-motion exceedance estimates for a single team's or single expert's scenarios, the problem of how to combine these estimates to obtain an overall distribution and single (in some sense) best estimate was treated differently by LLNL and EPRI/SOG.

IV.G.1. EPRI/SOG method

EPRI/SOG obtained a "best estimate" hazard curve for a site by determining the mean log exceedance value for each ground motion level calculated using a single team's inputs, and then weighting the values for each team according to the consistency of that team's results with the results of the other teams.

IV.G.2. LLNL method

In the LLNL study, each expert assigned himself a weight, and the self-weights were used in computing a mean hazard curve. A "best estimate hazard curve" was determined by evaluating each seismicity expert's best estimate or most likely source-zone scenario and seismicity parameters for each zone using each ground-motion expert's preferred ground-motion model (e.g., producing 55 hazard curves for 11 seismicity experts and 5 ground-motion experts). The hazard curves were then aggregated using the seismicity and ground-motion experts' self weights.

IV.G.3. Risk Engineering method

Risk Engineering combined EPRI/SOG and LLNL results for Portsmouth to determine a mean exceedance probability for each ground-motion level and to compute various fractiles, etc.: "For the development of combined hazard results, the EPRI/SOG results are represented by 30 equally weighted hazard curves. The LLNL results are represented by 10 equally weighted hazard curves, which correspond to the 0.05, 0.15, ... ,0.95 fractile curves shown in Section 3. We combine these 40 hazard curves, giving a weight of 1/60 to each EPRI/SOG curve and 1/20 to each LLNL curve. We then compute fractile and mean curves from these combined curves." (Risk Engineering, May 24, 1991, Section 4.1).

IV.G.4. Comments

IV.G.4.a. Mean probability vs. mean ground motion

In both the EPRI/SOG and LLNL studies, the probabilities of exceeding a specified ground-motion level at a site calculated for different scenarios and various attenuation relationships often varied by several orders of magnitude. This had the effect at least for LLNL (where the self-weights were similar for different experts), that the calculated *mean* exceedance probability was generally considerably higher than the *median* exceedance probability and might be near the top of the cumulative distribution of these calculated probabilities. Thus, for example, if probabilities of 0.0001, 0.0010, 0.0020, 0.0006 and 0.0150 (which differ by a factor of 150 from lowest to highest) are averaged, the average value 0.0037 exceeds four of the five probability values. However, if instead of averaging or otherwise combining probabilities that various ground-motion levels will be exceeded, the ground-motion levels calculated to have a fixed probability of exceedance are averaged, the average ground-motion level is more likely to be close to the median ground-motion level calculated for that probability (figure IV-3). (This is obvious if one considers that the calculated probabilities of exceeding a ground-motion level may differ by two or more orders of magnitude, but the ground-motion levels calculated to have a fixed probability of being exceeded typically differ by less than a factor of ten.)

IV.G.4.b. Preferred Mean

The approach of computing statistics for the exceedances of a specified ground-motion level seems inconsistent with the stated purpose of estimating ground-motion levels that have fixed probabilities of being exceeded. For any single scenario one may interpolate between the ground-motion levels for which the calculations

were performed in order to estimate the ground-motion level that has a specified probability of being exceeded. Given multiple scenarios, a ground-motion level corresponding to the fixed exceedance probability can be estimated for each scenario. The mean, median, range, etc., of these ground-motion levels (rather than range of exceedance probabilities of various ground-motion levels) are the quantities of interest. It is, therefore, appropriate to determine statistics for the interpolated groundmotion levels.

IV.H. Possibility of Input Errors

We are concerned that both the process of developing and entering the inputs required to do hazard calculations for many alternative scenarios and the "keeping track" of and combining a large number of hazard estimates are highly prone to human error. Input errors may significantly affect some (or all) of the hazard estimates with the consequence that the calculated mean, median estimates, etc., and the calculated fractiles may not accurately represent the true range of these quantities for the "intended" inputs.

IV.H.1. Actual Input errors

To investigate these concerns, we examined in detail the part of the report by Risk Engineering ("Seismic Hazard Evaluation for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky," Sept. 20, 1990) that discusses hazard calculations for Paducah based on source and seismicity inputs developed by the EPRI/SOG teams (as part of the EPRI/SOG methodology development program.) To verify the Risk Engineering inputs, we also looked at source zone identifiers, probability of activity p^* values etc., as reported by the EPRI/SOG teams (EPRI/SOG, 1986a-1986j). Unfortunately, we found numerous inconsistencies within the Risk Engineering

report (some of which were typographical errors), and inconsistencies between the Risk Engineering report and the original team reports. We noted these inconsistencies in a draft version of this report and Risk Engineering has made the necessary corrections.

IV.I. Conclusions

Both the EPRI/SOG and LLNL seismic hazard methodologies represent ambitious attempts to "capture" the diversity of scientific opinion regarding seismic hazard at sites in the Eastern and Central United States. On tests using the same inputs (source zones, earthquake rates, attenuation relationship, etc.) (Bernreuter and others, 1987, p. 140), the EPRI/SOG and LLNL computer programs yielded the same hazard estimates, and one might therefore expect, if the studies are not somehow biased, that EPRI/SOG and LLNL would obtain similar results "on the average." However, at many sites, statistics related to hazard estimates (e.g., means, medians, cumulative curves for estimated probabilities of exceeding various ground motion levels, etc.) are significantly different for studies performed using the two methodologies.

One might *a priori* expect less variability in the hazard estimates obtained using inputs of the various EPRI/SOG teams than in the estimates using inputs of the LLNL seismicity experts because (a) consensus within EPRI/SOG teams was required; (b) members of all teams interacted at a number of meetings; (c) the teams used a common data base for making their judgments; (e) teams defined source zone boundaries based on locations of potentially active features; (f) teams had a well-defined formalism for assessing the probabilities that features are active; (g) EPRI/SOG rather than individual teams fit Gutenberg-Richter a - and b -values for each source using a single

earthquake catalog, (the EPRI catalog) whereas the LLNL experts (a) acted independently and had few meetings; (b) selected their own data bases; (c) defined source zones and a - and b -values in any manner they regarded as desirable.

The most obvious likely source of systematic differences in the hazard estimates by EPRI/SOG and LLNL is the use of different attenuation relationships, which predict different median ground motions for earthquakes of the same magnitude and distance, and which assume different variability σ in log ground motion. (In the initial studies, each of five LLNL experts assigned weights to as many as six attenuation relationships, whereas in the EPRI/SOG studies, a total of three relationships were used.) Using different values of σ (standard deviation in log ground motion) or different hypocentral depths for the same basic attenuation equation can result in significantly different calculated probabilistic ground motions. In addition to possible differences in the mean probabilistic ground motions estimated using different attenuation relationships, one might expect the range of ground-motion estimates to increase as more attenuation functions, possibly representing more extreme viewpoints, are included in the calculations, causing LLNL to have greater variability than EPRI/SOG in the hazard estimates at a site.

However, not all differences in hazard estimates can be attributed to the differences in attenuation relationships; e.g., comparative studies performed by LLNL using a single attenuation relationship and the source and seismicity inputs for EPRI/SOG teams and LLNL experts showed significant differences in hazard estimates remain even if the effect of the attenuation relationship is "washed out".

On the average, lower earthquake rates *may* have been assigned to sources by EPRI/SOG teams than by LLNL experts. (EPRI/SOG and

LLNL had different source zones and different rates in different scenarios, and we are unable to make a direct source-by-source comparison of rates.) However, LLNL noted in some comparative studies (1987) that the "best estimate" rates of the LLNL experts yielded (combined) hazard curves that were a factor of two higher than those obtained using rates that were fitted (by LLNL) to the LLNL catalog by their so-called uniform method. They also noted that rates estimated by the "uniform" method had considerably less variability than rates estimated by the experts for the same sources, and that the LLNL catalog contained about 30 per cent more earthquakes than did the EPRI catalog. Some possible inferences are (a) the magnitudes in the EPRI earthquake catalog which have been converted to a "uniform" magnitude m_b^* by attempting to adjust for errors in the recorded magnitudes are generally too low and/or too many earthquakes have been identified as aftershocks and removed, resulting in estimates of earthquake rates by EPRI/SOG that are too low; (b) alternatively, magnitude conversions which do not take into account observational errors generally yield magnitudes that are too high, and hence too many earthquakes in the LLNL catalog have (converted) magnitudes $m_b > m_0$ the minimum magnitude of interest; (c) the LLNL algorithm for fitting a - and b -values leads to estimated rates that are too low on the average; (d) alternatively, LLNL experts left to their own devices overestimated earthquake rates on the average; (e) the range of rate estimates is considerably lower when the estimates are based on a single catalog and a standard procedure is used than when individuals estimate these rates using their own techniques and catalogs; (g) the combined "best estimate" ground-motion exceedance probability curve is dominated by the higher probabilities (because calculated individual "best estimate" exceedance probabilities of a motion level vary by one or more orders of magnitude, and even a single high probability value significantly increases

the mean estimate above the median estimate), and hence one would expect the combined best estimate curve to be higher than the average curve based on less variable "uniform" rates.

Different LLNL experts using their own catalogs, magnitude conversions, fitting techniques, etc., proposed widely varying "best estimate" a - and b -values for homogeneous source areas, whereas EPRI/SOG methodologists fit a - and b values for individual cells (e.g., $1^\circ \times 1^\circ$) using a standard technique and the so-called EPRI earthquake catalog, in accordance with specifications of a team regarding spatial smoothing of estimated a - and b -values, prior estimate of b , etc. This suggests that one might expect more variability in the overall "best estimate" earthquake rates assigned by LLNL experts to their source zones than in the most probable rates assigned by the EPRI/SOG teams.

Furthermore, an LLNL expert specified not only "best estimate" a - and b -values for each source, but also upper and lower bounds on these values (assuming a triangular distribution within these bounds) and to perform a hazard analysis, (a,b) -values are sampled repeatedly from their distributions using Monte Carlo techniques; EPRI/SOG does the calculations for all combinations of inputs, which generally is for one or two alternative pairs of (a,b) -values for each cell for each scenario. However, EPRI/SOG teams tended to define a large number of alternative source zone scenarios (for many combinations of active features and background sources) and different a - and b -values were assigned to each cell for different scenarios, greatly increasing the effective number of a, b pairs for which the calculations are done. (The variability in a - and b -values for a cell for different scenarios depends on the amount of spatial smoothing, prior estimates of b , strength of prior, etc.) However, the overall effects of the treatment of the seismicity parameters on the range of

hazard estimates at a site for an EPRI/SOG team compared with the range for an individual LLNL expert is difficult to evaluate without knowing actual inputs.

In many cases, an important factor in the hazard estimates is how much seismicity is assigned to background (or default or complementary) sources in the vicinity of a site. Much effort was expended in the EPRI/SOG methodology to identify potentially active features, and the background became primarily a repository for "leftover" seismicity that had not been assigned to features that are active in a given scenario. However, many sites are not near active features in a majority of the source zone scenarios and the background seismicity dominates the hazard estimates. Rates assigned to cells (e.g., $1^\circ \times 1^\circ$) in the background depend not only on which features are active, but also on the type of spatial smoothing of a - and b -values, prior estimate of b -value, etc., that is requested.

If "low spatial smoothing on a " is requested by an EPRI/SOG team, nearby cells in a background source may have significantly different fitted earthquake rates in a given scenario, whereas these cells would have a constant rate in an LLNL scenario (suggesting more variability in this case between nearby sites for EPRI/SOG than for LLNL).

If the inputs of one expert or team result in considerably higher calculated ground-motion exceedance rates than do the inputs of the remaining teams, these high rates will dominate the mean and possibly the 85th percentile cumulative probability curve, if results are weighted equally, or if expert self weights are used. (In addition, the mean may be very close to the 85th percentile curve.) On the other hand, if results are weighted according to their consistency with results of other teams, an outlier may be given very little weight, and have little effect on the mean or 85th percentile curves. Thus, if an LLNL expert whose inputs

yield high results does not assign himself a low weight, the LLNL median and 85th percentile curves might be expected to be further apart than EPRI/SOG curves.

The question of how to weight and combine widely varying estimates to obtain a single "best" estimate has not been satisfactorily resolved. For example, calculated ground-motion exceedance probabilities for LLNL ground-motion Expert 5 were so much higher than the probabilities calculated for other ground-motion experts that LLNL elected to present results (cumulative probability curves, means, etc.) "with and without Expert 5," leaving to the reader the decision of whether to include or ignore Expert 5. (We note that the average exceedance probability of a given ground-motion level is dominated by Expert 5's numbers, but the average ground-motion level for a fixed probability of exceedance may not be strongly affected by Expert 5's results. More generally, "outliers" do not have nearly so great an effect on the average ground-motion level calculated to have a fixed probability of being exceeded as do outliers on the average calculated exceedances of a fixed ground-motion level. The mean ground-motion level for a fixed probability of exceedance may actually be quite close to the median level.)

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Appendix A

(Reprinted from Table 3-1, Bernreuter and others, 1989, v. 1)

Panel Members in LLNL Study

EUS ZONATION AND SEISMICITY PANEL MEMBERS (S-Panel)

- Dr. Peter W. Basham (2)
- * Professor Gilbert A. Bollinger (1)
- * Mr. Richard J. Holt (1)
- * Professor Arch C. Johnston
- * Dr. Alan J. Kafka
- * Professsor James E. Lawson
- * Professor L. Tim Long (5)
- * Professor Otto W. Nuttli (1)
- * Dr. Paul W. Pomeroy (1)
- * Dr. Carl Stepp
- Dr Ann E. Stevens (3)
- Professor Ronald L. Street (1)
- * Professor M. Nafi Toksoz (1) (4)
- Dr. Carl M. Wentworth (3)

- (1) Also participated in the SEP [Systematic Evaluation Program—the use of probabilistic risk analysis to investigate the safety of older nuclear power plants] panels.
- (2) Only provided zones and seismicity parameters for Canada.
- (3) Only provided zonation—no seismicity parameters.
- (4) Also member of the Ground Motion Panel.
- [(5) There is no footnote 5 provided in the referenced table]

- (*) Final member of the zonation and Seismicity Panel.

EUS GROUND MOTION MODEL PANEL MEMBERS (G-Panel)

- * Dr. David M. Boore (1)
- * Dr. Kenneth Campbell
- Professor Otto W. Nuttli (1) (2) (3)
- Professor Nafi Toksoz (2)
- * Professor Mihailo Trifunac (1)
- * Dr. John Anderson (4)
- * Dr. John Dwyer (4)
- * Provided the final sets of ground motion models used.
- (1) Participated as a member pf the SEP EUS Ground Motion Panel.
- (2) Also member of the Seismicity Panel. . .
- (3) Left Panel in June, 1986.
- (4) Added to the Panel in the Fall of 1986.

Appendix B

Magnitude-Frequency Relationships: EPRI/SOG and LLNL

EPRI/SOG and LLNL assume earthquake occurrences follow a negative exponential magnitude-frequency (Gutenberg-Richter) relationship within some magnitude range, $m_0 \leq m \leq m_{max}$ (and earthquakes with magnitude greater than m_{max} do not occur). LLNL also alternatively allows higher magnitude earthquakes to follow a different relationship. We discuss the different relationships, and some possible consequences in hazard estimates.

The Gutenberg Richter magnitude-frequency relationship states that the logarithm of the expected number N of earthquakes exceeding magnitude m is

$$\log N = a - bm \text{ or } \ln N = \alpha - \beta m \quad (1)$$

(where $\alpha = 2.3026 a$; $\beta = 2.3026 b$).

Equivalently, the expected number of earthquakes exceeding magnitude m is $N \exp(-\beta m)$ and the number of earthquakes in the interval $m_i \leq m \leq m_i + \Delta m$ is

$$N \exp(-\beta m_i) [1 - \exp(-\beta \Delta m)]. \quad (2)$$

However, because it is usually assumed that earthquakes with magnitudes greater than some (regionally dependent) maximum magnitude m_{max} do not occur in a region, the relationship cannot be valid for magnitudes $m \geq m_{max}$.

For computational purposes in hazard analysis, EPRI/SOG, LLNL (and others) divide the magnitude range into intervals of width Δm , and allocate a fraction of the expected earthquakes to each magnitude interval. In the negative exponential earthquake recurrence model, the number of earthquakes allocated to each successive interval, $m_o + k\Delta m \leq m \leq m_o + (k+1)\Delta m$, is a factor $\exp(-\beta \Delta m)$ less than

the number of earthquakes allocated to the preceding interval.

Both EPRI/SOG and LLNL allow different values of m_{max} to be assumed for an area (where each value of m_{max} has a probability associated with it). EPRI/SOG assumes (by equation 1) that some number N of earthquakes have magnitudes $m > m_o$ and when earthquakes with magnitudes $m_o \leq m \leq m_{max}$ are used in the calculations, a fraction $N [1 - \exp(-\beta [m_o - m_{max}])]$ of the earthquakes are included and the "remaining" $N \exp(-\beta [m_o - m_{max}])$ earthquakes with magnitudes $m > m_{max}$ "disappear". Thus, if various values of maximum magnitude m_{max} (1), m_{max} (2), ..., are used, the EPRI/SOG model simply increases (or decreases) the number of earthquakes for a source in accordance with the constant factor $\exp(-\beta \Delta m)$ decrease in earthquakes per magnitude interval.

A common alternative interpretation of the truncated negative exponential model is to assume a constant total number of earthquakes exceeding the minimum magnitude m_o , regardless of m_{max} and then to redistribute the earthquakes when m_{max} is altered. Thus, if R , the number of earthquakes with magnitude m_o or greater is assumed to be constant, the number of earthquakes in the interval $m_o + k\Delta m \leq m \leq m_o + (k+1)\Delta m$ is given by

$$\begin{aligned} N(m_k) &= R \int_{m_o + k\Delta m}^{m_o + (k+1)\Delta m} \frac{\beta \exp(-\beta m) dm}{\exp(-\beta m_o) - \exp(-\beta m_{max})} \\ &= R \frac{\exp[-\beta(m_o + k\Delta m)] - \exp[-\beta(m_o + (k+1)\Delta m)]}{\exp(-\beta m_o) - \exp(-\beta m_{max})} \\ &= R_1 \exp[-\beta(m_o + k\Delta m)] \end{aligned} \quad (3)$$

$$\text{where } R_1 = \frac{R[1-\exp(-\beta\Delta m)]}{\exp(-\beta m_o) - \exp(-\beta m_{\max})}. \quad (4)$$

Thus, in this alternate version of the model R_1 depends on $m_{\max}$, whereas, in the EPRI/SOG version, R_1 is independent of $m_{\max}$, i.e.,

$$R_1(\text{EPRI}) = \frac{R[1-\exp(-\beta\Delta m)]}{\exp(-\beta m_o)} \quad (5)$$

In the alternate version of the model, all the earthquakes are assigned to some magnitude interval in the range $m_o \leq m \leq m_{\max}$, whereas in the EPRI/SOG version, only a fraction are assigned. The differences in using the two versions of the model can be significant if the difference $m_{\max} - m_o$ is small (e.g., 1 unit). For example, if $R = 1.0$ earthquakes with magnitude greater than or equal to $m_o = 5.0$ is assumed and $\beta = 2.0$, then if $m_{\max} = 5.6$, 0.70 earthquakes are assigned to the interval 5.0–5.6 in the original version, and if $m_{\max} = 6.4$, a total of 0.91 earthquakes are assigned to the range $5.0 \leq m \leq 6.4$. The differences become smaller as $m_{\max}$ increases, e.g., if $m_{\max} \geq 7.0$, 0.97 or more earthquakes are “used up”. (In each case, in the alternate model 1.0 earthquakes are assigned.)

The LLNL Model

Most of the experts in the LLNL study elected to use the so-called LLNL recurrence model. In the LLNL model, earthquake occurrences are assumed to follow the relationship $\ln N = \alpha - \beta m$ within some range (the “range of linearity” as specified by the analyst) $m_l \leq m \leq m_u$, where $m_l \geq m_o$ and $m_u \leq m_{\max}$.

For earthquakes with magnitudes $m_u \leq m \leq m_{\max}$, the number of exceedances is given by

$$N = \exp(\alpha - \beta m_u) \frac{(m - m_{\max})^2}{(m_u - m_{\max})^2}; \quad (6)$$

for earthquakes with magnitudes $m_o \leq m \leq m_l$ a constant rate λ_o may be specified. This model has the effect that there may be more earthquakes in the interval $m_u \leq m \leq m_u + \Delta m$ than in the interval $m_u - \Delta m \leq m \leq m_u$. Thus, in an example provided by LLNL (p. Q5-12, Bernreuter and others, 1989, Vol. 7), in which $m_u = 7.5$, $m_{\max} = 7.75$, there are 0.00047 earthquakes in the interval $7.25 \leq m \leq 7.50$ but 0.00069 earthquakes in the interval $7.50 \leq m \leq 7.75$.

In the previous example, if $m_u = 7.5$, but $m_{\max} = 8.0$, there would be 0.00052 earthquakes in the interval $7.5 \leq m \leq 7.75$ and 0.00017 earthquakes in the interval $7.75 \leq m \leq 8.0$ (for a total of 0.00069 earthquakes in the range $7.5 \leq m \leq 8.0$). Note that in this LLNL model, there is a constant number of earthquakes with magnitude $m \geq m_u$, and this number of earthquakes (0.00069 in the previous example) is distributed in the range $m_u \leq m \leq m_{\max}$, regardless of the value $m_{\max}$, so long as $m_{\max} > m_u$.

As noted above, most (all but one) of the experts in the LLNL study use the LLNL model. This suggests that if EPRI/SOG and LLNL assume the same a and b (or α and β values) for an area and the same value of $m_{\max}$, then:

(a) if $m_{\max} = m_u + \Delta m$ (i.e., $m_{\max}$ exceeds m_u by only one magnitude interval), then LLNL is likely to place considerably more earthquakes in the highest magnitude interval than does EPRI/SOG.

(b) if $m_{\max} = m_u + j\Delta m$, as j increases, a (constant) number, y , of earthquakes with magnitude $m > m_u$ is “spread out” over a wider range of magnitudes in the LLNL model, and the number in the interval $m_u \leq m \leq m_u + \Delta m$ decreases. In the EPRI/SOG model, y

earthquakes also exceed m_u , and as m_{max} increases, an increasing fraction of these earthquakes is assigned to magnitudes in the range $m_u \leq m \leq m_{max}$. As the difference $m_{max} - m_u$ increases, EPRI/SOG "uses up" a higher fraction of the y earthquakes, and the total number of earthquakes assigned to magnitudes $m > m_u$ becomes more nearly equal to the number assigned to these magnitudes by LLNL, although the distribution is different in the two cases. Note this suggests that if m_{max} is close to m_o , the minimum magnitude, EPRI/SOG might "use up" a relatively small fraction of the earthquakes and have a much lower effective rate in their analysis than would LLNL.

Comment

The LLNL experts specify the magnitude range for which the relationship $\log N = a - bm$ is valid. In some cases, the upper limit of the range of validity is $m_u = 5.0$, which is the same as m_o , the lowest magnitude currently used in the calculations. This means that the relationship $\log N = a - bm$ is not used to obtain the decrease in the number of earthquakes with magnitude for any magnitudes in the range for which the hazard calculations are done; the decrease with magnitude is given by equation (6) for the entire range in this case. (In this case, the b -value together with the a -value is used only to determine the number of earthquakes with magnitudes exceeding m_o .)

In some cases, m_u lies between the "lower limit" of m_{max} and the "upper limit" of m_{max} . In an example (Table B10.3, seq #17), $m_u = 7.25$, and $7.0 \leq m_{max} \leq 7.5$. There is a "jump" in the number of earthquakes when m_{max} increases from 7.25 to 7.5, i.e., *there are more earthquakes in the interval $7.25 \leq m \leq 7.5$ than in the interval $7.0 \leq m \leq 7.25$* . For the "best estimate" values of $a = 1.69$, $b = 0.57$, there are 0.00140 earthquakes in the interval 7.0–7.25 when $m_{max} = 7.25$ or 7.50, and 0.00361

earthquakes in the interval 7.25–7.50 when $m_{max} = 7.50$.

Uncertainty in a -value–LLNL

The LLNL experts specify a "lower limit", "best estimate" and "upper limit" value for a and for b in the relationship $\log N = a - bm$. The range of a may be two units or more (e.g., Table B2.3, in sequence #2, the range $2.194 \leq a \leq 6.534$, and in sequence #15 the range $0.959 \leq a \leq 3.459$ is shown). The a - and b values may be "uncorrelated", "partially correlated" or "fully correlated." In the example for which the range of a is $0.959 \leq a \leq 3.459$, the range of b is given by $0.80 \leq b \leq 1.2$, and a and b have "no correlation". In this case, the rate of earthquakes with magnitude $m \geq m_u = 5.0$ ranges from 0.00001 ($a = 0.959$, $b = 1.2$) to 0.28774 ($a = 3.459$, $b = 0.8$), with a "best estimate" of 0.00910 ($a = 2.959$, $b = 1.0$). *Obviously, a range in earthquake rates of 2.8774×10^4 will produce a wide range of exceedance probabilities calculated for a ground motion level in the hazard calculations.*

Estimates of a and b for an area are based on earthquakes recorded in a catalog, and estimates of the number of earthquakes that occurred but were not recorded. In the previous example ($a = 0.959$, $b = 1.2$) corresponds to 0.00147 earthquakes/year and ($a = 3.49$, $b = 0.8$) corresponds to 1.950 earthquakes/year with magnitude $m \geq 4.0$. If earthquakes with magnitudes $m \geq 4.0$ are completely recorded for 20 years, we expect to see 0.03 earthquakes in one case above, and 39 in the other, and 1.82 earthquakes for the "best estimate" values ($a = 2.959$, $b = 1.0$). If earthquakes are Poissonian, the usual estimate of the standard deviation of the number that will occur during a given time period is the number that occurred during a similar time period. *If earthquakes with magnitude $m \geq 4.0$ are used to estimate a - and b values, we think it is highly unlikely that*

observed earthquakes could yield a range of estimates as wide as $0.03 \leq N \leq 39$.

In many cases, the "best estimate" a -value is at the midpoint between the "lower limit" and "upper limit" a -value. But in a symmetric distribution, a at the center of the range (in log space) corresponds to an *expected* number of earthquakes considerably greater than the number corresponding to the best estimate a -value, if there is no correlation between a and b .

"Partial Correlation" and "Full Correlation" between a and b

Seven experts assumed "no correlation" between a and b . However, two experts used the option of "partial correlation" between a and b . To explain this option, we define $\hat{a}_e$ and $\hat{b}_e$ as the expert's overall best estimate of a and b ; $a_l \leq a \leq a_u$; $b_l \leq b \leq b_u$. For a_o in the allowable range of a -values there is similarly a best estimate of b ; this estimate $\hat{b}_o$ is derived by solving for b_o in the relationship

$$a_o + \hat{b}_o m_u = \hat{a}_e - \hat{b}_e m_u, \quad (7)$$

where m_u = highest magnitude for which the equation (1) is valid. (If $\hat{b}_o < b_l$, set $\hat{b}_o = b_l$; if

$\hat{b}_o > b_u$, set $\hat{b}_o = b_u$.) In this model, for any a_o in the range, the best estimate of b is such that the number of earthquakes exceeding m_u is a constant (if equation (7) has a solution). In all

cases, a triangular distribution for $b_l \leq \hat{b}_o \leq b_u$ is assumed, and as in the case of "no correlation", there is some probability that any value of b in the range will be associated with any a_o in the range, and as in that case, *the range of rates of earthquakes with magnitudes $m_u \geq m_o = 5.0$ can be very large.*

(Side comment: Expert 5 assumed partial correlation between a and b , and defined earthquake size in terms of intensity. This expert stated that he/she intended to use the LLNL model, but also stated that the range of the $a-bI_o$ model extended to $I_o = XII$, i.e., he/she in effect used the negative-exponential relationship throughout, and did not in fact use the LLNL model to represent earthquakes at the higher magnitudes.)

Two experts used the option "full correlation between a and b ." In this case, a single value of b is associated with a value of a such that the largest a corresponds to the highest (in absolute value) b in the range and the smallest a corresponds to the lowest (in absolute value) b ; a in the middle of the range of a values corresponds to b in the middle of the range of b values, etc. *This "full correlation" option tends to "anchor" the rates about some magnitude, and can reduce the overall variability in the rates obtained using the other options.*

(Side comment: Expert 6 assumed full correlation between a and b , in which case his/her "best estimate" b -value should be uniquely determined for the best estimate a -value. However, the "best estimate" b -value is generally not the value that would be given by the assumed correlation between a and b and the range of a and b .)

We conclude that apparently minor differences in modeling earthquake occurrences can significantly affect the rates assigned to various magnitude intervals.

ASSOCIATION WITH SEISMICITY TO GEOMETRY RELATIVE TO STRESS, SENSE OF SLIP DEEP CRUSTAL ASSOCIATION	MODERATE TO LARGE EARTHQUAKES		SMALL EARTHQUAKES ONLY		NO SEISMICITY	
	Favorable	Unfavorable	Favorable	Unfavorable	Favorable	Unfavorable
	YES	0.80	0.40	0.30	0.10	0.060
NO	0.64	0.20	0.15	0.05	0.024	0.004

ASSOCIATION WITH SEISMICITY GEOMETRY RELATIVE TO STRESS SEISMICITY LEVEL DEEP CRUSTAL EXPRESSION		MODERATE-TO-LARGE EARTHQUAKES		SMALL EARTHQUAKES ONLY		NO ASSOCIATION WITH SEISMICITY	
		FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY
DEEP CRUSTAL EXPRESSION NEAR INTERSECTIONS	HIGH	1.0	0.95	0.8	0.65	0.5	0.3
	LOW	0.99	0.9	0.7	0.5	0.3	0.1
DEEP CRUSTAL EXPRESSION NOT NEAR INTERSECTIONS	HIGH	0.95	0.9	0.7	0.55	0.4	0.2
	LOW	0.93	0.85	0.6	0.4	0.1	.05
NO DEEP CRUSTAL EXPRESSION	HIGH	0.85	0.8	0.55	0.4	0.2	.05
	LOW	0.83	0.75	0.4	0.2	.05	.005

Figure IV-1. Feature characteristic matrices proposed by EPRI/SOG teams (A) Bechtel and (B) Rondout. Each matrix shows the probability estimated by the corresponding team that a hypothetical feature with a given combination of the selected characteristics is active (i.e., capable of producing future earthquakes). Note the widely differing probability estimates by the two teams.

FEATURE ASSESSMENT FORM

Physical Characteristic	Probability that the Given Feature Exhibits a Given Level of Each Characteristic		
	Feature # EIIC10	Feature # EIIC11	Feature # EIIC12
1. Association with Seismicity			
1. Moderate-to-Large Earthquake	0.30	0.30	0.00
2. Small Earthquakes Only	0.40	0.40	0.20
3. No Seismicity	0.30	0.30	0.80
	1.00	1.00	1.00
2. Geometry of Feature Relative to Stress Orientation and/or Sense of Slip			
1. Favorable Geometry/Sense of Slip	0.50	0.80	0.50
2. Unfavorable Geometry/Sense of Slip	0.50	0.20	0.50
	1.00	1.00	1.00
3. Brittle Slip on Feature			
1. Pleistocene-Holocene Slip	0.00	0.05	0.00
2. Miocene-Pliocene Slip	0.10	0.15	0.10
3. Pre Miocene Slip or No Brittle Slip	0.90	0.80	0.90
	1.00	1.00	1.00
Probability that feature is seismogenic	0.20	0.24	0.02

Figure IV-2. Feature assessment form showing probabilities estimated by the EPRI/SOG Law Engineering team that each of three identified features has each of the characteristics shown in that team's feature characteristic matrix. Note the "informational" uncertainty associated with each of the answers.

Figure 4-5. Peak-acceleration hazard curves for Paducah (for soil site conditions) obtained by combining results from the EPRI/SQG and LLNL (all ground-motion experts) methodologies. The solid curves correspond to the following fractile hazard curves: 0.05 (bottom), 0.15, 0.25, 0.35, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, 0.95 (top); the dashed curve represents the mean hazard curve.

Figure IV-3. Fractile hazard curves (solid lines) for calculated probabilities of exceeding various ground-motion levels at Paducah, and mean curve (dashed line) for these calculated probabilities (reproduced from Risk Engineering Draft Report). Dashed line was calculated by averaging probabilities of exceeding each ground-motion level. The x's (added by us) show the average ground-motion levels calculated as having an annual probabilities of 0.004, 0.001 and 0.0005 of being exceeded. (Average of ground-motion levels was calculated "across" table for the given probabilities. The dashed line should not be interpreted as showing the mean ground-motion level having a fixed annual probability of exceedance.

V. Generic Issues

by

David M. Perkins

Summary

We have investigated the role played in the hazard analysis of (1) point-rupture models vs line-rupture models; (2) choice of depth of origin of strong ground motion; (3) choice of maximum magnitude; and (4) choice of which measure to use for "best estimate" of probabilistic ground-motion value.

1. Point-rupture models.

In general, a point-rupture model is adequate for the return periods met in hazard mapping (500 to 1000 years), for sources which are relatively inactive and for which the maximum magnitudes would not be expected to produce ruptures more than about 10-20 km in length. For conventional equations relating magnitude and rupture length, these dimensions correspond to magnitudes of about 5.5 to 6.5 M_S . In the central and eastern United States, if earthquake ruptures are half the length of ruptures usually experienced in the western United States for strike-slip faults, and where source zones may be limited in length in the probable rupture direction, it is likely that point-source models are adequate up to magnitude 7.0 M_S , especially at return periods which produce moderate to low ground motions (say, less than 0.3 g, peak horizontal acceleration). On the other hand, for sources with maximum magnitudes above 6.5 M_S , for sites closer to the source than 60 km, and for return periods yielding moderate to large ground motions (say, greater than 0.3 g, peak horizontal acceleration), it is desirable to model the source with line-ruptures.

Accordingly, early in the assessment process for Paducah, the USGS staff recommended to DOE that line-rupture models be used in modeling the large earthquakes likely to occur in the New Madrid Seismic Zone (NMSZ), and this recommendation

was implemented in the Risk Engineering and USGS studies.

2. Depth of origin of strong ground motion.

For the two sites studied, the role of depth of source of strong ground motion on the hazard estimate is such that the effect of changing depths between a nominal 7 km and 3 or 10 km is about as great as the effect of changing maximum magnitude by plus or minus 0.6 magnitude units, respectively. The sensitivity studies suggest that for both sites, at ground motions having return periods of 1000 years, the ground motions are low enough that the effect of depth is small compared to the observed range of alternative hazard estimates. In general, we expect that contribution of the uncertainty in source depth to the uncertainty in hazard is smaller than the contribution of the uncertainty in determination of source zone boundaries, seismicity parameters, or likelihood of zone existence.

3. Maximum magnitude.

We have observed that the hazard result obtained by integrating over the uncertainty of symmetric maximum magnitude distributions is approximately that obtained by using the center magnitude of the uncertainty distribution. Accordingly, in our sensitivity studies we let the maximum magnitude range between values of 5.5 to 7.3 M_S , where these values represent center magnitudes of symmetric magnitude distributions whose extremes range more widely than this. Center maximum magnitudes in this range represent fairly well the uncertainty distributions used in the EPRI/SOG and LLNL studies.

For choice of maximum magnitude, as with depth of source of strong ground motion, the sensitivity

studies suggest that for both sites, at ground motions having return periods of 1000 years, the ground motions are low enough that the effect of a choice of maximum magnitude over a range of plus or minus 0.6 magnitude units is small compared to the observed range of alternative hazard estimates. In general, we expect that the choice of maximum magnitude may generally be a smaller source of uncertainty in hazard than the determination of source zone boundaries, seismicity parameters, or likelihood of zone existence.

4. "Best" estimates.

In the EPRI/SOG and LLNL studies at Portsmouth, the mean hazard values differ by a considerable amount. On the other hand, the median values are quite similar, regardless of whether the opinion of ground-motion expert 5 has been removed.

Ordinarily we would prefer a mean as a best estimate of hazard, both because it is more in keeping with the idea of getting a result which is an expected value under uncertainty, and because the mean hazard is often similar to that obtained for sites close to source zones whose boundaries are based on clustering of historical seismicity. Furthermore, the mean estimate is relatively conservative, corresponding to higher fractiles of the distribution of hazard. Nevertheless, it seems clear that the large difference in variability in the constituent estimates of the EPRI/SOG and LLNL studies has a large component due to the interaction of methodology and opinion, rather than variability inherent in the data or tectonic processes. Thus there may be a methodological relative bias in mean estimates. On the other hand, the median estimate seems to be both resistant to extreme estimates as well as less sensitive to methodological differences, producing more stable results in these studies, and we think these two reasons are sufficient for preferring medians in this kind of work.

Introduction

In this section, we address certain issues which apply in general to hazard studies in the eastern United States — point-rupture vs finite-rupture source models, depth of origin of strong ground motion, maximum magnitude, and various aspects of using means or medians as "best estimates."

Other issues are dealt with in the course of development of other sections: choice of magnitude scale, obtaining of magnitude from intensity data, choice of minimum magnitude, choice of attenuation functions, site response, determination of *a*- and *b*-values, handling of parameter variation, and factors influencing differences between EPRI and LLNL results.

It is important to note that the conclusions we draw are often conditioned on aspects applicable to the sites. That is, we are not only interested in rules of thumb which apply in the eastern United States in general, we are also interested in rules of thumb which apply to changes in low-to-moderate ground motions of the size found at the two DOE sites for the return period of interest (about 1000 years). Because 0.3 g is a peak acceleration value of interest in engineering studies for the facilities at these sites, we are also interested in rules of thumb applying to changes in exceedance rates for peak accelerations of this size.

V.A. Point-rupture model vs generic line-rupture model

Earthquake ruptures in the eastern United States are frequently represented as point ruptures in hazard analyses, with the expectation that not much error is involved. First, it is assumed that earthquakes do not have large magnitudes, and therefore the expected rupture lengths should be small.

Second, there is a good possibility that for a given magnitude, rupture lengths in the eastern United States may be shorter than those in the western United States. Finally, given the low rates of seismicity in the eastern United States, ground motions for which extensive rupture lengths would be expected, occur only infrequently and do not affect the hazard analyses at short return periods. When the whole hazard curve is to be calculated, the latter consideration should not apply, and one should ascertain the effect of rupture length at all ground motions of interest. We briefly assess the effects of these assumptions in the first of the subsections to follow.

The above assumptions are questionable in the vicinity of the New Madrid fault zone, because it is known that earthquakes with magnitude greater than 8.5 have occurred with rupture lengths as great as perhaps 150 km. Accordingly we assess the effects of point-rupture vs finite-rupture models for large magnitudes and high-seismicity modeling in this region in the second of the subsections which follow.

V.A.1. Point-rupture model vs generic line-rupture model for eastern sources.

We explore here the use of *point ruptures* rather than *generic line-ruptures* as representations of the earthquake for source zones in which the rates and maximum magnitudes are relatively low compared to active California sources and for which no particular fault is to be modeled, but only the effect of elongate ruptures for earthquakes having random locations in a source zone, but rupturing in a common direction.

V.A.1.a. The point-rupture model.

A point-rupture model treats all earthquakes as having no finite dimension. A circle of radius R from the point source is the locus of ground

motions associated with magnitude M and distance R for the given attenuation function, $g(M,R)$. Circles of increasing radii represent the loci of decreasing ground motion for a given M . Within the circle of radius R_i are found ground motions exceeding g_i for a given M . We call the circle of radius R_i the *isoseismal* of ground motion g_i , or the "locus of equal ground motion." Thus, for a given M , there is a small area in which occur exceedances of a large ground motion, and a large area in which occur exceedances of a small ground motion.

V.A.1.b. The linear rupture model.

Consider what happens when the earthquake is treated as a linear rupture for which ground motion g_i has as its locus of equal ground motion all the points whose closest distance to the rupture is R_i . The locus is elongated by an amount equal to the length of the rupture. The area containing exceedances of g_i is greater than the corresponding area when the earthquake was treated as a point, the fractional increase being inversely proportional to R_i . In

other words, the larger the ground motion, the smaller the R_i , and the greater is the increase in isoseismal area due to elongation of the rupture. The net effect in a hazard analysis is that the exceedance probability of small ground motions is not much affected by modeling earthquakes as finite ruptures instead of points, *but the exceedance probability for large ground motions may increase several fold*. The sketches below illustrate the relative effect of elongation on increase of isoseismal area.

Thus, in the sketches, the area of exceedances for large ground motions has increased about a factor of four, for the medium ground motion by about a factor of two-and-a-half, and for the low ground motion about a factor of one-and-three-quarters.

This linear-rupture model with elongated loci of equal ground motion is an approximation, designed to represent the fact that the energy producing the ground motion can come from any or all parts of the rupture. The resulting idealized picture is sometimes called the "hot-dog model." Real, non-ideal ruptures produce energy irregularly along the rupture, and perhaps less near the ends, but rupture propagation direction also renders the ground motion higher in the direction of propagation. Before the real rupture occurs, we have no information as to the energy distribution, and the "hot-dog" model merely reflects this lack of information.

V.A.1.c. Expected applicability of the two models.

A finite-rupture model (often a line-rupture model, as above) treats the earthquake rupture

surface as having a length (and, sometimes width) that is an exponential function of magnitude. Such a model, together with an attenuation function which is dependent on the closest distance to the fault, increases the area over which a given ground motion is exceeded, the increase being greater the larger the magnitude and the closer to the rupture the site lies. Such models are important where larger magnitude earthquakes are relatively likely during the exposure time considered or in the case in which only very low probabilities of exceedance are acceptable.

In general, a point-rupture model would be expected to be adequate for the ordinary return periods met in hazard mapping (500 to 1000 years) for sources which are relatively inactive and for which the maximum magnitudes would not be expected to produce rupture dimensions more than about 10-20 km. For conventional equations relating magnitude and rupture length, these dimensions correspond to magnitudes of about 5.5 to 6.5 M_S . Tabulated below are three rupture-length vs magnitude relationships, used in our sensitivity studies. The first, labelled "long rupture," is one used to relate ruptures in California to magnitude. This is primarily a relationship for strike-slip mechanism earthquakes (Mark and Bonilla,

1977). The second relationship is designed to be a constant factor smaller than the first, such that it represents the approximate length of magnitude 7 to 7.5 M_S earthquakes in the Basin and Range Province. This is primarily a

relationship for normal faulting earthquakes. The third relationship is a factor of ten smaller than the second and is meant to be used to approximate point-rupture modeling in the tests below.

Table V.A-1. Rupture Lengths Used In USGS Sensitivity Studies

Magnitude M_S	Rupture Length (km)		
	Long Rupture	Medium Rupture	Short Ruptures
5	7.2	3.2	0.3
6	17.7	7.9	0.8
7	43.5	20.0	2.0
8	106.4	50.1	5.0
9	260.6	125.9	12.6

V.A.1.d. Model used in testing effect of magnitude and rupture length.

In this study to confirm the general rules-of-thumb about point-rupture vs finite-rupture models, we have chosen a source about 100 km wide and 350 km long, with the rupture direction oriented parallel to the 100 km side. Most source zones in the east that do not model active tectonic features but are meant to model geological correspondences with seismicity have limited size in the hypothetical rupture direction. Faults in this test zone are treated as having unknown location, uniformly distributed across the source zone. Using the Boore and Atkinson (1987) peak acceleration attenuation, we examined the hazard at a site inside the source, some distance from the boundaries of the zone, using relatively high maximum magnitudes and modeling long-, medium-, and short-length line ruptures according to the table above.

Two rupture model "boundary conditions" are examined. In one model, the source-zone boundary limits the extent of the ruptures. In the other, the source-zone boundary limits the extent of the *center* of the ruptures. This latter

case has two functions in modeling. First, it enables one to model a zone with an arbitrary division across it without an accompanying artifact of low hazard at this division. This also assures that contiguous sources will not have an artificially low hazard near the source boundary. Second, it can be used to express uncertainty that a hypothetical zone boundary actually limits large ruptures. Both rupture models are found in conventional hazard analyses. For convenience, we will term the first model, the "hard boundary" model, the second, the "soft boundary" model.

We contrast point sources and hard and soft boundary rupture models for maximum magnitudes of 7.3 and 8.5 M_S , and for both long, California strike-slip length ruptures and for somewhat shorter ruptures characteristic of Basin-and-Range normal ruptures. The results are shown in the exceedance rate vs peak acceleration curves of figures V.A.-1 to V.A.-5. The figures show the effect of line-rupture models across a wide range of ground motions.

Table V.A-2. Figure Numbers (V.A-n) In Which Given Model Combination Appears

Rupture Length Relationship	Center Max Mag 7.6			Center Max Mag 8.2		
	Boundary Restraint			Boundary Restraint		
	Hard	N/A	Soft	Hard	N/A	Soft
Short (Point)		-, -, -, 5		1, -, -, -		
Medium	-, -, -, -		-, -, -, -	1, -, -, -		-, -, -, -
Long	-, -, -, 5		-, 2, -, 4, 5	1, 2, 3, -, -		-, -, 3, 4, -

The curves represent the results for a generic source, so the yearly exceedance rates have no absolute value. However the contrasts in exceedance rates at a given probabilistic peak acceleration ought to be a good indication of the effect of different models. Peak accelerations near 0.1 g are near those obtained for Portsmouth in our model studies. Curves V.A-1 through V.A-5 do not show any significant differences in exceedance rates near 0.1 g. Peak accelerations near 0.3 g are of interest in engineering considerations for the DOE facilities. We discuss here the differences in exceedance rate ("hazard") at 0.3 g for the various modeling options studied. Table V.A-2 shows the various options modeled and which have been selected for each figure demonstrating a contrast.

Figure V.A-1 contrasts the hazard obtained from short ("point"), medium, and long ruptures in zones of distributed faulting for non-constraining ("soft") source-zone boundaries. The use of soft boundaries and a high center maximum magnitude emphasizes the differences in the effect of different rupture vs magnitude relationships. At 0.3 g, the effect of modeled finite ruptures is to increase the hazard over the point-rupture model by about 30 percent and 50 percent, respectively.

We next investigate the relative role of maximum magnitude and boundary constraints. Figure V.A-2 shows hazard calculated for a constraining ("hard") source-zone boundary with lower center maximum magnitude contrasted with the hazard calculated for a soft source-zone boundary with higher center maximum magnitude. Although the use of long rupture lengths should emphasize the role of maximum magnitude, these combinations should tend to diminish the contrast in hazard between the two cases. Even so, the difference is that the higher maximum magnitude case has an increase of hazard at 0.3 g of about 30 percent.

In the next two figures we investigate the relative effect of change in boundary constraint with change in maximum magnitude. Figure V.A-3 shows the contrast in hazard between the two boundary constraints, using long ruptures and a higher center maximum magnitude. The result is a very minor difference in hazard. At 0.3 g, the difference is less than 15 percent. Figure V.A-4 shows the contrast in hazard between two maximum magnitudes, using long ruptures and the hard boundary constraint. The difference in hazard is about 40 percent at 0.3 g, demonstrating the more dominant importance, in this model, of the role of maximum magnitude.

The source zone in this model is relatively short in the direction of faulting, for long ruptures. Hence there might be less contrast than if the maximum ruptures were a smaller fraction of the length of the source zone. Accordingly, in figure V.A-5 we show the difference in hazard between the two boundary constraints, using long ruptures, but a lower maximum magnitude. The role of difference in boundary constraint is indeed a little greater than in figure V.A-3.

V.A.1.e. Results of generic tests and anticipatory application to the DOE sites.

Although the model used here is for a generic source zone, we can use these figures as guides to the effects at the DOE sites (as mentioned in the introduction to this chapter). That is, we look at variation in ground-motion values near those assessed at the sites at 1000-year return period. We also look at the variation in exceedance rate at 0.3 g peak horizontal acceleration, a value of importance to the safety of the main facility structures. Remember that the conclusions given below apply to the particular circumstances of the generic site inside the zone modeled by generic faults, that is, unknown faults randomly located with a uniform distribution, but oriented in a particular direction.

The illustrations show that,

- (1) At 0.3 g, for sites inside a zone, modeling with generic finite-rupture faults instead of point ruptures increases the hazard by 30 to 60 percent, for a long-ruptures vs magnitude relation and for high zone maximum magnitudes. For a medium-rupture vs magnitude relation, for a zone with a "soft boundary condition", and lower zone maximum magnitudes, the effect may be to increase hazard by less than 25 percent.
- (2) At 1000-yr return period, probabilistic ground motion values at Portsmouth are

generally less than 0.1 g (see sensitivity studies in section VI.B). At this ground-motion value, the increase in hazard obtained by modeling with finite-rupture sources is expected to be less than 15 percent.

- (3) At 1000-yr return period, at Paducah, when a significant contribution to the hazard comes from the "host zone," that is, the zone containing the site (not the New Madrid Fault Zone), and modeling with point sources, probabilistic ground-motion values are around 0.25 to 0.31 g (see later section on sensitivity studies at this site). Modeling the host zone with finite-rupture sources may increase the ground motion by 0.02 to 0.08g.
- (4) Compared to the variability in estimated hazard and probabilistic ground motions from the LLNL and EPRI studies, these above effects in hazard and probabilistic ground motion are small. At Paducah, the effect on median ground motions may be significant for the medium rupture-length relationship in the host zone, if larger maximum magnitudes are likely, say, as with a St. Genevieve Fault Zone. (We believe that long ruptures are unlikely.)

V.A.1.f. General Conclusions

In general, for sites inside a source zone, and using the same attenuation function for all models, finite-rupture models do produce higher hazards than point-rupture models, and hard-boundary models produce slightly higher hazards than soft-boundary models. The hazard results are not strongly different between point ruptures, moderate-length ruptures, and long ruptures, even for ground motions exceeding 1.0 g. This lack of strong contrast with point-source models is largely due to the limited length of source-zone in the rupture direction but also in part due to the assumption of random location of faults. For sites near the boundaries of source zones and for sources which are relatively long in the rupture direction, the contrasts between point-rupture and line-rupture models may be higher. For

real, modeled faults, rather than random faults in a zone, the contrast between point-ruptures and line-ruptures would be even more pronounced.

We conclude that for models having the same conditions as those investigated, that is, generic fault locations and limited zone size in the rupture direction, for moderate-to-low probabilistic ground motions, and for maximum magnitudes smaller than 7.6 M_S , point-source models are acceptable for hazard analysis. Note that this conclusion applies to the Portsmouth site location, but not to that of Paducah.

V.A.2. Point-rupture Model vs Line-Rupture Models In the New Madrid Region

V.A.2.a. Modeling the alternatives

In the New Madrid region, it is possible to conceive a fault zone perhaps two hundred km or more in length, relatively narrow, and with large maximum magnitudes (greater than 8.2 M_S). (See section III.B and figures III-1 and III-2.) The EPRI teams have modeled this area with two types of source zones, one a dog-leg shape, approximating the concentration of seismicity observed in recent monitoring, the other a broader zone encompassing the entire hypothetical rift zone. Figures V.A-6 and V.A-8 show alternative zonations for the dog-leg shape zone and broader zone respectively and the location of Paducah with respect to the zones. Figures V.A-7 and V.A-9 show the range of locations of Paducah with respect to the northeastern terminus of the various source zones. Possible locations of Paducah range from several tens of kilometers within the broad rift zone to several tens of kilometers outside the concentrated seismicity zone. Similar models were investigated in the preparation of the USGS 1982 National Maps (Algermissen, and others, 1982).

In order to demonstrate the effect of finite-rupture modeling, we have used a source of the second type (broad rift zone) and investigated the hazard at a line of sites running from 10 km inside the source to 90 km away. Figure V.A-9 shows the line along which the hazard was calculated. We have used, as before, point sources and "hard" and "soft" boundary rupture models. Again, we have used the Boore and Atkinson (1987) peak acceleration attenuation functions.

Figure V.A-10 contrasts the ground motion hazard results between the use of point ruptures and line ruptures with a "soft" zone boundary. Figure V.A-11 contrasts the results for "soft" and "hard" boundaries. Figure V.A-12 repeats this contrast, but using the Toro and McGuire (1987) attenuation functions. The results show the great contrast in hazard results of the point-rupture vs finite-rupture models inside and near the end of the source zone. However, the further the site lies beyond the end of the zone, the more the rupture-model results approach the point-source results. This effect is less for the soft-boundary model, of course. The illustrations emphasize the great sensitivity of the hazard analysis to the location of the site with respect to the New Madrid fault zone. This sensitivity is more extensively studied later in this report (section VI.C., especially VI.C.5).

V.A.2.b. General conclusions

- (1) Hazard results for large ground motions (greater than 0.3 g) using a point-rupture model do not approximate results using a long line-rupture model and a soft zone boundary until a site is 60 to 90 km from the boundary of the New Madrid source.
- (2) Hazard results for large ground motions (greater than 0.3 g) using a point-rupture model do approximate results using a long line-rupture model and a hard zone boundary by the time a site is 30 km from the boundary of the New Madrid source.

- (3) Probabilistic ground motions (greater than 0.3 g) using a long line-rupture model and a hard zone boundary differ from those obtained using a long line-rupture model and a soft zone boundary by amounts as large as 10 percent for sites closer than 60 km from the boundary of the New Madrid source.
- (4) The above differences will be less for medium-length rupture vs magnitude relationships.
- (5) Probabilistic ground motions (greater than 0.3 g) using a long line-rupture model and the Toro and McGuire attenuation function differ from those obtained using the Boore and Atkinson model by only a small amount for sites outside the New Madrid zone, for both hard and soft zone boundary models. Probabilistic ground motions may differ by 10 percent or more for sites within the New Madrid zone for very large ground motions (greater than 0.6 g).
- (6) Based upon these studies, we expect that probabilistic ground motions for 1000-yr return period, all other things being equal except distance of site from source boundary of the New Madrid fault zone, should range from 0.2 to 0.5 g. Based on considerations of the most likely location of the source boundary, and the effect of the modeling of the "host" zone, most likely hazard values should range from 0.25 g to 0.4 g.

Figure V.A-1. Hazard Curves for Center Maximum Magnitude 8.2 M_S : Curves, left to right represent (1) Short ("Point") Ruptures, (2) Medium-Length Ruptures, and (3) Long Ruptures, with "Soft" Zone Boundaries. The use of soft boundaries and high center maximum magnitude emphasizes the role of different rupture-length relationships.

Figure V.A-2. Hazard Curves for Long Ruptures: Curves, left to right represent (1) a constraining ("hard") source-zone boundary with a 7.6 M_S center maximum magnitude and (2) a soft source-zone boundary with 8.2 M_S center maximum magnitude. This combination minimizes the contrast in hazard between the two maximum magnitude cases.

Figure V.A-3. Hazard Curves for Long Ruptures, Maximum Magnitude 8.2 M_S : Curves, left to right represent (1) Soft Boundary and (2) Hard Boundary.

Figure V.A-4. Hazard Curves for Long Ruptures, Hard Boundary: Curves, left to right represent (1) Center Maximum Magnitude 7.6 M_S and (2) Center Maximum Magnitude 8.2 M_S .

Figure V.A-5. Hazard Curves for Long Ruptures, Maximum Magnitude 7.6 M_S : Curves, left to right represent (1) Point Ruptures, (2) Soft Source-Zone Boundary, and (3) Hard Source-Zone Boundary.

WGC = Weston Geophysical Group
 D&M = Dames & Moore
 LE = Law Engineering
 BG = Bechtel Group
 RAI = Rondout Assoc. Inc.
 WCC = Woodward Clyde Consultants

Figure V.A-6. Generalized sketch of Various EPRI team models for the concentrated-seismicity part of the New Madrid fault zone, showing location of the northeastern terminus of the various source zones with respect to Paducah. Zone configurations are identified as to team and zone number assigned by that team.

WGC = Weston Geophysical Group
D&M = Dames & Moore
LE = Law Engineering
BG = Bechtel Group
RAI = Rondout Assoc. Inc.
WCC = Woodward Clyde Consultants

Figure V.A-7. Generalized sketch of a single generic model for the concentrated-seismicity part of the New Madrid fault zone, showing relative locations of Paducah with respect to the northeastern terminus of the various EPRI team source zones. Relative locations of Paducah are identified by the corresponding team and zone numbers of the previous figure.

Figure V.A-8. Generalized sketch of Various EPRI team models for a broader zone representing the New Madrid rift zone, showing location of the northern boundary of the various source zones with respect to Paducah. Zone configurations are identified as to team and zone number assigned by that team.

WGC = Weston Geophysical Corp.
D&M = Dames & Moore
LE = Law Engineering
BG = Bechtel Group

Rondout Assoc. Inc. and Woodward Clyde Consult.
did not use a comparable seismic zone.

Figure V.A-9. Generalized sketch of a single generic model for the broader New Madrid rift zone, showing relative locations of Paducah with respect to the northern boundary of the various EPRI team source zones. Relative locations of Paducah are identified by the corresponding team and zone numbers of the previous figure. Line beginning 10 km inside this zone and extending outside it to the northeast is locus of sites for which hazard analysis has been made for this study.

Figure V.A-10. Probabilistic ground motions (having 90 percent probability of non-exceedance in the labelled exposure times) for sites on a line running from 10 km inside a broad New Madrid rift zone source to 90 km outside the source. Point ruptures, dashed lines. Long ruptures/soft boundary, solid lines. Sites are labelled by location from beginning of line. (1000-yr return period values corresponds to lines labelled 100 years.)

Figure V.A-11. Probabilistic ground motions (having 90 percent probability of non-exceedance in the labelled exposure times) for sites on a line running from 10 km inside a broad New Madrid rift zone source to 90 km outside the source. Long ruptures/hard boundary, dashed lines. Long ruptures/soft boundary, solid lines.

Figure V.A-12. Probabilistic ground motions (having 90 percent probability of non-exceedance in the labelled exposure times) for sites on a line running from 10 km inside a broad New Madrid rift zone source to 90 km outside the source. Long ruptures/hard boundary, solid lines. Long ruptures/soft boundary, dashed lines. Calculations use Toro and McGuire attenuation functions rather than that of Boore and Atkinson.

V.B. Assumed Depth of Origin for Ground Motion

The distance from the earthquake energy source to the site is a controlling factor in determining the ground motion at that site. Inasmuch as the depth to the energy source is a component of the distance from the source to the site, the role of depth in determining ground motion from an earthquake can be very important. How important the depth is depends jointly on several factors—the size of the rupture, the depth of the *hypocenter* of the earthquake, and the distance of the site from the rupture.

The *hypocenter* is that part of the earthquake rupture that generates the seismic energy that produces the first motion on the seismograph records of that earthquake. For an extended rupture, the hypocenter may be very different from that part of the rupture which produces the largest ground motion at a site. There are physical arguments for supposing that the rupture propagates toward the surface from the hypocenter rather than deeper than the hypocenter. Although this is not a fixed rule, in general one would expect that some portion, maybe a major portion, of an extended rupture will lie shallower than the hypocenter. A site nearby on the surface is closer to the shallower parts of this extended rupture, and so one would expect that the energy source of the strongest motion at the site comes from a portion of the rupture that is closer and shallower than the hypocenter.

If the rupture is small, as with a small-magnitude earthquake, the depth of the hypocenter is very close to the depth from which the energy producing the peak ground motion comes. If, then, the site is close to the rupture, the hypocentral depth dominates the size of the distance to the site, and, hence, the hypocentral depth has great influence on the size of the ground motion at the site. If, on the

other hand, the site is far from the rupture, the depth is such a small component of the distance to the site, that hypocentral depth is of no significant influence on the size of the ground motion.

If the rupture is large, the hypocentral depth may not be a very good indication of where the major amount of energy is coming from. For sites close to the rupture, the source of the peak ground motion is likely to come from some location relatively near the surface, because even if larger amounts of energy are produced deeper on the rupture, the energy from deeper may attenuate more because of the increased distance to the site, and not produce as large a peak ground motion at the site. Again, for sites far from the rupture, the range of possible depths is such a small component of the distance, the depth of the source of the peak ground motion energy is of little or no importance.

Depth of energy is thus important for sites close to the rupture; this means not only for the hazard of relatively large ground motions, but also for the contribution of small and moderate earthquakes to the hazard of moderate ground motions.

V.B.1. Observed Depths in the Eastern United States.

V.B.1.a. Focal depths in hypocentral determinations.

Focal depths are in general very uncertain. The accurate determination of depth in routine earthquake location requires a recording station close to the earthquake (*close* means within a distance from the epicenter about equal to the focal depth). In the eastern United States, except for closely-spaced networks, placed for special studies, seismic stations are much too widely spaced for routine accurate determination of depths for most earthquakes.

As a result, we have to depend upon generalizing from information obtained from seismic networks or from other special studies to assess the typical range of hypocentral depths for earthquakes appearing elsewhere in the eastern United States. The hypocentral depths of the larger historical earthquakes of the past are completely unknown. The hypocentral depths and rupturing extent of future large earthquakes in the eastern United States can only be inferred.

In much of the eastern United States, the hypocentral depths of earthquakes currently being monitored by networks range from near the surface to 5 to 10 km (see, for instance, Marone and Scholz, 1988). Large earthquakes would have to have larger ruptures than those earthquakes currently monitored, and hence may have rupture depths, and possibly hypocenters, down to the greatest depths at which seismogenic ruptures can be sustained, perhaps 15 or 20 km, or more in some special cases.

V.B.1.b. Depths Inferred by other means.

Using a method depending on the location of a spectral minimum in the Rayleigh-wave motion, Herrmann determined depths in the range 1.5 to 22 km. (These would have to refer to average rupture depth rather than hypocentral depths.) Seventy-five percent of the earthquakes studied had depths between 5 and 16 km (referenced in Nuttli and Herrmann, 1978).

V.B.2. Inferences on depth of origin for strong ground motion.

For strong ground motion, we expect the source energy center to lie shallower than the hypocenter, but not shallower than the depth above which it is unlikely for the material to sustain high stress. This depth may be 3 to 5 km except where basement rock is shallower.

The larger the earthquake, the larger is the expected vertical and horizontal extent. As a result of these considerations, we expect the smaller-magnitude earthquakes to lie distributed about the average hypocentral depth or slightly shallower, say, in the range of 5 to 10 or 12 km. For larger magnitude earthquakes, which would have large rupturing extent, and hence likely to rupture to the top of the seismogenic zone, we would expect the effective depth to be as shallow as 3 to 5 km (or shallower).

V.B.3. Anticipated effects for hazard analyses at the sites.

V.B.3.a. Anticipated effects as a function of frequency of ground motion.

Hazard values for high-frequency ground-motion parameters, like peak acceleration, are dominated by the contribution of small-to-medium magnitude earthquakes, at least for low-to-moderate ground motion values of the sort of interest in the site hazard studies for Portsmouth and Paducah. Accordingly, we would expect the hazard analyses for high-frequency ground motions to be sensitive to the choice of depths used. In the sensitivity studies for the individual sites, found in a later section of this report, we have used a standard depth of 7 km, to reflect a reasonable depth for the small-to-medium magnitude earthquakes. Depths of 3 km and 10 km have been used as alternatives in sensitivity tests.

On the other hand, hazard values for long-period ground-motion parameters are usually dominated by the larger, more distant earthquakes. Accordingly we would expect the hazard analyses for long-period ground motion to be relatively insensitive to choice of depth.

V.B.3.b. Comparison with results of sensitivity tests.

The effect of depth on the hazard estimate for high-frequency ground motions in these sensitivity studies is that the effect of changing depths between a nominal 7 km and 3 or 10 km is often as great as the effect of changing maximum magnitude by plus or minus 0.6 magnitude units, respectively. (Both comparisons are found in the sections presenting the initial sensitivity studies for each site, VI.B.3 and VI.C.3, for Portsmouth and Paducah, respectively.) For 1.0 second response, as anticipated, the effect of changing depth was very low at either site for 1000-yr return period ground motions. (However, the effect of varying maximum magnitude was now substantially larger than the effect of varying depth.)

V.B.3.c. Size of possible underestimate for probabilistic ground motion values.

The Risk Engineering study used depths ranging from 2 to 22 km. If the distribution used were symmetric about some central value, say 12 km, we might expect that for the higher ground motions, there would be a significant (say, factor of 2) decrease in hazard compared with placing all of the depths at less than 12 km. At moderate-level ground motions the relative contribution of close, low magnitude earthquakes and larger, more distant earthquakes is complex; and it is difficult to estimate the extent of decrease in hazard. However, the sensitivity studies suggest that for both sites, at ground motions having return periods of 1000 years, the effect of depth is *small* compared to the observed range of alternative hazard estimates.

V.B.4. General Conclusion.

In general, we expect that the role of depth may generally be a smaller source of uncertainty

than the determination of zone boundaries, seismicity parameters, or likelihood of zone existence. Except for long-period ground motion at Portsmouth, the effect of varying depth is comparable to the effect of varying maximum magnitude in the host zone by plus or minus 0.6 magnitude units.

V.C. Maximum Magnitude

Maximum magnitude can be an important parameter in seismic hazard calculations, because the magnitude influences both the size of the earthquake ground motions that can be experienced and the size of the area over which those moderate level ground motions are experienced. As we have demonstrated in the section on line-rupture sources (V.A.1), long ruptures greatly extend the area over which damaging ground motions can be experienced. Inasmuch as rupture length is an exponential function of magnitude, it is reasonable to expect that maximum magnitude would have a profound effect on the hazard associated with moderate-to-large ground motions. In our sensitivity studies for both the Portsmouth and Paducah sites, where the probabilistic ground motion at 1000-year return period is about 0.1 and 0.3 g respectively, we need to test how important the choice of maximum magnitude may be. In those tests we allow the maximum magnitude to vary over a reasonable range in order to show the difference in hazard attributable to changes in maximum magnitude. Below we address the general problem of what is a reasonable range of maximum magnitudes and how seismic hazard can be assessed in view of this range of uncertainty.

V.C.1. Maximum magnitude is poorly determined in the eastern United States.

In the western United States, relationships between fault lengths and magnitude can be used to guide in the estimation of maximum magnitude. Furthermore, the frequency of earthquake events is sufficiently high that there is a good chance that the maximum magnitude earthquake has actually been experienced during historic times along some segments of the known active faults. For the eastern United States, however, very few active faults are known, and the rate of earthquake occurrences is about one-tenth of that in California. *Therefore, in the eastern United States maximum magnitude is a very poorly defined parameter.*

V.C.1.a. Some large magnitude earthquakes do not correspond to known structures.

In the eastern United States, earthquakes of magnitudes (M_S) 6 to 7.5 are known to have occurred at locations in which there is no clear association with a causative fault or tectonic feature. Accordingly, it is prudent to assume that magnitudes in this range are at least possible in other areas where the tectonic causes of earthquakes are unknown. In the light of such considerations, the U. S. Geological Survey cautioned the Nuclear Regulatory Commission that earthquakes of the size of the 1886 Charleston earthquake (magnitude estimated to be 7.0 to 7.5 M_S) could not be excluded from being possible at other areas along the eastern seaboard. (USGS letter to NRC, Nov 18, 1982.)

V.C.1.b. The maximum observed zone earthquake magnitude is not a helpful parameter.

Although, in the past, maximum magnitudes have sometimes been assessed according to the maximum earthquake experienced historically in individual seismic source zones, in general, we believe that it is a mistake to look at the largest historical earthquake in a limited area and use the magnitude of that earthquake as a maximum magnitude for zones in that area. Virtually no source zone has had a sufficient number of historical earthquakes to make a statistical case that the maximum observed magnitude can be a reliable indicator of the maximum possible in that zone.

V.C.1.c. The maximum magnitude either in a region, or for a source zone, is not only poorly determined, but also uncertain over a relatively wide range.

Figure V.C.1 shows the wide range in maximum magnitudes assessed by LLNL experts for the complementary zones, zones for which no tectonic principle has been urged to support any given magnitude estimate. (See, however, in figure V.C.-2, the somewhat narrower range in which the EPRI/SOG place maximum magnitudes for background zones.)

V.C.2. Maximum magnitude uncertainty can be modeled by center maximum magnitudes of symmetric distributions, with values ranging between 5.5 and 7.3 M_S .

Hazard assessment under this uncertainty is facilitated by the following fact. *We have observed that the hazard result obtained by integrating over the uncertainty of symmetric maximum magnitude distributions is approximately that obtained by using the center magnitude of the uncertainty distribution.* For example, if we represent the uncertain

maximum magnitude of a source zone by a symmetric distribution between 5.6 and 6.6, the approximate hazard result can be obtained by calculating the hazard for a maximum magnitude of 6.1. Given that the maximum magnitude is highly uncertain, it is no great restriction to assume a distribution of maximum magnitude which is symmetric. *Accordingly, in our sensitivity studies, we often let the maximum magnitude for ordinary source zones not associated with known faults or individually modeled faults range between values of 5.5 to 7.3, where these values represent center magnitudes of symmetric distributions which may range more widely than this. Maximum magnitudes in these ranges represent fairly well the uncertainty distributions used in the EPRI/SOG and LLNL studies. Our sensitivity studies, then, ought to give a reasonable range with which to bound the effect of maximum magnitude on probabilistic ground-motion hazard estimates.*

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Figure V.C.-1. Probability curve showing choice, for LLNL experts, of maximum magnitude, m_b , used in complementary zone. Graph shows percent of LLNL experts using a maximum magnitude whose value is equal to or less than the plotted value. (Note: one LLNL expert, not included, used a wide range of values for maximum magnitude, depending on the location of the complementary zone.)

Figure V.C.-2. Probability curve showing choice, for EPRI/SOG experts, of apparent center maximum magnitude, m_b , used in background zone. Graph shows percent of EPRI/SOG experts using a center maximum magnitude whose value is equal to or less than the plotted value.

V.D. Means, Medians, and Other Best Estimates

In order to understand the range of uncertainty in the estimate of hazard at a site, both the EPRI and LLNL methodologies utilize multiple experts at certain stages of their assessments. Given the range of uncertainty in the resulting hazard estimates, there remains a concern about what value in that range constitutes a best estimate for the application intended. The issue of which estimate to use can be a source of controversy. We believe it is useful to express at least some of the issues in order that any controversy will be illuminated by points of view which might otherwise go unexpressed.

V.D.1. The meaning of a mean.

V.D.1.a. Mean as minimum square residual estimate for location.

The *mean* is most usually understood as the *average value* of a set of observations. It corresponds to a least-squares estimate of a "location" parameter for the set the sample measurements represent. A least-squares estimate seeks to minimize the square of the differences of the observations from the value of the estimated location. Another way of speaking of the least squares estimate is to call it an estimate based upon a *quadratic penalty*. There is nothing natural about a quadratic penalty. However, the least-squares estimate, unlike the estimate for a linear penalty, is unique, and can be calculated without a set of successive approximations (see, for instance, Gentle, 1977). Furthermore, the least-squares estimate corresponds to a squared error law, and squared residuals can be partitioned nicely in certain statistical studies. These useful properties account for the popularity of least-square estimates.

V.D.1.b. Mean as expected value under uncertainty.

So far we have stated nothing to indicate that the means of the constituent hazard estimates of the EPRI or LLNL processes should be used to represent the hazard at a site. However, the mean also corresponds to the *expected value under uncertainty*, when samples are drawn from a variable having some probability distribution. Since the methodologies seek to represent all the uncertainties in hazard analysis, the use of a mean hazard estimate seems congruent with that aim.

V.D.1.c. The mean compared with median or most likely value estimate.

For certain classes of distributions, this expected value also corresponds to one of the parameters of a defined distribution. For instance, for symmetric, unimodal distributions, the mean corresponds to the middle or *central* value (or *median*) of the distribution, and also the *most likely value* of the distribution. In an intuitive sense, a value which is simultaneously the most likely value, the central value, and the expected value seems to be a reasonable "best" estimate.

On the other hand, for unimodal distributions which are *asymmetric*, the mean value lies on one side or the other of the most likely value and the central value. For certain asymmetric distributions, like the log normal distribution, the central value of the distribution is also the most likely value. It is reasonable to consider, then, that the central value and most likely value constitute in some sense a best estimate, even though neither of these values is the expected value (mean).

For other distributions, the central value, the mean value, and the most likely value may all differ, for instance bimodal distributions. Consider, for example, a *symmetric* bimodal distribution. The mean and the central value are

the same, but there are values to either side which have both greater likelihood. The mean is relatively unlikely. In what sense can it be a best estimate?

Consider next an *asymmetric* bimodal distribution. The mean may not have the greatest likelihood nor be central. The median may not be the expected value or the most likely. The most likely value may neither be central or expected. Which is the best estimate? Possibly the peak of one mode of a bimodal distribution may be neither the central, expected, or most likely value, but this peak value might be the preferred value if it corresponds to a suitably conservative estimate. It is possible that a best conservative estimate for some application is one whose fractile is not 0.5, as with the median, but rather 0.9.

These questions will be explored further in Sections V.D.2 and V.D.3, when we consider the issue of best estimate in the context of particular applications.

V.D.1.f. Outlier removal and trimmed means.

Many times in estimation it is found that unlikely data or blunders, which are far from the central value, are present in the data. Because of the quadratic penalty inherent in the mean, these "outlier" values have a powerful effect on the computed mean. To prevent this effect, means are often calculated with outliers removed, with an equal number of values removed from each end of the ordered set of data (trimmed means), or with these end values replaced with multiples of the next closer values (Winsorized means). (See Kendall and Stuart, 1973.) These measures render the mean more "robust" with respect to outliers; that is, less likely to change. In recent work, robustness in a location estimate is obtained by alternative measures, for instance, by a rule in which the penalty is other than quadratic (as with a least absolute deviation estimate, for

which the penalty is linear rather than quadratic). Robustness can also be obtained by using "influence" functions which reduce the contribution from outlying values by means of weights which are a function of how far the value is from a central value. (See Hampel and others, 1986, Hoaglin and others, 1983, Hoaglin and other, 1985, and Huber, 1981.)

V.D.2. The mean when the variability is due to fundamental uncertainty.

In V.D.1 we discussed some considerations of means under the condition of data measurement. In data measurement we presume that the source of a difference in measurement is assumed to be error in observation or uncertainty in measurability. It is possible that the variability is due to fundamental variability in the process which produces values. Let us consider two examples.

V.D.2.a. Ground motion example.

The variability of ground-motion values around a predicted value at a given distance from a certain magnitude earthquake is said to be log-normally distributed. That is, if we take the logarithm of the ground-motion values observed, the log values are observed to be normally distributed around a value which is the mean (of the logs), central, and most likely. The mean of the ground motion itself is larger than the anti-log of the mean value of the log ground motion. This mean ground-motion value is neither central nor most likely, but it is an expected value.

In what sense might this mean value be a best estimate value? Only in the sense that if we use this value a quadratic penalty is paid for the amount we were wrong in either direction. Suppose, for instance that too much overdesign is expensive, maybe impossible if requirements are too high. Too much underdesign may be catastrophic. A quadratic penalty represents a

strong incentive to avoid large over- or under-estimates.

On the other hand, perhaps a quadratic penalty does not correspond to the real penalty involved in using a "wrong" value. Perhaps we would pay a rather low penalty for over-estimation (if it were only marginally more expensive to over-design the structure), and a low penalty for underestimation (because of some large inherent safety factor), but a very great penalty for severe underestimation, if breakage, loss of function, or catastrophe were to occur. Note that the penalty is not only not quadratic, it is asymmetric, and this is just the situation in which we would expect a conservative estimate to be appropriate.

V.D.2.b. Earthquake Inter-occurrence time example.

Consider another example. Suppose that the empirical distribution of the length of time between earthquakes which cause damage at a city is found to be unimodal and strongly asymmetric toward long inter-occurrence times. The most likely inter-occurrence time is, say, about 2.5 years, but the mean inter-occurrence time is 4.5 years. Suppose also that the value 2.5 is much *more* likely than the times shorter than 2.5, but the value 4.5 is not much *less* likely than 2.5. In what sense is either of these values a best estimate? To forecast the next date of an earthquake damaging that city, which of these values should be used?

One could say "two-and-a-half years is the most likely time, but I don't *expect* such an event for four-and-a-half years." But what does this statement imply for mitigation action? There could exist a situation in which one hopes to complete some anti-seismic construction before the next damaging earthquake, and there would be some penalty for being late (not finishing before the next earthquake), and little or no penalty for being early (finishing before the next earthquake).

The early estimate (the most likely value) might then be the best estimate. Suppose instead there were an extraordinary effort required to finish before the earlier estimate, but normal effort to finish before the longer estimate. The near equivalence in likelihood between the early estimate and the later, expected value estimate suggests, in this case, some kind of cost-benefit analysis to select the "best estimate."

V.D.2.c. The most useful estimate may be the best estimate.

In both the examples above, the variability in the observations is not due to lack of precision in measurement, but rather to the natural variability of the process itself. Furthermore, it is not clear in either case that the mean value is to be preferred over any other estimate of location. It seems more likely that the nature of the estimate to be preferred, probably depends on the use to which the estimate is to be put. More specifically, it is not clear that the mean as the "expected value under uncertainty" is to be preferred.

V.D.3. The mean when the variability is due to scientific uncertainty.

In V.D.2 we examined the mean when the values we were considering were part of a measurement process, but for which the variability in observations was not primarily an error in the measurement process, but inherent variability in the phenomenon. Suppose instead, that we are not concerned with measurement but with *opinion*. Suppose we expect variability to be due to greater or lesser degrees of expertise. Does either the mean, median, or most frequent value of opinion represent a best estimate? Probably we would seek for some indication of the greatest expertise, rather than a central measure.

V.D.3.a. Argument based on stability of estimate.

If we expect variability to be due to differences in philosophy by which the opinion is arrived at, we would not expect that the common measures have anything to do with best estimate. Consider the crude example of what is the best estimate of "fruit size." One sample value is that of an apple, one is that of an orange, one is that of a coconut, one is that of a pineapple. If one were to obtain one of the classic measures from this set, what would be the effect of adding a cranberry to the set, or a watermelon? As we add more and more fruits to the set could we expect any tendency to stability in a mean value unless a very large, hopefully exhaustive set were assembled? A median or most likely value is likely to arrive at stability sooner than the mean.

V.D.3.b. The nature of the outliers causing instability.

What makes the mean an unstable estimate is its strong sensitivity to outliers, values which lie outside the clustered range of estimates, and whose inclusion greatly shifts the value of the mean. If one were collecting a set of citrus-size fruits, the inclusion of a watermelon would be an outlier. In opinion, it is not clear that a clustering tendency is a virtue, if the clustering is the result of a common, though incorrect, point of view. Likewise it is not clear that an outlier is "wrong," or a blunder, for this opinion could be the result of a rare, but insightful and correct thought process. If it is not possible to determine from closer observation which opinion is correct, the location measures have a descriptive character, like "consensus," "median," "F-th fractile" but not a clear meaning such as best estimate of an underlying distributional parameter.

V.D.3.c. Does expected value have meaning for opinion?

It is not even clear that the mean *opinion* has a real meaning such as "expected value under uncertainty," but rather "expected value under the process of sampling opinion." If there are two different methods of assessing opinion, it is very likely that the "expected values" will have no reason to reach a common value. (In statistical language, when two estimates do not trend to a common value as the sample size increases, the two estimates are said to be "inconsistent.")

V.D.3.d. Application to the two sites.

In comparing the EPRI and LLNL results at Portsmouth and Paducah, we find that the LLNL results across experts have more variability than the EPRI results across teams. Because the distributions of hazard estimates resulting from these opinions is asymmetric and skewed toward higher values, necessarily the mean of the LLNL results is larger than the mean of the EPRI results, even when the median value is the same. Furthermore, we find that when ground-motion expert 5 is removed, the LLNL mean changes greatly, although the median result does not change much. *These two observations argue that the median is at least a more stable estimate of hazard than the mean, being both consistent and robust, and for these reasons ought to be preferred to the mean.*

V.D.4. Mean and median hazard compared to hazard from historical seismicity.

V.D.4.a. Multiple zonations produce an effective net areal seismic rate less than that of the concentrations of historical seismicity.

In reporting on the LLNL work at the Third United States National Conference on Earthquake Engineering, Jean Savy showed curves which included results obtained using the USGS 1982 model source zones. These results fell in the upper fractiles of the distribution of LLNL estimates for many sites characterized by having historical seismicity in the vicinity. In the eastern United States, the USGS 1982 model used zones based primarily on containing historical seismicity. We conclude from this that the effect of the zonations in the LLNL methodology was generally to decrease the areal concentration of the historical seismicity. This is only natural, for if one does not zone closely on seismicity clusters, whatever zones one uses must contain both active and inactive areas, and hence, if one uses homogeneous source zones, the resulting zone seismic rate per unit area must be less than that of a zone encompassing the historical seismicity.

V.D.4.b. Multiple zonations produce an effective net areal seismic rate greater than that of areas of sparse or no historical seismicity.

If a site is characterized by little or no historical seismicity in the vicinity, some of the alternative zones will bring seismicity closer to the site than if the historical seismicity were zoned in place. This will result in higher hazard estimates than would be obtained by using zones encompassing historical seismicity.

V.D.4.c. Hazard from the historical seismicity as reference estimate.

Is a hazard estimate resulting from a zonation based on historical seismicity a best estimate? It is a *consistent* estimate, that is, if one waited long enough, the historical seismicity would represent the effect of a stable seismicity process. It is a *conservative* estimate in the cases of sites located in regions of historical seismicity, where the estimate falls in the upper fractiles of opinion. However, in the case of sites far from historical seismicity, zoning on historical seismicity would produce lower estimates than would be achieved in multiple zonations. In this case the historical estimate is not conservative. Furthermore, the historical estimate will not be a consistent estimate where data are sparse and where there is a reasonable basis to assume that seismicity ought to extend along tectonic or geologic features.

Although the median estimate of opinion is more stable than the mean, it is not clear that it is a best estimate in comparison with the historical estimate. One often finds that the mean estimate is a higher fractile estimate and hence close to the historical-basis estimate for sites in relatively seismic areas. In this case the mean is a better estimate than the median, taking the historical estimate as standard. However, because the historical-basis estimate could lie in lower fractiles for low seismicity sites, and the mean can only lie among the higher fractiles, the mean estimate has only one constant characteristic—it is conservative.

If one considered a set of, say, ten sites which have identical true hazard, historically, each would be subject to the vagaries of earthquake occurrence in a short period of time. In this sense, the historical hazard estimate, although consistent, is, in the short term, unstable. Estimates obtained from multiple alternative zonations are likely to be more stable, even though they may more slowly converge under increasing amounts of data.

V.D.5. Mean hazard when the tail of the attenuation variability distribution is the dominant contributor to the hazard.

One of the most prominent characteristics of the hazard curves produced by the EPRI and LLNL calculations is the strong asymmetry, biased to the larger hazard estimates. This asymmetry becomes increasingly strong at decreasing probability levels. At these levels the hazard estimates are strongly dominated by the role of attenuation function uncertainty. At a given magnitude and distance the attenuation function gives a ground motion whose distribution is approximately log-normal, with a standard deviation equivalent to a factor of about 2. At very low hazard levels, ground motions are produced that are a factor of 2 to 4 times larger than the highest ground-motion level which would be calculated without attenuation function uncertainty. These extreme ground motions strongly drive the mean values.

V.D.5.a. Origin and nature of ground motions in the low-probability hazard estimates.

One should contrast the usual hazard calculation with a hypothetical case in which a probabilistic ground-motion estimate is produced without taking into account attenuation function variability. Having obtained the ground motion at a given hazard level, then consider the variability around that ground motion. In the hazard analysis which takes into account attenuation variability as you go along, exceedances of the median ground motion at any magnitude come not just from the variability in ground motion of earthquakes of the given magnitude but also from the upper extremes of the variabilities from lower magnitudes. Peak ground motions from lower magnitude earthquakes do not have the same predominant periods or capacity for damage as

peak ground motions from higher magnitude earthquakes, even at the same ground-motion values. It appears, therefore, that the use of a mean hazard value which is strongly driven by extreme hazards exaggerates the contribution of higher frequency effects which could be of lesser importance in seismic design of longer-period structures. Avoiding this exaggeration could be considered an argument for avoiding mean values.

V.D.5.b. Mean ground motion at a given hazard probability level.

We note that in another section of this review we have discussed the difference between the curve showing mean ground motion at a given hazard probability level vs the curve showing mean hazard at a given ground-motion level. In the latter case, the mean curve is strongly affected by the wide range in hazard values and is considerably different from the median curve, for the LLNL values. On the other hand, the curve showing mean ground motion at a given hazard value lies much closer to the median curve.

V.D.6. Estimating a mean and standard deviation, when a datum is assumed in error or a blunder.

V.D.6.a. Trimmed or Winsorized means.

In routine work, where data are assumed to have large errors only in small proportion of the sample, "trimmed" or "Winsorized" means are often calculated. Trimmed means are calculated after removing an equal number of observations from each end of the ordered sample of values. Winsorized means replace the removed observations with a suitable multiple of the lowest and highest observations left in the distribution.

It seems obvious that removing expert 5's ground motion from the high-hazard end of the

LLNL distribution will strongly decrease the mean. LLNL staff do not argue for removing a compensating observation from the low-hazard end of the distribution, and as a consequence, an estimate of the mean obtained by this process would be too low. To compensate for single-sided trimming, a "Winsorized" estimate has been advocated (see discussion in Kendall and Stuart, 1973) in which, as before, the removed value is replaced with the next-in value, but a fractional multiple of the extreme value at the other end is also added in. The multiple chosen is selected so as to minimize bias if the unknown distribution were a normal distribution.

V.D.6.b. Fractile estimators of mean and variance.

Efficient estimators of the mean and variance are also obtainable from fractiles of the data. Choices of linear combinations of certain fractiles of the data other than the median offer estimates which are less sensitive to outliers than the mean, but provide a more efficient use of the data than does the median. ("Efficiency" is a statistical concept reflecting the information content of an approximate estimator compared to that of an estimator which is optimal when the data have a given assumed distribution. See particularly Andrews and others (1972) for extensive trials on various estimators in terms of their efficiency and resistance to outliers.)

If the hazard estimates are approximately log-normally distributed, it is possible that the parameters of the log-normal distribution could be robustly determined from the data, using robust methods on the logarithm of the hazard data, and a robust mean estimate calculated for the hazard by the usual formula,

$$\text{mean} = \exp(\mu + 1/2 \sigma^2),$$

where μ is the mean of the logarithm of the hazard values and σ is their standard deviation.

LLNL reports "pseudo-means" as well as means and medians. We presume that methods similar to those mentioned above are used, and we think such a pseudo-mean is an appropriate way to handle outlier estimates. (See the annotation for the reference Hoaglin and others (1983) for a further note on use of medians vs trimmed means.)

V.D.7. Conclusion.

Use of medians is a pragmatic and stable method of assessing best-estimate hazard value at the two sites studied, with due regard for the value of assessing estimates based on historical-based zones, considering the role of means as "expected values under uncertainty" as well as conservative estimates, and the need for investigation of the expertise and philosophy involved in apparent outliers.

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VI. Comparison Studies

by

David M. Perkins

Summary

The purpose of the USGS comparison studies is (1) to test the sensitivity of standard models at the sites to the generic model and parameter issues discussed in the previous section, (2) to identify those modeling issues most critical to the site, and (3) to identify a range of values in which to expect site hazard values to lie.

For the Portsmouth site, a 1000-yr probabilistic peak acceleration value of 0.082 g represents both the mean and median value of reasonable alternative values obtained in our studies. For the attenuation function used here, individual probabilistic ground-motion values for various combinations of assumptions could range plus or minus 0.04 g about this median value, or about plus or minus 50 percent. In addition, at these ground-motion levels, a variation of up to 50 percent might be expected owing to different choices of attenuation function. Our hazard curves lie in the higher fractiles of those curves given by the consultants. This effect could be expected if the site were in the vicinity of historical seismicity and if in this case the use of multiple alternative zonations had the effect of decreasing the net areal rate of seismicity near the site. Our use of fuzzed historical seismicity to obtain a hazard estimate seems to indicate some influence by nearby seismicity, although probably not at the size expected to account for the wide range of values between the USGS estimate and those of the median values for the EPRI/SOG and LLNL methodologies. It is likely that other systematic factors are at work. In section VIII we explore some of these factors, whose effect seems to suggest that the median hazard estimates of the EPRI/SOG methodology, 0.025 g, (and other spectral ordinates) are in the low range of reasonable estimates for the Portsmouth site, while the USGS

values are in the high range of reasonable estimates for the Portsmouth site.

For Paducah, a reasonable range of 1000-yr peak accelerations from our comparison studies has a median of 0.32 g and a mean of 0.38. The values range from about 0.26 g to 0.72 g. The EPRI/SOG and LLNL median results fall in the lower part of this range. In the light of this comparison study and the fact that some of the EPRI/SOG and LLNL zonations place Paducah very near or within the NMFZ, it is clear that the point-rupture assumption has had an important role in keeping these ground motions low. On the other hand, many of the zonations place the northern terminus of the NMFZ source far from the site. For the farthest locations of this terminus, the point-rupture assumption may not be greatly in error (see section V.A). Risk Engineering has modeled the NMFZ earthquakes as linear ruptures rather than point ruptures, obtaining a median 1000-year peak acceleration of 0.31 g. However, for the Risk Engineering model, strong ground motion is concentrated toward the interior of the rupture, hence, even though a rupture may run several kilometers past the site, the portion of the rupture contributing strong ground motion may not be close to the site. Therefore, we believe that the Risk Engineering model should be demonstrated for ruptures proceeding 40 or so kilometers beyond the site. Nevertheless, we believe that the *median* Risk Engineering values are very reasonable values to use for design for the Paducah site.

Introduction

In this section we address the sensitivity of the hazard results to various generic assumptions in the modeling as they apply to the specific

sites. Thus we test the role of maximum magnitude and depth at both sites. At Paducah we also test the role of rupture modeling both for the New Madrid fault zone and the "host" zone, that containing the site. In addition to these generic issues, we also provide site-specific alternative results based on alternative zonations or alternative treatments of data or treatments of zonations, in order to address both bounding the hazard and sensitivity to critical issues in modeling.

VI.A. Philosophy of Comparisons.

Before describing in more detail the nature of the modeling done by the USGS review group, it is useful to provide a context for that modeling by characterizing the approaches to modeling used by the DOE contractors.

VI.A.1. LLNL Models

The LLNL zones are relatively freely drawn to represent the individual experts' ideas about possible sources. The context is generic, that is, for the most part no particular site is focussed on, except perhaps for the vicinity of the Charleston, South Carolina earthquake of 1886. The LLNL zones are for the most part drawn rather broadly, occasionally with concentric zones to represent alternative boundaries. The modeling of source is by point ruptures. Our generic studies have shown that the use of point ruptures in the eastern United States is generally adequate, except in the vicinity of the New Madrid fault zone.

VI.A.2. EPRI/SOG Models

The EPRI/SOG models were allowed to be freely drawn, but for the most part teams sought to represent a large number of the possible tectonic features which were developed as candidates in a series of joint meetings. As a result the zonation is somewhat

constrained by the tectonic features, except insofar as teams sought to provide broader tectonic alternatives or default areas. Because of the general constraint, the EPRI/SOG zones tend to be smaller than those developed by LLNL. Again there is no particular site context, except for Charleston and perhaps a few other areas which may have been of special interest to the teams because of regional or local expertise or because of site consultations they may have done in the past. Again, the source modeling is by point ruptures.

VI.A.3. Risk Engineering Models

The Risk Engineering models were intended to respond to the necessity of representing the New Madrid fault zone seismicity with finite-rupture source models. In order to briefly represent the zonations of both the LLNL and EPRI studies, only insofar as they would affect the Paducah site, four alternative locations were chosen for the northern terminus of possible New Madrid fault ruptures. The zone in which the site was located ("host zone"), however, was modeled as one zone with point sources. This study was not intended to incorporate all the variability of the LLNL and EPRI studies, but only that aspect relating to the modeling of the New Madrid fault zone.

VI.A.4. USGS Models

The purpose of the USGS studies was (1) to test the sensitivity of standard reference models at the sites to the model and parameter issues discussed previously in section V for generic sites, (2) to identify those modeling issues most critical to the hazard assessment at the site, and (3) to identify a range of values in which to expect site hazard values to lie.

As a standard reference model we used the USGS sources which had been previously developed for the 1982/1990 national probabilistic ground motion hazard maps

(Algermissen and others, 1982, 1990). These sources, in the eastern United States, were primarily designed to constrain historic seismicity near the observed location of that seismicity by using zones that incorporated apparent geological correlations with the seismicity. Few clearly *tectonic* associations with historical seismicity could be made, except for the New Madrid area and several other, local areas where certain faults were presumed active as a result of studies supporting nuclear power plant applications.

Additional alternative zonations were attempted in order to discover how these might affect

hazard analyses and whether certain particular zonation alternatives would prove to be of primary or secondary importance in establishing hazard levels. Thus, beginning with a national context, alternatives were developed to address these two specific sites. Modeling of ruptures was by point ruptures except for the New Madrid fault zone and the zone in which the site was located ("host zone").

These characteristics of the USGS models and those of the DOE contractors are summarized in table VI.A-1.

Table VI.A-1. Summaries of the approaches in zoning and modeling.

	LLNL Models	EPRI Models	Risk Engineering Models	USGS Models
Zonation boundary constraints	Free	Free, but often constrained by tectonic features	Represent relevant features of LLNL and EPRI models	Constrained by historic seismicity or geology
Site Context	No site context	No site context	Site context	Site context for sensitivity analysis
Zone size	Large	Mostly small	Large	Large
Expression of zone-boundary uncertainty	Sometimes alternative boundaries	Usually alternative tectonics	Alternative boundaries for New Madrid Zone, only	Alternative boundaries and tectonics or fuzzy boundaries
Source rupture model	Point-rupture sources	Point-rupture sources	Point-rupture and line-rupture sources	Point-rupture and line-rupture sources

VI.A.5. Differing approaches in USGS comparison studies.

VI.A.5.a. Portsmouth approach.

For Portsmouth, we believe that there is little basis for a definitive zonation based on any known tectonics. Zonations from various teams or experts would therefore be relatively idiosyncratic, based upon any particular analyst's attempt either to constrain the historical seismicity in place or to express an

opinion about possible geological association with seismicity which might signal some unknown tectonic connection. The character of such generic zonation is therefore effectively two-fold — (1) to decrease the concentration of the historical seismicity to a greater or lesser extent and (2) to bring the historical seismicity closer to the site.

Rather than draw additional arbitrary zones we decided to model these two effects directly. This was done by two methods. Effect (2) was achieved by taking the USGS national hazard

map zones in the vicinity of Portsmouth, and applying to their boundaries various degrees of spatial smoothing, treating the zone boundaries as uncertain to the degree specified by the standard deviation of an applied Gaussian smoothing function. This in effect allows a fractional portion of the seismicity ordinarily constrained by the near source-zone boundary to come closer to the site. Effect (1) was obtained by treating the historical seismicity itself, regarding each historic location as uncertain in the past by an amount assessed by the assemblers of the earthquake catalog, and taking each such uncertain location as an indicator of future seismicity in a fuzzy area of influence characterized by an additional Gaussian smoother having a chosen standard deviation. The effect of the uncertain historical location and additional Gaussian smoothing is to decrease the areal concentration of historical seismicity. The impact on hazard determination was studied for various alternative standard deviations. In this study the role of location of historical seismicity with respect to the Portsmouth site was additionally modeled by alternative sites in the vicinity of Portsmouth, separated by 20 km distance.

In addition, the Portsmouth hazard results were subjected to variations in modeling source depth and source-zone maximum magnitudes.

VI.A.5.b. Paducah approach.

Whereas for Portsmouth the tectonic cause of seismicity is so poorly known that the zonations could be treated as essentially arbitrary, for Paducah a very prominent tectonic cause is associated with the strongest part of the historical seismicity. This cause is relatively close to the site. Accordingly, it is important to address the impact of the delineation of the zones representing this tectonic cause. Thus, we were interested in the effect on the hazard at the Paducah site of the modeling of the northern terminus of the New Madrid fault zone in the vicinity of the site, investigating both the effect of the source-zone boundaries and the effect of the modeling of ruptures within this source zone.

We were also interested in a broad alternative tectonic zonation that affected the host zone, that is, the zone occupied by the site. In addition we wanted to evaluate the role of linear rupture modeling for the host zone. Finally we wanted to address the role of modeling alternative depths and maximum magnitude for this host zone.

These alternative approaches for the USGS studies are summarized in table VI.A-2.

Table VI.A-2. Summaries of basis and approaches for USGS alternative calculations.

	Portsmouth	Paducah
Basis:	No known close association between tectonics and seismicity.	Several tectonic alternatives in vicinity of site.
Tests:	Test effect of fuzzing reference model source-zone boundaries.	Test sensitivity to modeling tectonic alternatives for host zone.
	Test effect on hazard calculated from fuzzy, smoothed historical seismicity at alternative sites in the vicinity of Portsmouth.	Test sensitivity to location of northern terminus of New Madrid fault zone.
	Test effect of alternative depths and maximum magnitude of reference model.	Test effect of alternative depths and maximum magnitude for host zone.

VI.A.6. Ground-motion and probability values used.

In these sensitivity studies we are interested in both the variation in exceedance probability at a given reference ground-motion level and also variation in ground motion at a given reference exceedance probability. We use a one-in-one-thousand annual exceedance probability (1000-year return period) as the reference probability, because this value corresponds to the probability permitted for these kinds of structures under the applicable regulation. We use 0.3 g as the reference ground motion, because this is a value of importance to the safety of the main facility structures. In general we would like to see the various ground motions at 1000-yr return period remain well below 0.3 g, and the various exceedance probabilities for 0.3 g remain well below one-in-a-thousand. When these are not the case, further study is indicated.

VI.A.7. Attenuation functions used.

The Boore-Atkinson (1987) attenuation functions for peak acceleration, 0.3 sec and 1.0 sec response are used in these sensitivity studies. The authors of the attenuation functions did not report values for the standard deviation of attenuation uncertainty, but suggested the use of those found in Joyner and Boore (1982). These sensitivity studies reported in this section are primarily for peak horizontal acceleration only. The effects for 0.3 sec and 1.0 sec response are essentially similar to those of peak horizontal acceleration (PHA), unless otherwise noted.

Differences in USGS, EPRI/SOG, and LLNL results at Portsmouth owing to differences in attenuation and other systematic factors not related to modeling issues investigated in this section are reported in section IX of this report.

VI.B. Portsmouth

VI.B.1. Effect of Source-Zone Boundary Uncertainty.

The USGS reference model (Algermissen and others, 1982, 1990) is one in which the source zones in the central and mid-western United States depend strongly on the historical seismicity. The zonation in the vicinity of Portsmouth is based in part on a hypothetical association of seismicity with basement uplifts; its primary character with respect to the site is to place the site in an area of relatively low seismicity, between two zones having higher seismicity.

We report on the effect on hazard at the site of modeling the source zones in a several-hundred kilometer radius of the site with Gaussian-smoothed boundaries. The effect of smoothing the adjacent source-zone boundaries is to bring a fraction of the seismicity, formerly fenced away from the site, into the vicinity of the site, as well as a fraction of the seismicity allowed to come within a certain distance of the site to be placed further away. The net effect is to produce more exceedances at the higher ground motions and hence increase the hazard at the site. Because the zones in the vicinity of the site are more elongated than circular (see figure VI.B.1), the smoothing does not produce as strong a decrease in areal rate of seismicity as under boundary fuzzing. Figure VI.B-2 shows the results of varying the smoothing standard deviation from 0 to 100 km, in steps of 20 km.

At 0.3 g peak horizontal acceleration, increasing the uncertainty standard deviation in all source-zone boundaries from 0 to 100 km, increases the exceedance rate of 0.3 g by a factor of 2. Virtually all of the increase is obtained by an increase of uncertainty from 0 to

40 km; thereafter, the hazard essentially changes only insignificantly.

At 1000-yr return period, the ground motion increases from 0.07 g to 0.09 g.

For the remainder of these parametric variation studies for Portsmouth, we have adopted the hazard curve obtained for 40 km as the reference curve for which the parameters vary.

VI.B.2. Effect of Maximum Magnitude Uncertainty.

The maximum center magnitude assumed in the reference model is 6.1 M_S . Recall (section V.C.2) that for symmetric distributions of maximum magnitude, the hazard value obtained by integrating over the distribution is well approximated by the hazard value calculated by the center magnitude of that distribution, for moderate levels of ground motion. Thus the use of a center maximum magnitude of 6.1 can approximate the result of the use of a symmetric distribution running from 5.8 to 6.4 or 5.5 to 6.7. For our parameter-variation calculations the use of the center magnitude is accurate up to ground motions of much higher return periods than are of concern here.

We report on the effect of varying the center maximum magnitude by plus or minus 0.6 magnitude units around magnitude 6.1. Figure VI.B-3 shows the results.

At 0.3 g peak horizontal acceleration, using the value for location uncertainty of 40 km, increasing the maximum magnitude by 0.6 (one intensity unit) increases the exceedance rate of 0.3 g by about 40 percent. Decreasing the maximum magnitude by 0.6 decreases the exceedance rate by almost a factor of 2.

At 1000-yr return period, the ground motion increases from 0.09 g to 0.10 g or decreases from 0.09 g to 0.07 g for increase or decrease of the maximum center magnitude by 0.6 magnitude units respectively.

VI.B.3. Effect of Source Energy Depth Uncertainty.

The depth used in the reference calculation is 7 km. We use alternative depths of 3 km and 10 km. If shallower sediments are incapable of sustaining seismogenic rupture, 3 km represents close to the shallowest source from which peak ground motions can emanate. For rock sites, 3 km is about the center of the distributions in depth observed for low magnitude earthquakes (Marone and Scholz, 1988). A depth of 10 km is about the center of the depth range, 5 to 16 km, reported by Herrmann for 75 percent of the earthquakes studied (reported in Nuttli and Herrmann, 1978), and is a reasonable value for the deepest source to expect the strong ground motion to emanate from, for a rupture having considerable vertical extent. Figure VI.B-4 shows the results.

At 0.3 g peak horizontal acceleration, using the value for location uncertainty of 40 km, decreasing the source depth from 7 km to 3 km increases the exceedance rate by about 40 percent. Increasing the source depth from 7 km to 10 km decreases the exceedance rate by about 30 percent.

At 1000-yr return period, the variation in probabilistic ground motion increases or decreases by only a small amount, approximately by 0.005 g for the alternative depth choices. This reflects the fact that most of the exceedances of ground motions at 0.09 g come from distances (horizontal) greater than the range of depths considered.

VI.B.4. Effect of Attenuation Function Variability Uncertainty.

In our review of the EPRI/SOG methodology for the NRC (Perkins and others, 1988), we were concerned that not all the model parameters were modeled with uncertainty. To

test the significance of variation of the attenuation function variability parameter, we used 0.44, 0.64, and 0.84 as the standard deviation of the log (base e) ground motion. The extreme values are about double the range expected for this parameter. (No figure is shown for the results of this test.)

At 0.3 g peak horizontal acceleration, increasing or decreasing the standard deviation from the central value to the two extremes produced roughly a factor of 2 change in the exceedance rate in each direction. As we think about half this range is reasonable, the probable bounding ranges for reasonable values of exceedance rate is about plus or minus 40 percent.

At 1000-yr return period, the modeled changes in attenuation function standard deviation produced peak acceleration changes from 0.09 g to 0.11 g or 0.07 g. A reasonable range for the expected range in parameter values is about 0.08g to 0.10 g. This percent range is small but not insignificant, being approximately the result obtained for variation in source depth.

VI.B.5. Overview of parameter variation study.

At 1000-yr return period, within the range of parameter variation studied (neglecting the role of attenuation uncertainty parameter), the lowest peak horizontal acceleration obtained is 0.06 g, with a maximum central magnitude of 5.5, location uncertainty of 0 km, and 10 km source depth; the highest peak horizontal acceleration obtained is 0.10 g, with a maximum central magnitude of 6.7, location uncertainty of 40+ km, and depth of 3 km. These values range plus or minus 25 percent around a nominal 0.08g, distributed toward the upper end of this range, with a median value about 0.082 g.

At 0.3 g peak horizontal acceleration, within the range of parameter variation studied

(neglecting the role of attenuation uncertainty parameter), the lowest exceedance rate at 0.3 g obtained is about 2.3×10^{-5} (return period 4.2×10^4), with a maximum central magnitude of 5.5, location uncertainty of 0 km, and 10 km source depth; the highest exceedance rate obtained is about 1.9×10^{-4} (return period 5.2×10^3), with a maximum central magnitude of 6.7, location uncertainty of 40+ km, and depth of 3 km. This range of exceedance probability is almost a factor of 10.

The range of a factor of 10 in exceedance rate of 0.3 g, obtained by means of variation in just these parameters studied is considerably smaller than the observed ranges of the constituent LLNL and EPRI/SOG estimates. Wider ranges are possible by use of parameter values outside the ranges tested or by changing parameters other than those tested. For instance, lower exceedance rates are achievable by means of steeper zone b-values, by lower zone seismicity rates, especially for the background zones in the LLNL and EPRI/SOG methodologies, and by more distant zone boundaries. Higher values of exceedance rate are achievable, by larger central maximum magnitudes, and flatter b-values.

In the EPRI/SOG methodology, the seismicity parameters are constrained by the data to a greater degree than in the LLNL methodology, for a number of reasons (See sections IV.D.3.d, g, and k). Thus, for hazard results from the LLNL methodology, we expect a wider range of exceedance rate values and a higher median value than the median EPRI estimate. However, for the EPRI/SOG methodology, some additional variability in zone seismicity rates is possible when the a-value is allowed to reflect very local historical seismicity rates rather than historical rates averaged over an entire zone (i.e., the case of low spatial smoothing for a-values). Also, the effective seismicity rate of a zone in the EPRI/SOG hazard estimate is modulated by the p^A value for the zone (which is often lower

than 0.5, if the zone is not a background zone or a high likelihood default zone). Thus, in the vicinity of historical clusters of seismicity not strongly associated with tectonic features, we expect *more* variability for the EPRI/SOG hazard, but a lower median value than with LLNL.

VI.B.6. Seismic Hazard Obtained from Historical Seismicity.

In this new USGS methodology we allow the source-zone concept to be replaced by the concept of discrete fuzzy sources associated with the location of each historical epicenter. This fuzzy location represents a possible future location for an earthquake. Because it is unrealistic to expect the future earthquake to occur exactly in the same location as the historical epicenter, and because that location itself is uncertain, two "fuzzing" operations are performed, one to represent the uncertainty of the *historical* location and one to represent the uncertainty of the *future* location. The location uncertainties are represented by Gaussian distributions.

The standard deviation of the historical location is one determined approximately by the assemblers of the catalog or estimated by the analyst. The value usually depends on date, the more recent earthquakes being more accurately located, and on isolation, the closer the epicenter to population centers or seismic networks the more accurately located is the epicenter.

The standard deviation associated with future location is a *variable* parameter. The value may be chosen to represent our notion of how much constraint is provided by some hypothetical tectonic association, or the value may be merely chosen for convenience to provide a smooth map.

The future seismicity expected over a region is spatially allocated among the fuzzy locations.

The magnitude distribution of that future seismicity associated with each location is just a proportionate fraction of the frequency-magnitude relationship determined for the regional rate of seismicity — that is, if 100 earthquakes were used to determine the regional rate, 1/100 of that regional rate is allocated to each fuzzy historical location. This allocation corresponds to a maximum likelihood allocation.

We report on the effect of various degrees of future-location smoothing on seismic hazard at six sites on a 3 by 2 site grid at 20 km spacing in the vicinity of the Portsmouth site. The sites have configuration and coordinates as follows:

Site D: 39.00°N, 83.08°W Site A: 38.98°N, 82.85°W

Site E: 38.82 , 83.10 Site B: 38.80 , 82.87

Site F: 38.64 , 83.12 Site C: 38.62 , 82.89

Figures VI.B.5 through VI.B.9 illustrate the effect on the hazard curves at the six sites using Gaussian smoothers having standard deviations of 0, 20, 40, 60 and 100 km. Table VI.B-1 shows the probabilistic peak accelerations at the sites, for 1000-yr return period, for the various smoothing parameters. The peak acceleration values range from 0.064 g to 0.108 g.

Table VI.B-1. Probabilistic Peak Accelerations Having 1000-yr Return Periods, for 6 Sites in the Vicinity of Portsmouth, Showing the Effect of Spatial Smoothing on Sites of Historical Seismicity.

Smoothing	Site					
	A	B	C	D	E	F
0	.102	.091	.074	.076	.071	.064
20	.108	.097	.080	.082	.076	.072
40	.109	.098	.088	.096	.090	.084
60	.103	.097	.091	.097	.095	.091
100	.098	.096	.093	.096	.096	.094

The effect of smoothing the historical seismicity is generally to increase the probabilistic ground motion hazard for all these sites in the vicinity of Portsmouth, indicating that historical seismicity is being brought nearer to the site. At higher values of smoothing than 40 km there is some subsequent slight decline in hazard at some sites, indicating some minor decrease in areal seismicity rate (the additional smoothing "dilutes" the seismicity rate). The initial increase in hazard is a sign that the Portsmouth vicinity is of relatively lower hazard than immediately adjacent areas.

VI.B.7. Overview of Portsmouth comparative study.

A 1000-yr probabilistic ground motion value for the Portsmouth site, of 0.082 g, represents both the mean and median value of reasonable alternative values obtained in our studies.

VI.B.7.a. Variations in probabilistic ground motions to be expected.

The range of numbers observed in section VI.B.6, for various values of smoothing

parameter and for various sites, from 0.064 to 0.108 g, or plus or minus about 0.02 g around the center of the range, or about 25 percent. This variation we take to indicate a reasonable range of values for the effect of *zonation*, without regard to choice of seismicity parameters, source depth, or maximum magnitude. Inasmuch as we observed a similar range for the *parametric variation* studies, we conclude that a natural range of uncertainty in probabilistic ground motion at 1000-yr return period, due both to variation in zoning and parameters *other than seismic rate*, is plus or minus about 35 percent or about plus or minus 0.03 g. (We have treated these two ranges as measures of independent sources of uncertainty and taken the square root of the sums of their squares.) Additional variation in the assignment of *regional seismic rate* of plus or minus 30 percent could produce variations of plus or minus about .013 g or about 15 percent. We would not, therefore, be surprised to find individual probabilistic ground-motion values ranging plus or minus 40 percent or about 0.033 g about the median value, using a single attenuation function.

Probabilistic ground-motion values less than 0.1 g are the result of contributions both from moderate-magnitude, nearby earthquakes and large, distant earthquakes. At large distances, attenuation functions may differ a great deal more than they do at moderate distances, where there is more data to constrain them. Consequently, we would not be surprised to see probabilistic ground-motion values differ by percentages approaching 40 percent at these ground-motion levels, owing only to different choice of attenuation function.

VI.B.7.b. Comparison with consultants' results.

Figures VI.B-10 through VI.B-14 depict EPRI/SOG and LLNL hazard curves and their various combinations, for use in comparing the hazard curves from our comparison studies.

Our curves lie in the higher fractiles of these curves, from the 60-th to 95-th percentiles. In section V.D.4.a we suggested why this should be expected to be the case — that the use of multiple alternative zonations should decrease the effective areal seismicity rate for sites in the vicinity of historical seismicity and hence decrease the apparent hazard, compared to the hazard calculated using single zonations based on historical seismicity. However the factor difference is larger than the reasonable estimates of variation suggested in the previous section. We conclude therefore that the differences in median hazard estimates of the EPRI/SOG and LLNL methodologies and those of this USGS study indicate the presence of some other systematic differences in the methodologies or assumptions other than zonation, choice of parameters, or seismicity rates.

Some systematic sources of variation in hazard estimates include choice of attenuation function, choice of minimum magnitude, radius from the site at which zones are excluded from the calculation, and treatment of earthquake size measures. The effects of these sources of variation have been the subject of additional special studies by the USGS staff and are discussed in sections VII and IX.

Figure VI.B-1. Above: Seismicity in Ohio and nearby portions of Indiana, Kentucky, and West Virginia. Below: Superposition of source zones from Algermissen and others (1990).

Effect of Earthquake Location Variability
 Boore and Atkinson Peak Horizontal Acceleration
 Reference Maximum Magnitude
 Reference Rupture Depth
 Portsmouth, Ohio

Figure VI.B-2. Hazard curves for Portsmouth for various choices of source zone uncertainty.

Effect of Maximum Magnitude Variation
 Boore and Atkinson Peak Horizontal Acceleration
 Earthquake Location Variability 40 Kilometers
 Reference Rupture Depth
 Portsmouth, Ohio

Figure VI.B-3. Hazard curves for Portsmouth for alternative choices of maximum center magnitude.

Effect of Rupture Depth Variation
Boore and Atkinson Peak Horizontal Acceleration
Earthquake Location Variability 40 Kilometers
Reference Maximum Magnitude
Portsmouth, Ohio

Figure VI.B-4. Hazard curves for Portsmouth for alternative values of depth of origin of strong motion energy.

Site Variance of Ground Motion
Earthquake Catalog Smoothing 0 Kilometers

Figure VI.B-5. Hazard curves based on future earthquake sources in the vicinity of historical epicenters in the region within 200-km of Portsmouth for six alternative sites in the vicinity of Portsmouth. Smoothing parameter for future location is 0 km.

Site Variance of Ground Motion
Earthquake Catalog Smoothing 20 Kilometers

Figure VI.B-6. Hazard curves based on future earthquake sources in the vicinity of historical epicenters in the region within 200-km of Portsmouth for six alternative sites in the vicinity of Portsmouth. Smoothing parameter for future location is 20 km.

Site Variance of Ground Motion
Earthquake Catalog Smoothing 40 Kilometers

Figure VI.B-7. Hazard curves based on future earthquake sources in the vicinity of historical epicenters in the region within 200-km of Portsmouth for six alternative sites in the vicinity of Portsmouth. Smoothing parameter for future location is 40 km.

Site Variance of Ground Motion
Earthquake Catalog Smoothing 60 Kilometers

Figure VI.B-8. Hazard curves based on future earthquake sources in the vicinity of historical epicenters in the region within 200-km of Portsmouth for six alternative sites in the vicinity of Portsmouth. Smoothing parameter for future location is 60 km.

Site Variance of Ground Motion
Earthquake Catalog Smoothing 100 Kilometers

Figure VI.B-9. Hazard curves based on future earthquake sources in the vicinity of historical epicenters in the region within 200-km of Portsmouth for six alternative sites in the vicinity of Portsmouth. Smoothing parameter for future location is 100 km.

Figure VI.B-10. EPRI/SOG hazard curves for Portsmouth for comparison with USGS median value (shown by a +) at annual exceedance probability of 10^{-3} .

PORTSMOUTH (ROCK, ALL G-EXPERTS)
LLNL HAZARD RESULTS - PEAK ACCELERATION

Figure 3-12. Seismic hazard at Portsmouth computed by LLNL using the LLNL methodology (all ground-motion Experts). The solid curves correspond to the following fractile hazard curves: 0.05 (bottom), 0.15, 0.25, 0.35, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, 0.95 (top); the dashed curve represents the mean hazard curve.

Figure VI.B-11. LLNL hazard curves for Portsmouth (all ground-motion experts included) for comparison with USGS value (+).

PORTSMOUTH (ROCK RESULTS, NO G-EXPERT 5)
LLNL HAZARD RESULTS - PEAK ACCELERATION

Figure 3-13. Seismic hazard at Portsmouth computed by LLNL using the LLNL methodology (excluding ground-motion Expert 5). The solid curves correspond to the following fractile hazard curves: 0.05 (bottom), 0.15, 0.25, 0.35, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, 0.95 (top); the dashed curve represents the mean hazard curve.

Figure VI.B-12. LLNL hazard curves for Portsmouth (all ground-motion experts included except expert 5) for comparison with USGS value (+).

PORTSMOUTH (ROCK, ALL LLNL G-EXPERTS)
COMBINED EPRI/SOG-LLNL RESULTS - PGA

Figure 4-1. Seismic hazard at Portsmouth (for rock site conditions). Obtained by combining results from the EPRI/SOG and LLNL (all Ground-motion Experts) methodologies. Results shown as fractile hazard curves and mean hazard curve for peak acceleration. The solid curves correspond to the following fractile hazard curves: 0.05 (bottom), 0.15, 0.25, 0.35, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, 0.95 (top); the dashed curve represents the mean hazard curve.

Figure VI.B-13. Combined LLNL and EPRI/SOG hazard curves for Portsmouth (all LLNL ground-motion experts included) for comparison with USGS value (+).

PORTSMOUTH (ROCK, NO LLNL G-EXPERT 5)
COMBINED EPRI/SOG-LLNL RESULTS - PGA

Figure 4-2. Seismic hazard at Portsmouth (for rock site conditions). Obtained by combining results from the EPRI/SOG and LLNL (no Ground-motion Expert 5) methodologies. Results shown as fractile hazard curves and mean hazard curve for peak acceleration. The solid curves correspond to the following fractile hazard curves: 0.05 (bottom), 0.15, 0.25, 0.35, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, 0.95 (top); the dashed curve represents the mean hazard curve.

Figure VI.B-14. Combined LLNL and EPRI/SOG hazard curves for Portsmouth (all LLNL ground-motion experts included except expert 5) for comparison with USGS value (+).

VI.C. Paducah

As with Portsmouth, the strategy of investigating alternative hazard calculations at Paducah is two-fold. We investigate the effects at Paducah of the *generic* issues which might have a site-specific effect — maximum magnitude uncertainty and source energy depth uncertainty. Also of interest at the site is the effect of *alternative zonations*. We are particularly interested in two issues — the modeling of the source zone which contains the site (the “host” zone) and the modeling of the New Madrid fault zone (NMFZ).

The sensitivity studies reported in this section are for peak horizontal acceleration (PHA) only. The results for 0.3 sec and 1.0 sec response are essentially similar to those of peak horizontal acceleration, unless otherwise noted.

VI.C.1. Characteristics of Reference Model

Although the USGS model which we will use for parameter variation study is one in which in general the source-zone boundaries depend heavily on historical seismicity in central and mid-western U.S., in particular in the vicinity of the New Madrid Zone, there is a stronger apparent correspondence between historical seismicity and geologic features representing possible tectonic zones. Figures VI.C-1 through VI.C-4 depict the recently-monitored seismicity in the New Madrid region, both a generalized and a dog-leg source for the New Madrid seismicity, and the USGS base or reference model. In this model, source zones represent a broad New Madrid fault zone, a St Francis Mountains zone (zone “85”), a broad zone associated with the Wabash Valley and southern Illinois, and a source zone (“zone 88”) encompassing the seismicity running up the Mississippi River toward St. Louis.

As we will see confirmed later, the results in this model depend primarily on the location boundary of a generalized New Madrid rift zone and on the seismicity parameters of the host zone (the “Mississippi River” zone). In this base model, the New Madrid zone is modeled with finite-ruptures whose magnitude-length relationship is that of the long ruptures tabulated in section V.A, and center maximum magnitude 8.5 M_S . In the host zone, earthquakes are modeled as point sources and have center maximum magnitude 6.1 M_S . At 0.3 g PHA, the annual exceedance rate is 1.2×10^{-3} (return period is 0.85×10^3). At 1000-yr return period, the PHA is 0.33 g.

VI.C.2. Effect of Maximum Magnitude Uncertainty in the Host Zone.

The maximum center magnitude assumed in the reference model in the host zone is 6.1 M_S . Figure VI.C-5 illustrates the effect on hazard of increasing the center maximum magnitude by 1.2 units.

At 0.3 g peak horizontal acceleration, increasing the maximum magnitude in the host zone by 1.2 (equivalent to two MMI epicentral intensity units) increases the exceedance probability by about 25 percent.

At 1000-yr return period, the ground motion increases from 0.33 g to 0.38 g or about 15 percent.

Note that this sensitivity to maximum magnitude is less than for the Portsmouth site. One explanation for the decrease in sensitivity could be that many of the exceedances of 0.3 g may be coming from the NMFZ. These would not decrease when changing the maximum magnitude in the host zone. Also note that the sensitivity would perhaps be greater than observed here if the source zone were modeled with line rather than point ruptures. (Later in model 3 we will estimate the contribution made by the host zone by modeling the earthquakes

in that zone as finite ruptures rather than point sources.)

VI.C.3. Effect of Source Energy Depth Uncertainty In the Host Zone.

The depth used in the reference calculation is 7 km. We use alternative depths of 3 km and 10 km. (See section VI.B.3 for more information on these choices of depth.)

At 0.3 g peak horizontal acceleration, decreasing the source depth from 7 km to 3 km increases the exceedance probability by about 28 percent. Increasing the source depth from 7 km to 10 km decreases the exceedance rate by about 17 percent.

At 1000-yr return period, decreasing the source depth from 7 km to 3 km increases the probabilistic peak acceleration from 0.33 g to .38 g, about a 15 percent increase. Increasing the source depth from 7 km to 10 km decreases the probabilistic peak acceleration to 0.30 g, about a 10 percent decrease. Notice that the increase in hazard is comparable to that obtained by increasing the maximum magnitude 1.2 units (2 intensity units), for a point-rupture model.

Notice also that in comparison with the hazard at the Portsmouth site, there is greater sensitivity to source depth for the Paducah site. At these higher probabilistic ground motion levels, the contribution is coming from closer earthquakes and the contribution of source depth to the source-to-site distance is greater.

VI.C.4. Modeling the role of a St. Genevieve Fault Zone.

We are interested in altering the basic reference model by placing a wide source zone to represent the possible truncation of the New Madrid fault zone by a hypothetical St. Genevieve fault zone, providing, in addition, a transition, wedge-shaped zone up to the former

generalized Wabash Valley Zone, which now begins north of the Cottage Grove-Rough Creek fault. Guided both by the distribution of local, recently-monitored seismicity and considerations of relative area (see figures VI.C-3 and VI.C-7), the rate of the generalized St. Genevieve Fault Zone is obtained from 50 percent of the rates in the reference model for each of the zones 88 and 85. The transition "wedge" zone has a rate 10 percent of that assigned to the former Wabash Zone. Point ruptures are used in the new zone wedge zone, but in the following models we test the effect of maximum magnitude, point ruptures and line ruptures in the St. Genevieve zone, which is the new host zone for the Paducah site.

VI.C.4.a. Model 1. Point Ruptures.

In this model, the higher maximum magnitude, 7.3 M_S , used in the magnitude sensitivity test of the reference model is retained in the new St. Genevieve zone, but point ruptures are used. Although there is a slightly decreased areal rate of seismicity in this host zone, the major decrease in hazard (see figure VI.C-9) is much greater than this decrease in rate. This great decrease in hazard is due to the fact that this new source zone has truncated the northern extent of the New Madrid fault zone source, so that it terminates much farther from the Paducah site.

VI.C.4.b. Model 2. One Modeled Fault.

Using this new source-zone configuration, we test the placement of a single modeled fault at the northern edges of the St. Genevieve fault zone and the transition wedge zone (see figure VI.C-10), placing three-quarters of the respective zonal seismicities on these faults. Although we have placed a fault closer to the site than the NMFZ, the hazard curve has decreased even lower than in Model 1 (see figure VI.C-11) because the areal seismicity rate in the immediate vicinity of the site has decreased by a factor of 4.

VI.C.4.c. Model 3. Distributed Finite Ruptures.

With the same source-zone configuration, we restore the seismicity uniformly in the two zones, but now model the seismicity in the host zone with finite ruptures, using the California ("long") magnitude-rupture relationship of section V.A.1.c for conservatism (figure VI.C-12). However, the host zone has as maximum center magnitude the original value of 6.1 M_S . Figure VI.C-13 shows this new model to have higher exceedance rates than the reference curve only beyond 0.7 g.

Figures VI.C-14 and VI.C-15 summarize the models 1, 2, and 3 results, using both the original reference curve (first graph) and a reference curve in which the maximum magnitude in the original host zone is 7.3 M_S rather than 6.1 M_S (this curve is that having 0.38 g at 1000-yr return period in the first sensitivity study. Notice that the new reference dominates the other curves at ground-motion values lower than 1.5 g. This is due to the strong influence of the northern boundary of the NMFZ in the reference model. Clearly, the placement of the northern boundary of the fault zone has an important and usually dominating effect. The sensitivity of the Paducah hazard to the placement of this boundary needs to be investigated in more detail.

VI.C.5. The NMFZ sensitivity models.

In order to investigate the sensitivity of the hazard results to the location of the northern terminus of the New Madrid fault zone, the sources were reconfigured as follows (see figure VI.C-16). First, the seismicity of the NMFZ in the reference model was placed entirely on three fault segments, two of which model the location of the north-northwestern trending and northeastern trending portions of the most active part of the currently monitored seismicity. The third fault segment models an

alignment of seismicity about 40 km southeast and parallel to the northeastern-trending active segment. These three faults model recurrence of the New Madrid seismicity at a rate corresponding to the historical rate, with the assumption that the cluster of large-magnitude events experienced in 1811 and 1812 has a recurrence interval of about 800 years.

Second, we hypothesize that northeast of the north-northwest trending portion of the dogleg zone, seismicity like that experienced historically in the active portion of the NMFZ could happen on northeast-trending faults randomly located over an area about 60 km wide. (In figure VI.C-16, these are shown as three faults, but the computer models them as having a random uniform distribution over a width of 60 km.) The northeastern boundary of this fault zone has six possible termini: three at (1) 50 km, (2) 30 km, and (3) 10 km short of the Paducah site, and three at (4) 10 km, (5) 30 km, and (6) 50 km beyond the site. The recurrence rate for this seismicity for magnitudes about 6.4 M_S is taken to be one-third of that assumed for the NMFZ in the reference model. The argument is basically that there were three major earthquakes of the 1811-1812 sequence whose location is taken to be 50-km long segments lying along the most active portion of the currently-monitored seismicity. Thus we treat this northeastern extension as equivalent to one of those segments, but of unknown total extent, from 50 to 120 km and with recurrence rate equal to one-third that of the three major earthquakes taken together.

Figure VI.C-18 shows the effect of using the "short" rupture-length vs magnitude relation tabulated in section V.A.1.c. Figure VI.C-17 shows the hazard curves when this northeastern extension is modeled with rupturing sources, using the "medium" rupture-length vs magnitude relation tabulated in section V.A.1.c. Table VI.C-1 shows 1000-yr probabilistic peak acceleration for the three

Table VI.C-1. Paducah Site 1000-yr Probabilistic Peak Horizontal Acceleration for Various Rupture Length vs Magnitude Relations and Various Northeastern Termini for New Madrid Fault Zone

Rupture-Magnitude Relationship	Northeastern NMFZ Terminus with respect to Site					
	-50 km	-30 km	-10 km	+10 km	+30 km	+50 km
Short	0.27	0.29	0.36	0.48	0.52	0.49
Medium	0.28	0.31	0.42	0.59	0.70	0.70
Long	0.28	0.35	0.55	0.82	0.90	0.93

rupture length vs. magnitude relationships for the six modeled termini for the NMFZ.

These results demonstrate the dramatic effect that result from changes in the northeastern terminus of the NMFZ, and from the representation of the earthquake source by finite-ruptures of moderate to long extent. Figure VI.C-19 shows how the 1000-yr return period peak acceleration at the Paducah site changes as a function of the rupture-length vs magnitude relation, for the six northeastern termini of the fault zone. This figure demonstrates that for termini close to or beyond the site, the rate of increase of hazard with respect to choice of rupture length relationship is about the same, going from "medium" to "long," amounting to about a fifty percent increase.

Figure VI.C-20 shows how the 1000-yr return period peak acceleration at the Paducah site changes as a function of the location of the northeastern terminus of the fault zone, for the three different rupture-length relationships. This figure shows that the factor of change of ground motion with respect to terminus location reaches its maximum rate for termini between 20 km short of the site and 10 km beyond the site. This demonstrates the extreme sensitivity of the hazard result to the location of

the northern terminus of the New Madrid Fault Zone.

VI.C.6. Overview of Paducah comparative study.

Figure VI.C-21 is a probability graph showing the distribution of 1000-yr probabilistic ground motion values for the Paducah site, representing the parameter variation models, models 1, 2, and 3, and reasonable choices of the model 4 (medium rupture length, termini slightly beyond the site to moderately short of the site). These values have a median of 0.32 g and a mean of 0.38.

The acceleration values in figure VI.C-21 range from about 0.26 g to 0.72 g. The consultants' median results fall in the lower part of this range. In the light of this comparison study and the fact that some of the EPRI/SOG and LLNL zonations place Paducah very near or within the NMFZ, it is clear that the point-rupture assumption has had an important role in keeping these ground motions low. On the other hand, many of the zonations place the NMFZ source far from the site. For the farthest locations, the point-rupture assumption may not be greatly in error (see section V.A).

The Risk Engineering results are intended to represent much of the variability of the EPRI/SOG and LLNL models, but to model the larger NMFZ earthquakes as linear ruptures rather than point ruptures. The Risk Engineering study obtains a median 1000-year peak acceleration of 0.31 g. Values above about 0.45 g in our sensitivity study depend upon either long rupture lengths, or fault rupturing sufficiently beyond the site that significant strong ground-motion energy is released very near the site. We believe that long rupture lengths are incorrect for this region, the corresponding relationship having been derived from strike-slip faults primarily in California. However, the role of rupture past the site in the Risk Engineering model needs to be examined in more detail.

In our fault-rupture ground-motion model, the conventional "hot-dog" model (see section V.A), strong ground motion of a given level is assumed to be experienced at all sites a constant distance from the rupture. This model assumes that in advance of an earthquake we do not know where the source of strong motion experienced at a site will originate, but that it can occur anywhere along the rupture, and that for a given site it should occur most likely at a location on the fault near to the site. An alternative physical argument can be made that strong ground motion should not be experienced except where relatively large displacements exist along the rupture. Since large displacements cannot occur at the end of the rupture (there is no displacement there), strong ground motion could only be experienced at sites interior to the ends of the rupture. The Risk Engineering model for ground motion and rupture makes this assumption. As a result, even though a rupture may run several kilometers past the site, the portion of the rupture contributing strong ground motion may not have arrived near the site.

We believe it is this difference in the strong-motion modeling assumptions that accounts for the fact that the USGS probability curve for 1000-year peak horizontal acceleration shows very high ground motions at upper fractiles, while the upper fractiles of the Risk Engineering values are more restrained. Therefore, we have recommended that the Risk Engineering model should be demonstrated for ruptures proceeding 40 or so kilometers beyond the site, in order to make it possible to detail the effects of their strong-motion model for ruptures close to the site. This demonstration is probably a complex modeling task, inasmuch as the simulated ground motions produced by their Greens function model for sites located beyond the end of the fault are different (and smaller) than ground motions produced for sites at located beside the fault.

Nevertheless, we believe that the *median* Risk Engineering values are very reasonable values to use for design for the Paducah site.

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Figure VI.C-1. Illustration of recently-monitored seismicity in and around the New Madrid fault zone and some surface faults (from Al-Shukri and Mitchell, 1990).

Figure VI.C-2. As in figure VI.C-1, with broad, generalized New Madrid fault zone source and narrow, dog-leg source indicated. (See section V.A. for examples of such sources.)

Figure VI.C-3. As in figure VI.C-1, but with sources from basis zonation ("reference zonation") of Algermissen and others, 1990) superimposed.

Figure VI.C-4. Basis zonation ("reference zonation") of Algermissen and others (1990), only. Only the New Madrid fault zone source has modelled line ruptures.

Effect of Magnitude Variation
Boore and Atkinson Peak Horizontal Acceleration
Earthquake Location Variability 0 Kilometers
Paducah, Kentucky

Figure VI.C-5. Hazard curves for Paducah for alternative choices of maximum center magnitude for zone containing site. "Reference" zonation uses maximum center magnitude of 6.1 M_S for this zone.

Effect of Rupture Depth Variation
 Boore and Atkinson Peak Horizontal Acceleration
 Reference Maximum Magnitude
 Earthquake Location Variability 0 Kilometers
 Paducah, Kentucky

Figure VI.C-6. Hazard curves for Paducah for alternative values of depth of origin of strong motion energy. Hazard curve for "reference" zonation has rupture depth of 7 km.

Figure VI.C-7. As in figure VI.C-1, but with "Model 1" zonation superimposed. Broad New Madrid fault zone source has been truncated by hypothetical St. Genevieve fault zone source.

Figure VI.C-8. Model 1 zonation only. Only the New Madrid fault zone source has modelled line ruptures.

Model 1 versus Reference

Figure VI.C-9. Hazard curves for Paducah for reference model and model 1. Zones containing site in the respective models have maximum center magnitude of 6.1 M_S . Hazard is lower in model 1 because the northern terminus of the New Madrid fault zone is now farther from the site than in the reference model.

Figure VI.C-10. Model 2 zonation only. Location of linear fault lines on which linear ruptures are modelled are indicated by heavy lines on northern part of St. Genevieve zone and "wedge" zone. Maximum center magnitude in these two zones is now 7.3 M_S . Three-quarters of the two zones' seismicity is now placed on these two faults.

Model 2 versus Reference

Figure VI.C-11. Hazard curves for Paducah for reference model and model 2. Hazard is lower than for the reference model or model 1 because seismicity in the zone containing the site has been decreased by a factor of 4 in the vicinity of the site.

Figure VI.C-12. Model 3 zonation only. A uniform distribution of modelled faults has now been placed in the St. Genevieve fault zone source containing the site. Maximum center magnitude in this zone is 7.3 M_S .

Model 3 versus Reference

Figure VI.C-13. Hazard curves for Paducah for reference model and model 3. Hazard is roughly comparable for the reference model and model 3 because the greater distance from the New Madrid fault zone source seismicity in models 1, 2, and 3, has been compensated for by the increased maximum magnitude in the zone containing the site and the modelling of line ruptures in this zone.

Figure VI.C-14. Recapitulation of hazard curves for Paducah for reference model and models 1, 2, and 3.

Maximum Magnitude 7.3 vs Models 1 - 3

Figure VI.C-15. Hazard curves for Paducah for models 1, 2, and 3. Curve labelled magnitude 7.3 is reference model with maximum center magnitude increased. Note that at long return periods this model and model 3 converge because of similar maximum magnitude. At shorter return periods, model 3 is dominated because of greater distance to the New Madrid fault zone source.

Figure VI.C-16. Model 4 zonation only ("sensitivity model"). New Madrid fault zone seismicity has been placed on three line faults. Hypothetical future seismicity for the northern part of the New Madrid fault zone has been placed on a 60-km wide zone modelled with linear ruptures and having six alternative northeastern termini, 50, 30, and 10 km short of the Paducah site and 10, 30, and 50 km beyond the Paducah site. Only seismicity for magnitudes above 6.4 M_S has been placed in this zone. Magnitudes below 6.4 in the vicinity of the site are modelled as point sources as part of the St. Genevieve fault zone source.

Northern Sensitivity Fault Model
 Faults have Magnitudes 6.7 - 8.5
 Shortened Ruptures

Figure VI.C-17. Hazard curves for Paducah for model 4. Rupture-length model is that of medium-length ruptures given in section V.A.

Northern Sensitivity Fault Model
 Faults have M_s 6.7 - 8.5
 Shortest Ruptures

Figure VI.C-18. Hazard curves for Paducah for model 4. Rupture-length model is that of shortest ruptures given in section V.A. These are effectively point sources.

1000-yr Peak Accelerations for 3 Rupture-Length v Magnitude Relationships

Figure VI.C-19. Graph showing 1000-yr return period probabilistic peak acceleration values at the Paducah site as a function of rupture-length relationship, for various locations of the northeastern terminus of the extension of the New Madrid fault zone source. Distances with plus signs indicate distances (in km) termini extend past and beyond the site. Distances with minus signs indicate distances termini fall short of reaching the site

Figure VI.C-20. Graph showing 1000-yr return period probabilistic peak acceleration values at the Paducah site as a function of various locations of the northeastern terminus of the extension of the New Madrid fault zone source, for the three rupture-length relationships. Note the high sensitivity of probabilistic ground motion for termini from 20 km short of the site to 10 km beyond the site.

Probability Curve for USGS Model Values
(all models equally weighted)

Figure VI.C-21: Probability graph for "reasonable" alternative values of 1000-yr return period peak accelerations at Paducah. (Medium rupture length, termini slightly beyond to moderately short of the site for model 1, 2, and 3, and parametric variations of the "reference model")

VII. Response Spectra

by

Edgar V. Leyendecker

Summary

Response spectra at the Paducah and Portsmouth sites obtained by various methodologies — Electric Power Research Institute/Seismicity Owners' Group (EPRI/SOG), Lawrence Livermore National Laboratory (LLNL), combined EPRI/SOG-LLNL, Risk Engineering, Inc. (REI) rupture model, and U. S. Geological Survey (U.S.G.S.) models — are compared with spectra obtained using several approaches permitted by UCRL-15910, some based on building code provisions. In general the spectra differ less at short periods than at long periods. At long periods, methods using a spectral shape scaled by peak acceleration produce higher values than those methods for which the spectral ordinates have been calculated by the methods of seismic hazard analysis.

For the U.S.G.S. models at both sites and the REI rupture model (only calculated for Paducah), the spectra have similar shape but do not seem to be converging to the short period values obtained by EPRI/SOG, LLNL, or the values used in the building-code based methods. This effect appears to be due to higher short-period spectral levels obtained from the rupture models at Paducah.

At longer periods, the spectral levels obtained by the EPRI/SOG methodology are very different from those obtained by the other methodologies. It is believed that the higher U.S.G.S. spectral values at long periods are due in part to higher-rate models in the vicinity of the site in the case of Paducah and in part due to higher maximum magnitudes for source zones in the case of Portsmouth. Similarly, the generally low spectral results, particularly at long periods, for the EPRI/SOG methodology results are due in part to lower-rate models and lower maximum magnitudes in those models.

Considering the sites individually, at the Paducah site the spectra for both soil and rock are bounded on the high side by the UCRL spectrum and on the low side by the EPRI/SOG spectrum for rock. An ordinary building code spectrum, which is not site-specific, exceeded the EPRI/SOG, LLNL, and combined EPRI/SOG-LLNL spectra for periods around one second and the EPRI/SOG spectra for all periods. The spectrum for the REI fault rupture model was similar in shape to the U.S.G.S. spectrum for rock but slightly lower in amplitude than the U.S.G.S. spectra for periods less than about one second.

At the Portsmouth site it was also found that the spectra for both soil and rock were bounded on the high side by the UCRL spectrum and on the low side by the EPRI/SOG spectrum for rock. The ordinary building code spectrum, which is not site-specific, exceeded the EPRI/SOG and USGS spectra for all periods. The U.S.G.S. spectrum was not significantly lower than the building code spectrum.

While it is not surprising to see differences between the spectra for individual sites and the spectra for building codes, the large differences for the spectra obtained using the EPRI/SOG methodology are surprising. While it can be argued that the information for the specific sites is more accurate, it must also be noted that (1) the annual probability for the code spectra is twice that for Moderate Hazard facilities and (2) ordinary buildings would be required to meet the code spectra if seismic design requirements were enforced.

Introduction

Seismic design guidelines for General Use, Low Hazard, Moderate Hazard, and High Hazard Department of Energy (DOE) facilities are contained in the UCRL-15910 report "Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards" (Kennedy et al, 1990). According to these guidelines the earthquake evaluation approach for Moderate and High Hazard facilities should include elastic dynamic analysis. A basic step in such an analysis includes developing a response spectrum. This section includes a comparison of elastic response spectra prepared by U.S.G.S. along with those included in the REI reports for the Paducah and Portsmouth sites (Risk Engineering, Inc., 1991). For these two sites the REI reports include spectra determined by REI using the EPRI/SOG methodology, spectra prepared by LLNL (Davis and Savy, 1990) using the LLNL methodology, and spectra using a combination of the EPRI/SOG-LLNL methodologies prepared by REI. In addition a rock spectrum was developed for Paducah using a simplified methodology intended to incorporate much of the variability of the EPRI/SOG and LLNL studies but also incorporating modeling of ground motion from finite rupture for the New Madrid Fault Zone. Most comparisons are based on an annual exceedance probability of 10^{-3} , the level corresponding to Moderate Hazard facilities as defined by UCRL-15910. Spectra corresponding to ordinary building code requirements are also included for comparison with the annual probability of exceedance of 2×10^{-3} corresponding to Low Hazard facility requirements. The ground motion appearing on national maps for ordinary building codes is based on a 10% probability of exceedance over a 50 year exposure period, corresponding to an annual probability of about 2×10^{-3} .

VII.A. Development of Response Spectra

Response spectra developed in accordance with UCRL-15910 may use specified shapes scaled in amplitude by peak acceleration so that this quantity is the only measure of ground motion that is needed. Response spectra prepared by U.S.G.S. as well as those presented in the REI reports and the LLNL report do not use peak acceleration as a scaling parameter. Rather these response spectra are constructed using spectral velocities determined at specific periods (or frequencies). This approach requires a separate attenuation function for each period (or frequency) for which a spectral velocity is desired. Thus *shape* of the spectra as well as amplitude may vary.

U.S.G.S. spectra were determined in terms of spectral velocity in cm/sec as a function of frequency and/or period. The attenuation function of Atkinson and Boore (1990) was used for rock spectra and the attenuation function of Boore and Joyner (1991) was used for soil spectra. Rock is a material corresponding to a Soil Profile S_1 described in Section VII.D. Soil is a material corresponding to a Soil Profile S_2 also described in Section VII.D.

The rock and soil spectra in the REI reports (Risk Engineering Inc., 1991) are in terms of spectral velocity in cm/sec as a function of frequency in Hz and were determined using attenuation functions described in those reports. The reports also include the LLNL spectra. The curves in the REI reports were digitized by U.S.G.S and plotted for use in this section. Accordingly, there may be minor differences in curves shown here from the ones in the original source. These minor differences do not affect any conclusions.

All plots of response spectra in this section are for 5 percent damping and are shown with tripartite axes for convenience in determining conventional parameters such as spectral acceleration and velocity. Spectral response velocity is shown with scales for units of in/sec and cm/sec. Spectral velocity is plotted against both frequency and period. For simplicity, symbols are shown only for the first and last data points of each curve.

VII.B. DOE Response Spectra

The UCRL-15910 guidelines allow determination of ground motion by a specific site study or by using the response spectral shapes for DOE facility sites reported in UCRL-53582 (Coats and Murray, 1984) and the peak ground accelerations listed in UCRL-15910 (graphically in UCRL-15910). Since this scaling approach involves use of peak horizontal acceleration, Table VII-1 was prepared to facilitate comparisons among the various procedures.

The response spectra shown in Figures VII-1 and VII-2 for Paducah and Portsmouth, respectively, were provided in graphical form by Martin Marietta Energy Systems (Joe Hunt, personal communication). The curves were digitized at selected points and plotted in the figures. Accordingly, there may be minor differences between the figures and the original source. As before, any such minor differences do not affect the conclusions of this report. The spectra in Figures VII-1 and VII-2 were apparently constructed using the peak values of the horizontal components listed in the UCRL column of Table VII-1.

U.S.G.S. peak ground acceleration values are for the randomly-oriented horizontal components of ground motion, and it is believed that those of the other investigators are the same. Selection of any of the horizontal peak

accelerations in the table leads to a straightforward determination of the spectra in accordance with the UCRL reports. For similar peaks in Table VII-1, the spectra determined using the peaks would also be similar. For example, the median U.S.G.S. and REI peak accelerations for Paducah would result in similar spectra using the standard shapes in UCRL-15910. It should be recognized that the peak horizontal acceleration is not the same as the randomly-oriented horizontal component. Joyner and Boore (1988) suggest reducing the peak value by 13 percent in order to approximate the randomly-oriented value.

VII.C. Building Code Response Spectra

Requirements in UCRL-15910 for General Use and Low Hazard DOE facilities are patterned after the 1988 Uniform Building Code (Uniform Building Code, 1988), although with more extensive site information required in lieu of the general building code requirements for ground motion. In particular, site-specific ground motions are required for use with the UBC design equations. The spectra used for developing general building code requirements provide a useful comparison with the spectra developed in the U.S.G.S. and REI studies for an annual probability of 2×10^{-3} . Much of the background material for the 1988 UBC (UBC, 1988), particularly for spectral shapes, is included in the 1988 NEHRP (NEHRP, 1988), hence this document is referenced for background.

The effects of site conditions on building response is incorporated by the use of soil factors established on the basis of four standard soil profiles described below. The descriptions in the UBC and the NEHRP are slightly different, the UBC wording is used below.

Soil Profile Type S_1 is a profile with (a) a rock-like material characterized by a shear-wave

velocity greater than 2,500 feet per second or by other appropriate means of classification, or (b) stiff or dense soil conditions where the soil depth is less than 200 feet.

Soil Profile Type S_2 is a profile with deep cohesionless or stiff clay conditions, including sites where the soil depth exceeds 200 feet and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays.

Soil Profile Type S_3 is a profile with soft- to medium-stiff clays and sands, characterized by 30 feet or more of soft- to medium-stiff clays with or without intervening layers of sand or other cohesionless soils.

Soil Profile Type S_4 is a profile with more than 70 feet of soft clays or silts characterized by a shear wave velocity less than 400 feet per second.

The NEHRP includes spectra for these profiles and includes procedures for determining design lateral force coefficients from the spectra. The site factors applied to the spectra (but not to the lateral force coefficients for design purposes) for soil profiles S_1 , S_2 , and S_3 are 1.0, 1.5, and 2.0 respectively (Donovan, 1987). The factors are 1.0, 1.2, and 1.5, respectively, when used to determine lateral force coefficients used for design purposes. These factors are independent of frequency. The main point being that in the NEHRP and UBC, soil conditions always result in an increase in ground motion over that of rock except at short periods where the two coincide. There is still considerable debate over the influence of soil type on ground motion.

Spectra for rock (Soil Profile S_1) based on the NEHRP are shown in Figures VII-3 and VII-4 for Paducah and Portsmouth respectively. Acceleration coefficients used in determining the spectra are shown in Table VII-1. These spectra would apply for typical buildings located at the two sites and designed in

accordance with the requirements of UBC or NEHRP. Spectra were determined using the NEHRP provisions. UBC spectra would be similar for Paducah since the acceleration factors are the same. There would be minor differences in lateral force coefficients due to slightly different factors used in UBC equations. The Portsmouth spectra would be different due to the different acceleration coefficients (Table VII-1). As stated earlier, the building code requirements are for a 10% probability of exceedance in a 50 year period corresponding roughly to an annual probability of 2 times 10^{-3} (rather than 1 times 10^{-3} required for Moderate Hazard structures). The ground-motion parameters used to construct the spectra were determined from the NEHRP generalized maps (for Paducah and Portsmouth these also correspond to parameters determined from the UBC zone map). The spectra obtained are not necessarily expected to correspond to those obtained from a site-specific study for different probability levels of exceedance. Site-specific studies would be expected to be more accurate since they are based on a detailed study reflecting characteristics of the site. The spectra do provide a basis for comparison between building code design requirements for ordinary buildings and the U.S.G.S. spectra and the spectra in the REI report prepared for an annual probability of exceedance of 2×10^{-3} .

VII.D. Paducah Spectra

Spectra for three of the U.S.G.S. source models examined in this report that might affect Paducah are shown in Figure VII-5. Two spectra are shown for each of the three models, one for rock and one for soil. U.S.G.S. model A is described in Section VI.C.1 as the "reference" model, the one based on the zonations (Algermissen and others, 1982; Algermissen and others, 1990) used for parameter variation study. Model A reflects the

basis for the national hazard map estimations. U.S.G.S. Model B is that referred to in Section VI.C.5 as Model 2. Model B is considered a reasonable lower bound model. U.S.G.S. Model C is one selected from the New Madrid Fault Zone sensitivity models of section VI.C.7, the one having the New Madrid Fault Zone ruptures terminating about 10 km short of the site and using a medium length rupture vs magnitude relationship. Model C is the "preferred model" for the purpose of generating spectra, and produces a peak acceleration at a 1000-year return period near the median of the values produced by "reasonable" U.S.G.S. models studied.

Figures VII-6 and VII-7 show spectra taken from the REI report on Paducah (as described in Sec. VII.B). Spectra are shown in Figure VII-6 for both rock and soil based on the EPRI/SOG and LLNL methodologies and the combination of these two. The LLNL spectra represent median results including all ground-motion experts (This was done for simplicity since the median results excluding ground-motion expert No. 5 differ only slightly. Refer to the REI and LLNL reports for spectra with and without Expert No. 5). Figure VII-7 includes only the rock spectra of Figure VII-6 and the median rock spectrum developed by REI considering fault rupture. Only rock spectra are shown to simplify the figure and because a median spectra for soil was not available for the REI fault-rupture model. The shape of the median curve, which considers fault rupture length, differs from the others particularly in the short period range. The EPRI/SOG spectrum forms a lower bound while the LLNL and REI spectra form upper bounds.

The REI median rock spectrum from Figure VII-7 is also shown in Figure VII-8 along with U.S.G.S. rock spectra for models A, B, and C. The REI fault-rupture model exhibits the same shape and trends as the U.S.G.S. spectra for Models A, B, and C although the U.S.G.S.

preferred model C has higher amplitude except at two seconds, where they coincide. The results for Models A and B are quite similar in amplitude to the REI curve (except at periods of 1 and 2 sec).

The rock spectra for the three U.S.G.S. models from Figure VII-5; the EPRI/SOG, LLNL, and REI median spectra in Figure VII-7; and the UCRL spectra from Figure VII-1 are compared in Figure VII-9. Only the rock spectra are shown in order to simplify the figure. The UCRL curve establishes a clear upper bound, except for the short period region of the spectrum. It should be noted that this curve apparently considers specific site conditions whereas the others are for rock. The UCRL spectrum was prepared using a standard shape scaled by using the peak horizontal acceleration. The EPRI/SOG rock spectrum establishes a lower bound.

Rock spectra for an annual probability of exceedance of 2×10^{-3} are compared to the building code rock spectrum in Figure VII-10. The building code spectrum exceeds the EPRI/SOG median curve for all periods. For periods larger than 0.15 second the building code spectrum exceeds the USGS spectrum.

VII.E. Portsmouth Spectra

Spectra for source U.S.G.S. Model D for Portsmouth are shown in Figure VII-11. Two spectra are shown in the figure, one for rock and one for soil. U.S.G.S. source Model D, the U.S.G.S. "preferred" model for generating a Portsmouth spectrum, is the modified reference model of section VI.B.1, in which the national hazard map zonation (Algermissen and others, 1982; Algermissen and others, 1990) has been altered by modeling the uncertainty in the source zone boundaries as having a Gaussian distribution with a standard deviation of 40 km.

Figure VII-12 shows spectra taken from the REI report on Portsmouth (as described in Sec. VII.B). Spectra are shown for both rock and soil based on the EPRI/SOG and LLNL methodologies and the combination of these two. The LLNL spectra include all ground-motion experts. The rock spectra from this figure are compared with the rock spectrum for the preferred U.S.G.S. model in Figure VII-13. Only rock spectra are shown to simplify the figure. The U.S.G.S. spectrum forms an upper bound while the EPRI/SOG spectrum forms a lower bound. All spectra are similar in shape except that the U.S.G.S. spectrum does not begin to decrease at a period of around 0.1 second as the other spectra do.

The rock spectra from Figure VII-13 are compared with the UCRL spectrum from Figure VII-2 in Figure VII-14. Soil spectra are not shown for simplicity. The UCRL curve establishes a clear upper bound, except for the short periods. It should be noted that this curve apparently considers specific site conditions. The EPRI/SOG spectrum once again establishes a lower bound.

The rock spectra for an annual probability of exceedance of 2×10^{-3} are compared to the building code rock spectrum in Figure VII-15. The building code spectra in general forms an upper bound, followed by the U.S.G.S. spectrum. The EPRI/SOG spectrum is considerably less than the building code spectrum.

VII.F. Spectral Shapes

Response spectra at the Paducah and Portsmouth sites obtained by various methodologies (EPRI/SOG, LLNL, combined EPRI/SOG-LLNL, REI rupture model, and U.S.G.S. models) are compared with spectra obtained using several approaches permitted by UCRL-15910, some based on building code

provisions. In general the spectra differ less at the short period end than at the long period. At the long-period end, methods (UCRL 15910) using a spectral shape scaled by peak acceleration produce higher values than those methods for which the spectral ordinates have been calculated by the methods of seismic hazard analysis.

For the U.S.G.S. models at both sites and the REI rupture model (only calculated for Paducah), the spectra have similar shape but do not seem to be converging to the short-period values obtained by EPRI/SOG or LLNL, or the values used in the building-code based methods. This effect appears due to higher short-period spectral levels obtained from the U.S.G.S. rupture models at Paducah.

At longer periods, the spectral levels are very different between the values obtained by the EPRI/SOG methodology and those obtained by either the LLNL methodology or U.S.G.S. This effect can possibly be explained in terms of the influence of the maximum magnitude earthquake in the spectral attenuation functions. A general rule is that the longer the spectral period, the greater is the increase in ground motion for a given increase in magnitude. This fact means that the longer the spectral period the more maximum magnitude affects the probabilistic ground-motion result.

In the EPRI/SOG methodology, if there is no known tectonic influence and the historical seismicity is low, there tends to be low maximum magnitudes assigned to sources. Background maximum magnitudes would be low for this reason. For the LLNL methodology, the experts have chosen maximum magnitudes for background zones which range from magnitude 5.0 to 7.5 (m_b), two-thirds of the values being from magnitude 5.0 to 6.0. The U.S.G.S. model uses a minimum central maximum magnitude of 6.1 (M_s) regardless of whether the zone is background or not.

Accordingly, it would be expected that at longer periods the lowest spectral values would be those of the EPRI/SOG methodology, followed in turn by the combined EPRI/SOG-LLNL values, the LLNL values, and the U.S.G.S. values. Examination of Figures VII-7, VII-9, and VII-11 shows this to be the case. However, it can also be argued that the U.S.G.S. models yield higher values at short periods, and that the true comparison in spectral shapes ought to be made by forcing the short period ordinates to be the same. If this adjustment is made, it appears that the U.S.G.S. preferred spectrum falls between the LLNL spectrum and that of the combined EPRI/SOG-LLNL result.

It is concluded that the higher U.S.G.S. spectral values at long periods are due in part to higher-rate models in the vicinity of the site in the case of Paducah and in part due to higher maximum magnitudes for source zones in the case of Portsmouth. Similarly, the generally low spectral results, particularly at long periods, for the EPRI/SOG methodology results are due in part to lower rate models and lower maximum magnitudes in those models.

In view of the differences between U.S.G.S. spectra and spectra based on the EPRI/SOG methodology, some of the possible reasons for the differences were examined quantitatively. Comparisons are made only for rock spectra for the Portsmouth site. Some of the possible reasons for the differences include (1) attenuation function, (2) earthquake magnitude, (3) minimum earthquake magnitude, and (4) source zones.

- (1) Attenuation function—The U.S.G.S. used the Moment Magnitude version of the 1990 Atkinson-Boore attenuation function for developing the site rock spectra. REI used the Nuttli Magnitude version of the 1987 Boore-Atkinson, Toro-McGuire, and Nuttli attenuation functions, weighting the results to obtain rock spectra. In order to provide some

insight on the effects of the different attenuations, three figures differing only in attenuation function were prepared. Figure VII-16 is based on the Atkinson-Boore attenuations. Figure VII-17 is based on the Toro-McGuire attenuation, and Figure VII-18 is based on the Nuttli attenuation. Results in Figure VII-16 are used in discussing the remaining three factors since the three figures provide the same type of information except for the attenuation function used in determining the spectral shapes. Following the discussion of Figure VII-16, comparisons of all three figures are made.

- (2) Earthquake magnitude scale—The U.S.G.S. hazard analysis in the rest of this report used the Moment Magnitude scale for the measure of earthquake size. The EPRI/SOG uses essentially the Nuttli Magnitude for the measure of earthquake size. Since the conversion between the two scales is not completely resolved (see section VIII of this report), U.S.G.S. did some limited analysis presented in Figures VII-16 through 18 based entirely on use of the Nuttli magnitude scale and thereby avoiding any conversions. This provides a common ground for comparing the spectra. The original U.S.G.S. spectra, the LLNL spectra, and the EPRI/SOG spectra are shown dashed in Figure VII-16 (and in Figures VII-17 and 18) for comparison with results based strictly on use of the Nuttli Magnitude. It is clear that basing the analysis on the Nuttli Magnitude results in spectra much closer to the EPRI/SOG methodology but differing according to the minimum earthquake magnitude used in analysis. This is discussed below.
- (3) Minimum earthquake magnitude—The influence of minimum earthquake magnitude on results is clearly shown in Figure VII-16 by comparing the spectra resulting from using minimum magnitude of 4.3, 4.9, and 5.5. The differences are significant for the short periods but converge for periods near one second. The smaller the minimum magnitude used in the analysis, the larger the spectral also

dependent on the source zones used in the analysis as discussed below.

- (4) Source zones—In order to allow comparison of the attenuation functions the same source zones were used in developing all three figures. All source zones used are the U.S.G.S. source zones described elsewhere in this report, but rates are based on observed Nuttli magnitudes in those zones. To show the effect of using or neglecting distant sources, comparisons are made for a minimum magnitude of 5.5. When only nearby sources are used in the analysis, the spectra are about the same for periods less than about 0.5 second. There is a sharp drop off in spectral response for longer periods as compared to the case when all distant sources are included.

These observations are the same for the Toro-McGuire function in Figure VII-17. It is worth noting that the spectral results using the U.S.G.S. source zones and this attenuation are larger than the results using the Atkinson-Boore attenuation. It is also larger than results using the EPRI/SOG methodology.

Once again, the general observations hold for the Nuttli attenuation in Figure VII-18. The spectral values are near the LLNL results for short periods but near the U.S.G.S. for longer periods except for 2.0 seconds where it is larger.

These results have shown that it is critical for a site such as Portsmouth to include distant sources to avoid distortion of the spectra at long periods. Similarly the selection of minimum magnitude is important to spectral values at short periods.

However, some questions have been raised that cannot be fully resolved at this time. There are indications that the U.S.G.S. results obtained starting with Moment Magnitudes may be somewhat high, on the other hand there seem to be no indications that the results should be as low as that obtained by use of the EPRI/SOG

methodology. This is particularly true since there have been historical earthquakes at Portsmouth producing damage, which does not appear consistent with the EPRI/SOG results.

The spectra developed using the Nuttli Magnitude form of the Atkinson-Boore equation gives results lower than that obtained by using the other two attenuation equations. It is not clear that this is true for the Moment Magnitude form of the Atkinson-Boore equation (see section VIII).

This brief study on spectral shapes has answered some questions about spectral shapes, but it has also raised some questions about spectral amplitude. It has indicated that there may be some reason to change the U.S.G.S. results but at this time it is not clear by how much and in what direction. It has also raised some question about the EPRI/SOG results. It is concluded that it is prudent not to prematurely modify the results of the U.S.G.S. analysis until some of these questions have been answered.

VII.G. Conclusions

Response spectra at the Paducah and Portsmouth sites obtained by various methodologies (EPRI/SOG, LLNL, combined EPRI/SOG-LLNL, REI rupture model, and U.S.G.S. models) were compared with spectra obtained using several approaches permitted by UCRL 15910, some based on building code provisions. In general the spectra differ less at the short period end than at the long period. At the long-period end, methods using a spectral shape anchored by peak acceleration produce higher values than those methods for which the spectral ordinates have been calculated by the methods of seismic hazard analysis.

For the U.S.G.S. models at both sites and the REI rupture model (only calculated for Paducah), the spectra have similar shape but do

not seem to be converging to the short-period values obtained by EPRI/SOG or LLNL, or the values used in the building-code based methods. This effect appears due to higher short-period spectral levels obtained from the U.S.G.S. rupture models at Paducah.

At longer periods, the spectral levels obtained by the EPRI/SOG methodology are very different from those obtained by the other methodologies. It is believed that the higher U.S.G.S. spectral values at long periods are due in part to higher-rate models in the vicinity of the site in the case of Paducah and in part due to higher maximum magnitudes for source zones in the case of Portsmouth. Similarly, the generally low spectral results, particularly at long periods, for the EPRI/SOG methodology results are due in part to lower-rate models and lower maximum magnitudes in those models.

Considering the sites individually, at the Paducah site the spectra for both soil and rock are bounded on the high side by the UCRL spectra and on the low side by the EPRI/SOG spectra for rock. An ordinary building code spectrum, which is not site-specific, exceeded the EPRI/SOG, LLNL, and combined EPRI/SOG-LLNL spectra for periods around one second and the EPRI/SOG spectra for all periods. The spectra for the REI fault-rupture model was similar in shape and amplitude to the U.S.G.S. spectra.

At the Portsmouth site it was also found that the spectra for both soil and rock were bounded on the high side by the UCRL spectrum and on the low side by the EPRI/SOG spectrum for rock. The ordinary building code spectrum, which is not site-specific, exceeded the other spectra for periods around one second and the EPRI/SOG spectrum for all periods. The U.S.G.S. spectrum was not significantly lower than the building code spectrum.

While it is not surprising to see differences between the spectra for individual sites and the spectra for building codes, the large differences

for the spectra obtained using the EPRI/SOG methodology is surprising. While it can be argued that the information for the specific sites is more accurate, it must also be noted that ordinary buildings would be required to meet the code spectra if seismic design requirements were enforced.

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Table VII-1. Comparison of 0.50 fractile peak accelerations for an annual probability of exceedance of 10^{-3}

Location	Profile	EPRI/SOG ¹	LLNL with All Experts ¹	LLNL without Expert No. 5 ¹	Combined EPRI/SOG and LLNL with All Experts ¹	Combined EPRI/SOG and LLNL without Expert No. 5 ¹	Risk Eng., Inc. ¹	USGS	UCRL ⁴	NEHRP ⁵ A _a , A _v	UBC ⁶ Z
Portsmouth	Rock	0.025g	0.045g ²	0.03g ²	0.03g	0.03g		0.082g		0.050g	0.075g
	Soil ³	0.06g	0.075g	0.055g	0.07g	0.06g			0.11g	0.075g	
Paducah	Rock	0.21g	0.325g	0.26g	0.225g	0.23g	0.32g	0.32g		0.150g	0.150g
	Soil ³	0.26g	0.30g	0.26g	0.26g	0.26g			0.45g	0.225g	

1 Values were read from curves in the Risk Engineering, Inc. May 9, 1991 revised seismic-hazard results for Paducah, and May 24, 1991 Seismic Hazard Evaluation for the Portsmouth Gaseous Diffusion Plant, Portsmouth, Ohio.

2 Values were extrapolated beyond the curves in the Risk Engineering, Inc. reports.

3 Soil is as defined by the particular methodology. It is not necessarily the same for each.

4 Values were obtained from UCRL-15910, 1990. Values are listed as soil since they are for specific site conditions.

5 The NEHRP Effective Peak Acceleration, A_a, and Effective Peak Velocity-Related Acceleration, A_v, are mapped only for rock. The two coefficients are not always the same although they are for these two DOE sites. Soil values were obtained by using a soil factor of 1.5 for spectral values.

6 The UBC Z factor is taken to be equivalent to an effective peak acceleration.

Table VII-1. Comparison of 0.50 fractile peak accelerations for an annual probability of exceedance of 10^{-3} determined by LLNL, EPRI/SOG, Combined EPRI/SOG and LLNL, Risk Engineering, Inc., UCRL-15910, and U.S.G.S.

Figure VII-1. Paducah response spectrum corresponding to UCRL-53582 (supplied by Martin Marietta Energy Systems). The annual probability of exceedance is 10^{-3} .

Figure VII-2. Portsmouth response spectrum corresponding to UCRL-53582 (supplied by Martin Marietta Energy Systems). The annual probability of exceedance is 10^{-3} .

Figure VII-3. Building code rock response spectrum for Paducah. This spectrum, with modifications, forms the basis for the NEHRP and UBC lateral force coefficients. The annual probability of exceedance is about 2×10^{-3} .

Figure VII-4. Building code rock response spectrum for Portsmouth. This spectrum, with modifications, forms the basis for the NEHRP and UBC lateral force coefficients. The annual probability of exceedance is about 2×10^{-3} .

Figure VII-5. Paducah response spectra for an annual probability of exceedance of 10^{-3} using three different source models. Two spectra are shown for each of the three models, one for rock and one for soil. U.S.G.S. A is the Reference Model. U.S.G.S. B is the Model 2. Model C is the Sensitivity Model. U.S.G.S. C is the preferred model.

Figure VII-6. Comparison of Paducah spectra for an annual probability of exceedance of 10^{-3} for rock and soil as determined by EPRI/SOG, LLNL, and the two methodologies as combined by Risk Engineering, Inc. The LLNL results include all ground-motion experts.

Figure VII-7. Comparison of Paducah spectra for an annual probability of exceedance of 10^{-3} for rock as determined by EPRI/SOG, LLNL, and the two methodologies as combined by Risk Engineering, Inc. The LLNL results include all experts. The Risk Engineering, Inc. (REI) spectrum for rock is based on a model that considers fault rupture length.

Figure VII-8. Comparison of Paducah REI rupture spectrum for an annual probability of exceedance of 10^{-3} for rock from Figure VII-7 with the U.S.G.S. rock spectra for Models A, B, and C from Figure VII-5.

Figure VII-9. Comparison of Paducah spectra for an annual probability of exceedance of 10^{-3} for rock from Figures VII-7 and 8 with the spectra for UCRL-53582 from Figure VII-1.

Figure VII-10. Comparison of Paducah spectrum for rock for NEHRP requirements with rock spectra based on USGS model C and the EPRI/SOG methodology. The latter two spectra are for an annual probability of exceedance of 2×10^{-3} .

Figure VII-11. Portsmouth response spectra for an annual probability of exceedance of 10^{-3} using the U.S.G.S. preferred source model. Spectra are shown for rock and soil.

Figure VII-12. Comparison of Portsmouth spectra for an annual probability of exceedance of 10^{-3} for rock and soil as determined by EPRI/SOG, LLNL, and the two methodologies as combined by Risk Engineering, Inc. The LLNL results include all ground-motion experts.

Figure VII-13. Comparison of Portsmouth spectra for an annual probability of exceedance of 10^{-3} for the U.S.G.S. preferred model (U.S.G.S. D) for rock with rock spectra as determined by EPRI/SOG, LLNL, and the two methodologies as combined by Risk Engineering, Inc. The LLNL results include all ground-motion experts.

Figure VII-14. Comparison of Portsmouth spectra for an annual probability of exceedance of 10^{-3} for rock from Figures VII-11 and 12 with the spectra for UCRL-53582 from Figure VII-2.

Figure VII-15. Comparison of Portsmouth spectra for rock for NEHRP requirements with rock spectra based on USGS model D and the EPRI/SOG methodology. The latter two spectra are for an annual probability of exceedance of 2×10^{-3} .

Figure VII-16. Rock spectra for Portsmouth using the Atkinson-Boore attenuation based on use of Nuttli magnitude. Spectra are prepared using minimum magnitudes of 4.3, 4.9, and 5.5 using all distant sources. A minimum magnitude of 5.5 using only near sources is provided for comparison with the minimum 5.5 magnitude using all distant sources. For comparison, the rock spectra based on the USGS model D, the EPRI/SOG methodology, and the LLNL methodology are also shown.

Figure VII-17. Rock spectra for Portsmouth using the Toro-McGuire attenuation based on use of Nuttli magnitude. Spectra are prepared using minimum magnitudes of 4.3, 4.9, and 5.5 using all distant sources. A minimum magnitude of 5.5 using only near sources is provided for comparison with the minimum 5.5 magnitude using all distant sources. For comparison, the rock spectra based on the USGS model D, the EPRI/SOG methodology, and the LLNL methodology are also shown.

Figure VII-18. Rock spectra for Portsmouth using the Nuttli attenuation based on use of Nuttli magnitude. Spectra are prepared using minimum magnitudes of 4.3, 4.9, and 5.5 using all distant sources. A minimum magnitude of 5.5 using only near sources is provided for comparison with the minimum 5.5 magnitude using all distant sources. For comparison, the rock spectra based on the USGS model D, the EPRI/SOG methodology, and the LLNL methodology are also shown.

VIII. Relations between Magnitude Scales from Measurements of U.S. Earthquakes—Preliminary Results

by

G. A. Bollinger

Summary

The purpose of this study is to determine a method of uniform size classification for intraplate eastern U.S. (EUS) earthquakes and interplate western U.S. (WUS) earthquakes. In principle, the various magnitude scales in use by seismologists should give such uniformity. However, because of the use of different seismic phases, frequencies, and seismographs in regions with markedly different attenuation properties, along with the variability in the definitions of magnitudes and the changes with time in their calculation, the requisite uniformity has not been achieved.

All of the principal magnitude scales (m_b , $m_b(Lg)$, M_L , M_S , M) are investigated using averages of multiple values as published by the International Seismological Centre. Moment estimates are taken from a special compilation by Stover and Coffman of the U.S. Geological Survey. These two data sets are judged to represent the most accurate size estimates that are presently available in catalog form.

Intercomparisons between the various scales indicate that:

$$m_b \text{ (EUS)} \approx m_b(Lg) \text{ (EUS)}$$

$$M_L \text{ (WUS)} \approx m_b \text{ (WUS)}$$

$$M_S = -3.23 + 1.57 m_b \text{ (EUS and WUS)}$$

$$M \approx M_L \text{ (WUS)} \quad (4.5 < M_L < 7.0)$$

$$M = -0.70 + 1.09 m_b(Lg) \text{ (EUS)}$$

It is recommended that the latter two equations be used when uniformity of earthquake size classification across the U.S. is required.

Introduction

The objective of this investigation is to: (1) Assemble a sample of the most recent and most accurate magnitude estimates available for U.S. earthquakes and (2) compare the various scales, especially in an EUS or eastern North America (ENA; east of the Rocky Mountains) versus WUS context. At the present time, 5 magnitude scales and 1 intensity scale are used to categorize U.S. earthquakes according to size. The magnitude scales are: m_b (body wave magnitude - SPZ teleseismic, P-wave), M_L (Local magnitude - SPH for western U.S. S-waves), $m_b(Lg)$ (or Lg Nuttli magnitude - SPZ for eastern U.S. higher mode surface-waves), M_S (surface wave magnitude - LPZ for 20 sec. teleseismic fundamental mode Rayleigh waves) and M (moment magnitude - based on an estimate of the radiated seismic energy). As pointed out by Hanks and Kanamori (1979), the m_b , M_S and M_L scales saturate at large magnitudes, ~ 7 for m_b and M_L ; and $\sim 8+$ for M_S , due to their foundation in narrow-band, time domain amplitude measurements. Nuttli's (1973) $m_b(Lg)$ magnitude was designed to be an m_b equivalent at less than teleseismic distances ($<20^\circ$ - 25°) for eastern North America and, thus, shares the saturation property. However, because m_b and $m_b(Lg)$ are derived from different seismic phases, they do not saturate in exactly the same manner. M is based on the seismic moment (M_o) and does not saturate. The m_b , M_S , and M scales are in use for global earthquakes and not just those occurring in the U.S. The intensity scale for the

U.S. is the Modified Mercalli Scale (Wood and Neumann, 1931).

During the past two decades, considerable attention has been devoted to biases present in the global or regional results from individual scales and to the relationships between the various individual scales (see, e.g., Evenden and Kohler (1976), Chinnery (1978), Der and others (1979), Herrmann and Nuttli (1982), Chung and Bernreuter (1981), Nuttli and Herrmann (1982), Chulick and Herrmann (1986), Ekström and Dziewonski (1988)). Some of these studies lead to differing or contradictory results. There has also been considerable evolution in the exact manner in which the scales are applied (see, e.g., Herrmann and Kijko (1983), Nuttli (1983), Atkinson and Boore (1987), and Hutton and Boore (1987), Bender (1987), Habermann and Cray (1988), Rong-Song and Shumway (1989), and Michaelson (1990)). This high level of research concentration on the magnitude scales resulted in large part from the requirements of nuclear test discrimination and seismic hazard assessment.

Incorporation of the results from seismic hazard assessment into national building codes and into earthquake mitigation, preparedness and response programs necessitates that the size classification of shocks be uniform across the contiguous U.S. In principle, this should present no difficulty, but, in practice, a number of difficulties arise. First, two of the magnitude scales, M_L and $m_b(Lg)$ are tied to specific areas, and, in the case of M_L , to a specific seismograph (the Wood-Anderson torsion instrument) which is not part of the worldwide Standard Seismograph Network instrumentation. Relation to a specific area implies being tied to the attenuation characteristics of that area. Secondly, both M_L and $m_b(Lg)$ are "local" or "regional" scales in that they were both designed to be applied primarily or exclusively at distances less than teleseismic (M_L at ≤ 600 km ; $m_b(Lg)$ at 55 km

to 3,335 km). M_L was, of course, the original magnitude measure and was originally calibrated for southern California, while $m_b(Lg)$ was designed as a similar local/regional measure for eastern North America that was to be, at teleseismic distances, the equivalent of m_b . The point of primary interest here is the fact that M_L and $m_b(Lg)$ are not designed to be directly comparable.

A second difficulty stems from the fact that the overall size of the contiguous U.S. is near the distance range specified as teleseismic. Estimation of m_b for U.S. earthquakes generally requires data from seismograph stations outside of the country. This, in turn, results in virtually no U.S. earthquakes with m_b estimates from both eastern U.S. (EUS) and western U.S. (WUS) seismograph stations. Finally, there have been very few, less than 10, EUS earthquakes with magnitudes large enough (≥ 5) to be recorded teleseismically during the past two decades. This makes for a sparse data base with which to compare to the much more seismically active WUS.

A full review of the nature and evolution of the magnitude scales is beyond the requirements of the present stage of this study. Rather, it is accepted that problems with various scales have been present in the past and that an evolution of the scales has occurred and, indeed, is continuing to occur.

The following text will first present the data base (catalog of U.S. earthquake magnitudes) and then discuss the various relationships between the individual magnitude measures that can be developed therefrom. Finally, recommendations are made concerning uniformity in earthquake size estimation between the EUS and the WUS.

VIII.A. Data Base Development

Required for this study are as many different types of magnitude estimates as possible for EUS and WUS earthquakes. Also, each of the estimates should be as accurate as possible and should avoid well-known published pitfalls, inconsistencies and biases. The best sources for this type of data known to the writer are the Bulletins of the International Seismological Centre (ISC) in Newburg, United Kingdom. Their annual *Felt and Damaging Earthquakes* is especially convenient for studies such as this one. Since 1970, the ISC has published in an enlarged format (8x11 inches) and has collected magnitude estimates of all types, in addition to calculating its own m_b and/or M_S . The most frequent "other" magnitudes are m_b and M_S from the U.S. Geological Survey, U.S.A. and Institute of Earth Physics, U.S.S.R. and M_L from Pasadena and Berkeley, California. The seismic labs at Beijing, China, and at Harvard University, Massachusetts, also contribute size estimates. Individual $m_b(Lg)$ values from the U.S.G.S. and from University-based Seismological Observations in the EUS are also reported as available. This collection of magnitude estimates for a given earthquake is possible because of the 2- to 3-year lag between the occurrence of a shock and the listing of its parameters in an ISC publication. For the m_b - M_S - M_L - $m_b(Lg)$ comparisons herein, the averages of the ISC values for each magnitude type are used. If a total of 4 or 5 estimates are available for the pair of magnitude types being considered, a weight of 2 is assigned to the average value and if a total of 6 or more estimates are used, then a weight of 3 herein is used. Three or fewer magnitude values result in a weight of unity.

For moment magnitude (M) versus m_b and versus M_L , the moment values (M_o) as listed in *U.S. Earthquakes, 1569-1989 Revised* by Stover and Coffman (1991) are converted to M

according to Hanks and Kanamori (1979). The $m_b(Lg)$ and M_L values are also from Stover and Coffman (1991).

VIII.B. Comparison of the m_b , $m_b(Lg)$, M_L and M_S Magnitudes

VIII.B.1. $m_b(Lg)$ versus m_b in the eastern U.S.

As previously noted, Nuttli (1973) designed $m_b(Lg)$ to be the equivalent, at teleseismic distances, of m_b . Figure 1 shows this to be the case, i.e., $m_b(Lg) \approx m_b$ for $4 \leq m_b \leq 6$.

Wetmiller and Drysdale (1982) compared Nuttli's (1973) $m_b(Lg)$ to m_b for 6 Canadian earthquakes with $3.8 \leq m_b \leq 5.4$. They found that Nuttli's formula for 1 sec Lg waves and $400 \text{ km} \leq \text{Epicentral } \Delta \leq 3,000 \text{ km}$ gave unbiased estimates of m_b with a standard deviation of ± 0.4 units when used for 2-10 Hz Lg waves and $25 \text{ km} \leq \text{Epicentral } \Delta \leq 1,000 \text{ km}$ for the Canadian earthquakes. Herrmann and Kijko (1983) argued that using Nuttli's formula in that manner violated the basic physics of wave propagation (a substantially different geometric spreading was being used at distances less than 400 km) and that the Canadians should instead replace the $\log(A/T)$ term by a $\log(A)$ term when they used Lg waves whose frequencies were much higher than 1 Hz. Herrmann and Kijko (1983) developed such a formula that included a term containing the coefficient of anelastic attenuation applicable to the Lg frequencies and to the raypath volume. They used synthetic seismogram studies to support their, and Ebel's (1982), contention that for Lg waves in the 5- to 10-Hz range, the $\log(A)$ term should be used.

Ebel (1982) found that $m_b(Lg)$ calculated using the high-frequencies and the $\log(A/T)$ term were 0.4 units higher on the average than M_L

estimates from Wood-Anderson seismographs at Weston Observatory for $1.5 \leq m_b(Lg) \leq 5$. Ebel, as well as others, termed the "high-frequency" $m_b(Lg)$ as m_N (N for Nuttli). More recently, however, it appears that m_N has also come to be used as an equivalent symbol for $m_b(Lg)$ rather than just to indicate the "high-frequency" version. It is sometimes very difficult to interpret with certainty the m_N symbol. The Canadians continue to use their high frequency m_N and take care to assure that it is indeed the equivalent of m_b and/or $m_b(Lg)$ (Wetmiller, 1991, pers. comm.).

The preceding discussion indicates that some early 1980's catalog $m_b(Lg)$'s may indeed be m_N 's and thereby an overestimate of the true size of the earthquake. However, since that time, the effect of frequency on the $m_b(Lg)$ formula has become well known and modern estimates should be made properly.

Chung and Bernreuter (1981) stated that, while differences due wave types in m_b and $m_b(Lg)$ (body waves versus surface waves) might be expected to result in some differences between the two scales, the available published data indicated good agreement as long as enough stations were used to ensure that azimuthal variations average out. They did not, however, present any data or quantitative results.

VIII.B.2. M_L versus m_b in the Western U.S.

Chung and Bernreuter (1981) devoted considerable attention to the M_L - m_b relationship in the WUS as they sought a conversion of m_b in the EUS to an M_L in the WUS. They used some 18 "Nuttli corrected" m_b values (their Figure 3), all of which were lower than the NEIC values (National Earthquake Information Center, U.S.G.S.), yielding a lower m_b value for a fixed M_L value or vice-versa. Based on theoretical arguments, Chung and Bernreuter (1981) assumed that,

$$m_b(\text{WUS}) \cong m_b(\text{EUS}) - \Delta m_b,$$

and that

$$\Delta m_b \approx 1/3.$$

Using that value, their final WUS-EUS result was,

$$M_L(\text{WUS}) = 0.57 + 0.92 m_b(\text{EUS})$$

This formula yields an $M_L = 4.25$ for an $m_b = 4.0$ decreasing to $M_L = m_b$ at $m_b = 7.0$

Herrmann and Nuttli (1982) calculated $m_b(Lg)$ values at 3 California WWSSN stations using region-specific values for the spatial coefficient of anelastic attenuation. Their comparison of the resulting $m_b(Lg)$ values with published M_L values for the same shocks showed the two to be essentially equivalent between magnitudes 3 to 5. (It is important to note here that it is magnitudes greater than 5 that are of interest in calculation of seismic hazard.) They stated that, "This agreement is accidental, but is pleasant nonetheless." It is accidental because the M_L scales use the peak 5-wave amplitude recorded on a Wood-Anderson horizontal torsion seismograph (natural frequency = 1.25 Hz) irrespective of frequency, while the m_b scale uses teleseismic vertical component P-wave amplitudes with frequencies near 1 Hz on electromagnetic seismographs.

The relationship between $M_L(\text{WUS})$ and $m_b(\text{WUS})$ derived from the ISC catalogs is shown in Figure 2. These results indicate that,

$$M_L(\text{WUS}) = -0.03 + 1.02 m_b(\text{WUS}),$$

$$4 \leq m_b \leq 6$$

which compares with Chung and Bernreuter's,

$$M_L(\text{WUS}) = 0.54 + 0.88 m_b(\text{WUS})$$

NEIC data base

$$M_L(\text{WUS}) = 0.85 + 0.92 m_b(\text{WUS})$$

Nuttli data base

The ISC data base indicates virtual equality with the NEIC data base results, while the

Nuttli data used by Chung and Bernreuter (1981) gives an M_L of 4.5 for $m_b = 4.0$ and $M_L = 6.4$ when $m_b = 6.0$. B. Bender (1991, written comm.) also showed that $M_L(\text{WUS}) \approx m_b(\text{WUS})$ using an updated version of the NEIC catalog (the HDS catalog). The recency of the ISC magnitudes (1976-1987) and their derivation from calculations at multiple research centers, together with similar results derived from NEIC catalogs, provide a strong case for the equivalency of M_L and m_b in the WUS.

VIII.B.3. M_S versus m_b in the Eastern and Western U.S.

This comparison essentially looks at two different periods of the source spectra in opposite parts of the country in that m_b 's are derived from 1 sec data while M_S 's are based on 20 sec data. This particular comparison has received extensive study because of its relevance to nuclear test detection programs. Some of these studies report various regional biases (see, e.g. Basham (1969), Liebermann and Pomeroy (1969)). Chung and Bernreuter (1981) used various Nuttli catalogs to show that $m_b(\text{WUS})$ may be systematically lower by about 1/3 unit than $m_b(\text{EUS})$, but that, due to sparsity of EUS data and scatter in both EUS and WUS data, it could be that systematic source differences are also contributing to any regional differences.

Figure 3 presents the M_S - m_b comparison based on ISC data. The data distribution suggests that EUS and WUS belong to the same population but are sparse enough and scattered enough that it is impossible to conclude this with any certainty. Unfortunately, while more EUS data are needed, they are not available at this time.

VIII.B.4. Moment Magnitude (M) versus $M_L(\text{WUS})$ and $m_b(Lg)$ (EUS)

The preceding discussions demonstrate the virtual impossibility of a direct comparison of

magnitudes between eastern and western U.S. earthquakes. The interplate - plate marginal - intraplate setting for U.S. earthquakes also complicates any comparison. However, the advent of the seismic moment (M_0) as a direct measure of earthquake energy and its subsequent utilization in moment magnitude does offer a valid basis for East-West comparison. Here, too, probable differences in source physics across the country provide again for possible regional biases. Figures 4 and 5 present such comparisons as derived from the U.S. data base of Stover and Coffman (1991). Moments have been converted to moment magnitudes, M , according to Hanks and Kanamori (1979) and all M_L and $m_b(Lg)$ are instrumentally derived except for the three New Madrid $m_b(Lg) \geq 7$.

Within the scatter of data, Figure 4 shows that,

$$M \approx M_L (\text{WUS}),$$

while Figure 5 indicates that M and $m_b(Lg)$ are not equal. The difference ranges from 0.34 at $m_b(Lg) = 4$ to 0.16 at $m_b(Lg) = 6$ to nearly zero at $m_b(Lg) = 7$. Interestingly, other published relations between M and m_b or $m_b(Lg)$ (e.g., Johnston, 1991, Somerville, 1988, Nuttli, 1983) also show that $m_b(Lg)$ or m_b do not translate directly to M but rather imply an M value some 0.3 lower than a given $m_b(Lg)$, especially for $m_b < 6.5$.

Boore and Atkinson (1987) developed the relationship,

$$M = 2.715 - 0.277 m_b(Lg) + 0.127 (m_b(Lg))^2$$

using data from 13 ENA earthquakes, 5 of which were from pre-WWSSN instruments. For determination of $m_b(Lg)$ they used wave periods up to 10 sec (the Nuttli magnitude is based on periods near 1 sec) and horizontal motion measurements which were converted to the vertical motion required by the Nuttli magnitude. Additionally, they adjusted the Street and Turcotte M measurements for: (1)

constant factors (radiation pattern; free-surface effect, (2) their source spectrum definition, (3) crustal properties, and (4) their assumed H/V ratio. These adjustments were made "for consistency". Thus, both their $m_b(Lg)$ values and the moment magnitude values have been subject to considerable adjustment. These adjustments may or may not be completely valid, but the available data base is too small to allow the validity to be tested.

The approach herein has been to avoid entirely the host of problems associated with the pre-WWSSN data as well as those that developed during the early years of the application of the Nuttli $m_b(Lg)$ scale. As previously mentioned, that approach consisted of using only post-1976 data. The following table compares the Boore and Atkinson $m_b(Lg)$ to M conversion (M_1) to the $m_b(Lg)$ to M conversion developed herein (M_2)

Table VIII-1. Comparison of $m_b(Lg)$ conversion to moment magnitude according to Boore and Atkinson, M_1 , and Bollinger (this section), M_2 .

$m_b(Lg)$	M_1	M_2
4	3.64	3.66
5	4.50	4.75
6	5.62	5.84
7	7.00	6.93

VIII.C. Recommendations

This study investigated the relationships between the various magnitude measures in use to classify U.S. earthquakes according to size. Being sought was some way to assure that intraplate eastern U.S. earthquakes and interplate western U.S. earthquakes with the

same magnitude numbers represented equivalent amounts of strain energy release. The approach to the problem differs from previous such studies in the data bases employed. For magnitudes, only those earthquakes for which the ISC had calculated its own values were selected. That selection process assured that multiple magnitude values would be available (at least since 1971) because of the ISC's reporting practice of including such estimates from other major worldwide seismic centers. For seismic moments, the values selected from those available for each shock by two long experienced investigators (Stover and Coffman, 1991) were utilized. The writer knows of no better catalogs for U.S. earthquake size measures.

The objective of eastern-western size uniformity can be realized by comparisons of M_L in the West and $m_b(Lg)$ in the East with moment magnitude M . The procedure recommended is:

- (1) West of the Rocky Mountains use:

$$M = M_L \quad (4.5 < M_L < 7.0)$$

- (2) East of the Rocky Mountains use:

$$M = -0.70 + 1.09 m_b(Lg)$$

Clearly, this problem warrants additional study. The source of the ~ 0.3 unit difference between $m_b(Lg)$ and M remains unidentified. The regional relationships between magnitudes and MM intensity, not addressed herein, also needs study. A serious impediment remains in the sparse instrumental data base in the eastern U.S., especially for larger earthquakes. Until additional new data or new analyses of existing instrumental data are forthcoming, some uncertainties will remain.

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283.

Eastern U.S.

$m_b(Lg)$ -vs- m_b

$$m_b(Lg) = 0.45 + 0.91m_b \quad R=0.85$$

Figure IX-1. Relationship between $m_b(Lg)$ and m_b in the eastern United States.

Western U.S.

M_L -vs- m_b

$$M_L = -0.034 + 1.02m_b \quad R=0.89$$

Figure IX-2. Relationship between M_L and m_b in the western United States.

Figure IX-3. Demonstration that M_s in the eastern and western United States appear to have the same relationship with m_b .

Western U.S.

M-vs- M_L

$$M = -0.40 + 1.05M_L \quad R = 0.93$$

Figure IX-4. Relationship between moment magnitude M and M_L in the western United States.

Eastern U.S.

M -vs- $m_b(Lg)$.

$$M = -0.70 + 1.09m_b(Lg) \quad R=0.97$$

Figure IX-5. Relationship between moment magnitude M and $m_b(Lg)$ in the eastern United States.

IX. Discussion and Conclusions

by

David M. Perkins

Summary

The two sites under review test two very different types of probabilistic ground-motion hazard analysis. These sites test the methodologies in two different ways. In the case of Portsmouth, there is a low level of historical seismicity in the vicinity of the site and no known nearby tectonic sources. The challenge is that of characterizing the density and spatial distribution of future seismicity. In the case of Paducah there is a low-to-moderate level of historical seismicity in the vicinity of the site, but a well-known tectonic source of high-rate seismicity whose boundary near the site is not well defined. The challenge is that of how to represent the magnitude and uncertainty of the impact of that source.

The assessments for bedrock spectra for Paducah which have been designed to represent the finite-rupture property of the New Madrid source differ only a minor amount from one another and give reasonable estimates for the hazard.

In contrast, the range of median ground-motion estimates at Portsmouth is large between assessors. The increase from EPRI/SOG to LLNL to USGS estimates is almost a factor of two at each step. We have reviewed various possibilities that could account for these contrasts in probabilistic ground motion.

Consideration of the sensitivity studies of sections V and VI suggests that a systematic difference in the treatment of depth or maximum magnitude may produce at most a bias of plus or minus 25 percent. Choice of source zones and the dilution effect of multiple source zones can each produce an effect believed to have a range of about plus or minus 40 percent. Although all these possible sources of bias combined could result in differences approaching a factor of two, the nature of the

methodologies is such that this total bias could conceivably occur between the EPRI/SOG and LLNL estimates but not between the LLNL and USGS estimates.

We believe that the range of median LLNL, EPRI/SOG, and USGS estimates is larger than a reasonable range attributable only to parameter bias. Accordingly, we have investigated other possible sources of discrepancy due to systematic differences in methodology, namely, attenuation function differences, exclusion of distant sources, differences in magnitude conversion in the catalog, differences in assessment of seismicity, and use of p^A methodology. Only the exclusion of distant sources and the use of the p^A methodology are found to be of such a size as to be capable of accounting for the size and direction of the discrepancy between EPRI/SOG and LLNL median peak acceleration results at Portsmouth, and are a more likely source of bias than the parameters discussed previously—depth, maximum magnitude, choice of source zones, "dilution" by multiple source zones. For spectra, an additional source of discrepancy is the use by LLNL of relatively high weighting for attenuations based on Newmark-Hall spectral shapes anchored to peak ground motion.

Finally, we investigated the USGS use of epicentral intensity to guide magnitude conversion, a procedure designed to ensure near-field comparability in the eastern and western United States of ground motions associated with particular epicentral intensities. We find that this procedure can account for the difference between USGS values at Portsmouth and those of EPRI/SOG and LLNL. However, this resulting difference in probabilistic ground motion exists because the relation between epicentral intensity and moment magnitude differs systematically

between the eastern and western United States, for magnitudes between 4 and 6 $m_b(Lg)$. This fact strongly suggests that moment magnitude attenuation functions constructed using random vibrations models in analogy with western United States sources may underestimate, by a factor of two or more, low-level high-frequency probabilistic ground motions in the eastern United States (but probably not the longer period ground motions). Similarly, attenuation functions in which $m_b(Lg)$ is the parameter, rather than moment magnitude, but which are based on a moment magnitude to $m_b(Lg)$ conversion will also underestimate high-frequency probabilistic ground motions.

Comparison of the historical record of intensities experienced in the vicinity of Portsmouth and conversions of those historical intensities to both acceleration and velocity seem to indicate that the USGS estimate of the probabilistic ground motion is more consistent with the seismic history than are the LLNL or EPRI/SOG estimates, which are roughly a factor of two and three lower, respectively, than the USGS estimate.

Notice that these results obtained apply to the Portsmouth site situation, specifically, low probabilistic ground motions. Because the correspondence between epicentral intensity and moment magnitude for higher magnitudes in the east is similar to that of the western United States, the above conclusions probably do not hold for higher probabilistic ground motions, such as those calculated for Paducah.

IX.A. Overview of Results

The two sites reviewed reflect two very different situations in probabilistic ground-motion calculations. In the vicinity of Portsmouth there are no known tectonic sources. There is a moderate-to-low level of historical seismicity in the site vicinity. It appears that the methodological treatment of source-zone boundaries is probably not of much importance, and the use of a point-

rupture model is adequate. Because probabilistic ground motions are low, the value of ground motion given by an attenuation function for a source at large distance from the site is important, especially for larger magnitude earthquakes. Inasmuch as the far-field portion of the attenuation function is not very well controlled by data, the choice of attenuation function may lead to important differences in hazard estimates.

On the other hand, not far from the Paducah site there is a well-known tectonic source (the New Madrid fault zone) whose boundaries are uncertain. Moderately high seismicity is associated with that source, though moderately low seismicity occurs in the immediate site vicinity. Methodological treatment of sources is found to be of great importance. Linear-ruptures are required in modeling the New Madrid source zone and are probably important in modeling the seismicity of the host zone (zone containing site). Probabilistic ground motion values are likely to depend on earthquake ground motions generated by moderate-to-large magnitude earthquakes at moderate-to-short distances from the site. Because many alternative ground-motion models are well-controlled by data at these magnitudes and distances, choice of attenuation function is likely to be of less importance in determining probabilistic ground motions.

The characteristics given above are summarized in table IX-1.

For the Paducah site, the USGS and Risk Engineering methodologies give similar peak acceleration and spectral values. This agreement is not surprising, considering the relative similarities in methodology—few alternative areal sources, linear ruptures and multiple models for terminus of New Madrid fault zone. On the other hand, although the LLNL result is somewhat similar to the USGS and Risk Engineering results, the EPRI/SOG spectral result is quite different from the others.

The failure to model finite ruptures is likely to be the reason for much of the EPRI/SOG discrepancy. However, this argument suggests that the LLNL result, although in agreement with the USGS and Risk Engineering results, is likely to be high if redone with finite ruptures in the source modeling. We have not explored these discrepancies, because these methodologies were not intended to be used to estimate hazard for sites in a seismotectonic setting such as that in the vicinity of Paducah.

At Portsmouth, however, the range of median estimates is large between assessors, the factor increase from EPRI/SOG to LLNL to USGS estimates being almost a factor of two at each step. Although this variability may be of low practical importance (because the probabilistic ground motions are low), it is desirable to assess the source of this discrepancy in the event that it may represent a methodological issue that may result in a greater discrepancy at other sites. Our investigation is documented in the following section.

Table IX-1 Contrasting site characteristics

Portsmouth	Paducah
No known local tectonic source in vicinity	Well-known tectonic source in vicinity
Local source boundaries uncertain	Local source boundaries uncertain
Low level of historical seismicity in site vicinity	Low-to-moderate level of historical seismicity in immediate site vicinity; high-rate source may reach site vicinity
Detailed treatment of sources of less importance	Detailed treatment of sources of great importance
Point-rupture modeling adequate	Finite-rupture modeling required in high-seismicity zone; desirable in host zone
Low-level 1000-yr probabilistic ground motion	Moderate-to high level of 10000-yr probabilistic ground motion

IX.B. Sources of Discrepancy in Hazard Estimates at Portsmouth Site

In this section we review various possibilities for accounting for the contrasts in probabilistic ground motion between the EPRI/SOG, LLNL, and USGS results. First, we examine the results of the sensitivity studies to suggest possible ranges of differences because of systematic bias in the treatment of those parameters studied, that is, (a) choice of

maximum magnitudes, (b) source-zone boundary delineation, (c) choice of source depth, and (d) value of attenuation function uncertainty.

Second, we investigate the consequences of possible bias in other parameters and aspects of methodology, namely, (a) attenuation function differences, (b) exclusion of distant sources, (c) effect of magnitude conversion in the catalog, (d) determination of seismicity rate, and (e) use of the p^A methodology.

Third, we investigate the use by the USGS of epicentral intensity to guide conversion to

moment magnitude, the implications of the historical seismicity in the vicinity of Portsmouth, and the consequences in probabilistic assessment of differences in the correspondence between intensity and magnitude between the western and eastern United States.

IX.B.1. Range of PHA values Owing to Bias In Parameters of Sensitivity Studies

In this subsection we investigate the possibility that biases in the parameters investigated in the sensitivity studies of sections V and VI can account for the differences in PHA results of the EPRI/SOG, LLNL, and USGS studies.

IX.B.1.a. Possible bias from maximum magnitudes

From the sensitivity study at Portsmouth, we conclude that a decrease of about one-half to three-quarters of a unit in maximum magnitude is required to account for a decrease from about 0.09 g to about 0.07 g, that is, about 0.02 g, or about 25 percent. However, it appears that on average, the center maximum magnitudes for EPRI and LLNL active sources are about equal to those used by the USGS. Hence it is unlikely that choice of this parameter, by itself, can account for the differences in median probabilistic ground-motion estimates at Portsmouth. (However, the effect of maximum magnitude in *background* zones will be examined in connection with the p^A methodology, below.)

IX.B.1.b. Possible bias from treatment of source zones.

Uncertainty in source-zone boundaries can contribute significantly to differences in individual hazard assessments. However, when a number of individual assessments are made, and the median assessment is chosen, there is considerably less uncertainty in that

median due to the variation of individual zonations. When there are no known tectonic sources, the effect might be rather that of almost random zonation. In our sensitivity study, we focussed on the idea of representing this random uncertainty by fuzzing a particular zonation by a greater or lesser extent. This method does not capture the entire sense of uncertainty.

Also available to us are the effects of using a random site in the vicinity of the true site, together with fuzzing of the historical seismicity using a greater or lesser fuzzing parameter (see section VI.B.6). (Recall that this method assumes each historical epicenter as a possible future earthquake source with uncertain future location.) This second method in effect captures more of the source-zone uncertainty, with the random site playing the role of random source zone.

For six sites twenty kilometers apart in the vicinity of the Portsmouth site probabilistic ground motion for zero source-zone smoothing ranges from 0.064 g to 0.108 g at the return period of 1000 years. This amounts to a variation of about 25 percent around 0.082 g. This effect is larger than that of maximum magnitude, but it is unlikely that choice of this parameter, by itself, can account for the differences in median probabilistic ground-motion estimates at Portsmouth.

IX.B.1.c. Possible bias from source-depth differences.

According to the sensitivity studies, depth modeled deeper than our modeled 7 km may account for about 0.01 g decrease at the return period of 1000 years, or about 12 percent. The difference resulting from the choice of this parameter is too small to be important in accounting for the differences in median probabilistic ground-motion estimates at Portsmouth.

IX.B.1.d. Possible bias from value of attenuation function uncertainty.

For peak acceleration, the attenuation function uncertainty parameter generally has been measured to range from 0.5 to 0.6. At the 1000-yr return period, decrease of the parameter value from 0.6 to 0.5 results in about a 15 percent decrease in probabilistic ground motion. This decrease is probably a negligible effect. For random vibration model spectral attenuation functions there is no measured value of the attenuation function uncertainty. Boore (oral communication) has recommended using the attenuation uncertainty parameters determined by regression for the Joyner and Boore (1982) spectral attenuation functions. For these functions, the uncertainty parameters reach 0.7 at the longer periods. Decreasing the uncertainty in variability of the attenuation from 0.7 to 0.5 may decrease the ground motion by about 25 percent. This decrease for spectral values at 1 Hz is of greater importance than that of peak acceleration, but does not in itself account for the observed differences in ground motion between the EPRI/SOG, LLNL, and USGS assessments.

IX.B.1.e. Total maximum bias likely from modeling parameters.

Using the above estimates of sensitivity, we can calculate the total possible decrease in probabilistic peak acceleration attributable to bias from the above parameters, assuming the same attenuation function used: We take the USGS value of 0.082 g, decrease by 12 percent for possible deeper depth modeling (yielding .0722 g), by 15 percent for possible lower size of attenuation variability parameter (yielding .0613 g), decrease by 25 percent for possible lower background maximum magnitude (yielding .046 g), decrease by another 25 percent for source-zone uncertainty (yielding 0.034 g), yielding a total decrease of a little more than a factor of two, enough to

account for the discrepancy in peak horizontal acceleration either between the USGS and LLNL or between the LLNL and EPRI/SOG estimates.

Accepting this factor of two we have *calculated* in order to account for the *observed* factor of two differences between the USGS probabilistic peak acceleration value and that of LLNL requires presuming almost the full range of bias across all these parameters. Because these parameters are under the control of the LLNL team experts rather than the administrators of the LLNL methodology, it seems unlikely that the full bias would be experienced in the *median* estimate across team experts. Thus this modeling-parameter bias is not a viable answer to the observed difference between the USGS and LLNL results.

On the other hand, two of these modeling parameters (depth of source of ground motion and size of attenuation function variability) *are* under the control of the EPRI/SOG administrators rather than the EPRI/SOG teams, so a full bias in these parameters is at least conceivable. Furthermore, maximum magnitudes for background zones are in general lower for the EPRI/SOG teams than for the LLNL experts. Thus, the EPRI/SOG value could possibly be considered consistent with the LLNL estimate in the presence of parameter bias. Again, however, it seems unlikely that the bias in all the parameters would be such that the EPRI/SOG vs LLNL bias would always be in such a direction as to make the EPRI/SOG estimate always lower than the LLNL estimate to the extent observed at Portsmouth. Thus, the unlikelihood of the full size and direction of the bias occurring argues for the presence of yet other methodological biases. These will be explored in the next section.

IX.B.2. Other Possible Methodological Biases

In the conclusions of section IV, we suggested a number of possible sources of differences in results between the EPRI/SOG and LLNL methodologies. Among these are (a) choice of attenuation functions, (b) seismicity rate determination in the presence of different magnitude conversions, and (c) interaction of active zones and background zones. In the following subsection we investigate the extent to which these sources of bias account for the differences in EPRI/SOG and LLNL results.

IX.B.2.a. Attenuation Function Differences

Figures IX-1 and IX-2, show comparisons between the Atkinson-Boore (1990) and Toro-McGuire (1987) spectral response velocity attenuation functions at 1 Hz (1 sec) and 5 Hz (0.2 sec) respectively. The Atkinson-Boore (1990) spectral attenuations for rock give approximately the same values as those of Boore-Atkinson (1987); the former are used because they have been more simply parameterized to facilitate use in calculating many spectral ordinates. Using these curves, we want to estimate possible differences in probabilistic ground motions attributable to the use of one rather than the other attenuation function. We will attempt two approaches and then use the reference USGS zones to make a direct calculation.

A response velocity of one cm/sec, corresponds roughly to the probabilistic ground motion value at 10^{-3} annual exceedance probability for the EPRI/SOG calculation, both at 1 Hz and 5 Hz. According to the curves, for 1 Hz response velocity, exceedances of one cm/sec are contributed by earthquakes of the magnitude 5.0 $m_b(Lg)$ (the minimum magnitude of the EPRI/SOG analysis) at roughly twice the distance for the Toro-

McGuire attenuation function than for the Atkinson-Boore attenuation function. This means that using the Toro-McGuire attenuation function in a hazard analysis for a given model of sources and rates, exceedances of one cm/sec would be contributed by earthquakes near magnitude 5 by sources in an area over 4 times the area around the site as for the area using the Atkinson-Boore attenuation function. This suggests considerably larger exceedance values for one cm/sec for the Toro-McGuire attenuation function than for the Atkinson-Boore attenuation function.

As an alternative approach, consider that for response at 1 Hz (1 sec), at a common distance, corresponding to a magnitude of 5.0 for the Toro-McGuire attenuation function, only magnitudes above 5.3 for the Atkinson-Boore attenuation function contribute exceedances of one cm/sec. The difference, $5.3 - 5.0 = 0.3$ magnitude units, corresponds to an increase in rate of exceedance of one cm/sec of about a factor of $(10^{0.3}) = 2$ (following the Gutenberg-Richter Law). A rule of thumb observed for peak acceleration (p. 29-31, Algermissen and others, 1976) is that doubling the seismic rate increases the probabilistic ground motion by 30-40 percent for low-to-moderate ground motions generated by point ruptures. This rule of thumb is approximately the same for 1 Hz response in our reference model. Thus, we would expect this doubling of exceedance rate to correspond to about a 35 percent increase in probabilistic ground motion. (The calculation for 5 Hz (0.2 sec) yields a similar estimate.)

The distribution of real source zones affects a probabilistic ground motion result in a way somewhat different from the above indicated estimates. Using the USGS source zone model with rates based on historical $m_b(Lg)$'s occurring in the model source zones, we obtain uniform hazard spectra for 1.0 and 0.2 sec period. Comparing spectral hazard curves in figures IX-5 and IX-6, we find increases of a

factor 1.2 for 1.0 sec and from 1.2 to 1.6 for 0.2 sec (depending on minimum magnitude) using the Toro-McGuire $m_b(Lg)$ attenuation versus the corresponding Atkinson-Boore attenuation.

The EPRI/SOG and LLNL methodologies use combinations of attenuation functions. The EPRI/SOG results are dominated by the high weight given to the Toro-McGuire attenuation function. The LLNL results put more weight on the Atkinson-Boore attenuation function. If their probabilistic ground-motion results used only these two attenuation functions the increase of probabilistic ground motion calculated above would be in a direction contrary to that appearing in the reported EPRI/SOG and LLNL uniform hazard spectra. This indicates that there has to be another cause acting in an opposite direction in order to account for the EPRI/SOG and LLNL spectral differences.

Among the other attenuation functions used for spectra are those based upon Newmark-Hall spectral shapes anchored to peak accelerations or peak velocities. The LLNL work placed greater weight on such attenuations than did the EPRI/SOG work. Figures IX-3 and IX-4 show a comparison between the Atkinson-Boore and Nuttli-derived response spectral attenuation functions for 1 Hz and 5 Hz. The curves are very different, and hence the effects of source distance and magnitude are so different that it is difficult to estimate the effective difference in probabilistic ground motion in a manner similar to that which we have used previously. We might rather guess, just from the roughly factor of 4 ground motion level difference at magnitude 5 (see figures IX-3 and IX-4), that the probabilistic ground motions should also have a factor of about 4 difference. Comparing figures IX-6 and IX-7, we find increases in probabilistic ground motion for the Nuttli-derived vs Atkinson-Boore attenuations by factors of 5.7 for 1 Hz response and factors ranging from 3.8 to 4.8 for 5 Hz response.

It is possible to conclude from the above discussion that the differences in Toro-McGuire and Atkinson-Boore attenuation functions contribute little to the observed differences in EPRI/SOG and LLNL spectra, but the greater weight given to the Newmark-Hall based spectra by LLNL ought to contribute substantially.

IX.B.2.b. Effect of Distant Sources

To ease the burden of calculating hazard for many source-zone scenarios, users of the EPRI/SOG methodology typically exclude the more distant sources, after making some kind of check on the significance of the contribution of the distant sources. Low but significant values of long-period ground motions can be produced from large-magnitude earthquakes located at substantial distances from the site. Thus, the larger the maximum magnitude of a source, the more important it is to include the source in the calculation. Any tendency of LLNL experts to use higher maximum magnitudes than the EPRI/SOG teams for equivalent sources, or to include more distant sources would contribute to the difference in probabilistic ground motions. Note also that any difference in the number of standard deviations at which attenuation function variability is truncated affects the distance at which sources can contribute.

Figures IX-5, IX-6, and IX-7 indicate the effects of exclusion of distant sources for the USGS reference sources and rates determined from catalog m_b 's found in those sources using the Toro-McGuire, Atkinson-Boore, and Nuttli-derived attenuation functions for $m_b(Lg)$. "Near sources" includes all sources within 400 km except for the Appalachian source, which approaches 250 km at its closest. "All sources" includes the Appalachian source and the New Madrid source, which contributes at nearly 800 km. For reference we have included Risk Engineering's EPRI/SOG

results from a preliminary draft report for Portsmouth (Risk Engineering, 1990).

Notice that the greater sensitivity of longer-period ground motions to distant sources produces about factors of 2 to 6 difference in spectral hazard levels at periods of 1 second and 2 seconds respectively. The illustrations show the powerful effect the exclusion of distant sources can have (keeping in mind the fact that the maximum magnitudes assumed in these distant sources make a difference, too). It is important to note that this sensitivity is characteristic of *low-level* probabilistic ground motions for which exceedances can come from far distances.

In its preliminary report, Risk Engineering included the TEC's sources within 200 km of the site and Appalachian sources for most TEC's, but excluded New Madrid sources. In its revised calculations for Portsmouth using the EPRI/SOG methodology (Risk Engineering, 1991), Risk Engineering included both Appalachian and New Madrid sources provided by the TEC's. In the screening tests to determine the relative contribution of these sources, for most TEC's a New Madrid source provided a significant contribution to the hazard of 1 Hz response at a level of one cm/sec. For only two TEC's were Appalachian sources significant. The revised EPRI/SOG spectral curve has increased over that of the earlier draft report by about a factor of 2 at 1 and 2 sec period (see fig VII-13, this report). Though distant sources are now included in the latest Risk Engineering EPRI/SOG calculations, differences in maximum magnitude, rate, and zone configuration for those sources could still account for some remaining difference between LLNL and EPRI/SOG long-period results.

IX.B.2.c. Effect of Lower Minimum Magnitudes and Conversion of Catalog Intensities to Uniform Magnitude Scale

Earthquakes appearing in eastern U.S. catalogs have a number of different size measures associated with them. Usually the primary assessment is that of intensity effects, particularly that maximum intensity observed or inferred to have been experienced near the supposed source. This latter intensity is termed epicentral intensity and has the symbol I_o . The use of intensity, which depends upon the effects on people and buildings, makes possible an estimate of the earthquake size for events that have occurred before recording by seismographs. However, if the source of the earthquake has not been near human habitation, the epicentral intensity underestimates the true size.

Epicentral intensities VII and higher indicate earthquakes which have caused damage. It is important to ensure that damaging levels of ground motion corresponding to intensity VII are included in an analysis of ground-motion hazard. In this section are discussed practices which may result in some of the historical earthquakes with epicentral intensity VII being ignored and, as well, most of the future earthquakes capable of causing intensity VII.

Since the recording of earthquakes by seismographs in the central and eastern U.S., felt area has been found to be a better and less variable estimate of earthquake size than I_o . Accordingly, most of the larger earthquakes have been assigned magnitudes based on felt area rather than on a conversion from epicentral intensity.

In recent years, the definition of an instrumental magnitude scale, $m_b(Lg)$, specifically designed for the eastern U.S. has been used to assess earthquake magnitudes. This scale uses actual far-field seismograph

recordings of surface waves to estimate m_b magnitude, and the correspondence of this scale with western U.S. earthquakes has been investigated. (see the discussion on magnitudes in section VIII). Currently in eastern earthquake catalogs, earthquake size measures include epicentral intensity, felt-area magnitude (calibrated to m_b), and $m_b(Lg)$. For any hazard analysis, a common magnitude scale is required for the earthquakes in order to be able to analyze the historical seismicity. Because current attenuation functions use either moment-magnitudes or $m_b(Lg)$ magnitudes to predict ground motion in terms of distance, most common hazard analyses try to convert older earthquakes with only epicentral intensities or felt areas into moment magnitudes or $m_b(Lg)$ magnitudes.

For the central and eastern U.S. the $m_b(Lg)$ scale is that currently favored for analysis. An earthquake for which an $m_b(Lg)$ value doesn't exist, has to have whatever size measure does exist converted to an $m_b(Lg)$ value. The formula used to make that conversion has to be based upon the correspondences observed among earthquakes which have both $m_b(Lg)$ values and values for the size measure being converted. The earthquakes which have the most kinds of size measures tend to be the larger and more recent events. It should be appreciated that these earthquakes which have these multiple measures are likely to come from statistically different populations than those earthquakes being converted.

The earthquake size conversions vary from investigator to investigator, and indeed, the correspondences which are required for these conversions are not stable in time. As an example of this sort of difficulty, the distribution of $m_b(Lg)$'s corresponding to a given epicentral intensity has a median which decreases from 1938 to 1983. Using the catalog "CENA," obtained from Bollinger (written communication), for epicentral intensities tagged "IG" (meaning that the source

is the USGS state seismicity maps), and magnitudes tagged "MNG" (meaning Nuttli-type Lg-wave data magnitudes), also from the USGS, we have tabulated distributions of MNG for $I_o = 5, 6, 7,$ and 8 , for the date ranges 1938–1962, 1962–1974, and 1974–1983. The medians of these distributions are shown in table IX-2. According to this table, the use of conversions calibrated since 1962 for earthquakes observed prior to 1962 may underestimate the size of the earlier earthquakes. The use of an inappropriate conversion may place historic damaging earthquakes below the minimum magnitude threshold for earthquakes to be included in the hazard analysis (5.0 in the EPRI/SOG methodology).

If an empirical relationship of $m_b(Lg)$ with epicentral intensity is used to convert historical intensities to $m_b(Lg)$, it matters very much whether the historical epicentral intensities for which the conversions are being made are considered to be typical of those observed between 1938 and 1962 or more typical of those observed after 1962. It appears that most of the earthquakes having epicentral intensities in the range V to VIII after 1962 have $m_b(Lg)$ values determined for them. Therefore most of the older earthquakes having epicentral intensities but which do not have $m_b(Lg)$ magnitudes determined for them are likely to be more typical of those determined from 1938 to 1962. If we compare the actual distributions, in figures IX-3a,b, and c, of intensity vs magnitude for this earlier period with the distributions for later period we can conclude that these earlier earthquakes are the larger of the earthquakes having these intensities. Hence the conversion to be used ought to be one determined for that period of time rather than for a more recent period of time. If this rule is followed, then, according to Table IX-2, $m_b(Lg)$ magnitude values converted from epicentral intensity V using a pre-1962 relationship would be assigned values 0.4 to 0.6 units higher than would be assigned based

on an empirical relationship observed after 1962. Similarly, those converted from

epicentral VI would be 0.2 to 0.9 units higher, and intensity VII's, -0.1 to 0.6 units higher.

Table IX-2. Median $m_b(Lg)$, Given an Epicentral Intensity

Intensity	Date Range			Overall
	1938-1962	1962-1974	1974-1983	
V	3.9	3.5	3.3	3.5
VI	4.5	4.3	3.6	3.8
VII	5.1	4.5	5.2	4.95
VIII	5.5	n/a	n/a	5.5

Number of Above Events			
16	46	56	118
5	21	31	57
2	3	1	6
2	-	-	2

Depending on the minimum magnitude used for hazard analysis, use of an inappropriate conversion formula might result in a substantial difference in the number of earthquakes assigned a magnitude above the threshold minimum. The magnitude range 4.0 to 4.5 is usually ignored in hazard analysis in the western U.S. because significant damage is not usually observed for this size earthquake. In the central and eastern U.S. ignoring this range may be undesirable since this range is associated with epicentral intensity VI, which is a threshold damage level. In table IX-2, we notice that the earlier time periods have median magnitudes for intensity VI in this magnitude range and a significant number of earthquakes of intensity VI occur in those time periods.

It is important to remember that regardless of the time span involved, the variability of magnitude observed for given epicentral intensities is sufficiently high that a certain fraction of those earthquakes having a given intensity will have magnitudes falling more

than 0.5 units above the overall median magnitude. Tables IX-3a, IX-3b, and IX-3c show the actual distributions which led to the summary appearing in table IX-2. The observed number of earthquake magnitudes falling more than 0.5 units above the overall median for V is 15 percent; for intensity VI, the number is 30 percent. That is to say, about 25 percent of the intensity VI's will have magnitudes which will fall at or above magnitude 4.5. For historical earthquakes previous to 1962 having epicentral intensity VI, it is likely, by the above argument, that more than 50 percent would have magnitudes falling at or above magnitude 4.5. Hence, if it were decided to lower the minimum magnitude to 4.5, in order to take into account the apparent increased intensity observed in the eastern U.S. for earthquakes in the magnitude range 4.5 to 5.0, it would be crucial to use an appropriate conversion of intensity to magnitude for the earlier earthquakes.

Table IX-3a. Distribution of $m_b(Lg)$ for epicentral intensity, $I_0 = V$,
by date range.

$m_b(Lg)$	Date Range			Overall
	1938-1962	1962-1974	1974-1983	
2.0				
2.1				
2.2				
2.3				
2.4				
2.5				
2.6				
2.7				
2.8				
2.9				
3.0				
3.1				
3.2				
3.3			median	
3.4				
3.5		median		median
3.6				
3.7				
3.8				
3.9	median			
4.0				
4.1				
4.2				
4.3				
4.4				
4.5				
4.6				
4.7				

Table IX-3b. Distribution of $m_b(Lg)$ for epicentral Intensity $I_0 = VI$,
by date range.

$m_b(Lg)$	Date Range			Overall
	1938-1962	1962-1974	1974-1983	
2.0				
2.1				
2.2				
2.3				
2.4				
2.5				
2.6				
2.7				
2.8				
2.9				
3.0				
3.1				
3.2				
3.3				
3.4				
3.5				
3.6			median	
3.7				
3.8				median
3.9				
4.0				
4.1				
4.2				
4.3		median		
4.4				
4.5	median			
4.6				
4.7				
4.8				
4.9				
5.0				
5.1				

Table IX-3c. Distribution of $m_b(Lg)$ for epicentral intensity $I_o = VII$, by date range.

$m_b(Lg)$	Date Range			Overall
	1938-1962	1962-1974	1974-1983	
3.7				
3.8				
3.9				
4.0				
4.1				
4.2				
4.3				
4.4				
4.5		median		
4.6				
4.7				
4.8				
4.9				___ median
5.0				
5.1	median			
5.2			median	
5.3				
5.4				
5.5				
5.6				

Felt area magnitude is gradually being replaced by measured $m_b(Lg)$, but significant numbers of earthquakes in the catalogs have felt-area magnitudes without also having an associated $m_b(Lg)$. We have compared felt area magnitudes associated with epicentral intensities VI and VII. We noted that about as many earthquakes with $I_o=VI$ and felt areas (13 out of 69) have felt areas above 200,000 square kilometers as those with $I_o=VII$ (12 out of 23). These felt areas correspond to felt-area magnitudes in the range 4.7–5.0. Therefore it must be supposed that many earthquakes with $I_o=VI$, and with large felt areas would have had $I_o=VII$ had their epicenters been closer to

towns. This is an additional argument that some care must be addressed to the conversion of earlier earthquake intensities to magnitude and that earthquakes with magnitudes lower than 5.0 are capable of causing damage.

If a minimum magnitude of 5.0 is used, most intensity VII's and large felt area VI's converted using equations governed by recent or overall correspondences between intensity or felt-area magnitude and $m_b(Lg)$ will be assigned magnitudes below 5.0 and hence will fall out of the analysis. *It is undesirable to conduct a hazard analysis which ignores the contribution by lower-magnitude earthquakes known to have caused damage, or capable of*

causing damage. An alternative is to conduct the hazard analysis with lower minimum magnitude, in order to assure that historical earthquakes having modified Mercalli epicentral intensities of VII will be retained in the analysis. (We will return to this important point in section IX.B.3.) (However, certain earthquakes with very low felt areas and magnitudes as low as 3.8 have caused damage. These represent a special case and are probably properly excluded from a hazard analysis.)

IX.B.2.d. Treatment of Seismicity Rates

As related in section IV, LLNL studies suggest that LLNL seismicity rates above magnitude 5.0 are 30 percent greater than those of EPRI/SOG. Seismicity rate differences of a factor of two produce only about 40 percent changes in probabilistic ground-motion values at the low probabilistic ground motions produced at Portsmouth. Thus, we believe that the treatment of seismicity rates is unlikely to be a general source of discrepancy when high smoothing or strong priors are applied in the EPRI/SOG methodology.

However, in the light of the previous discussion in section IX.B.2.c, it is possible that a considerable number of damaging earthquakes, as well as those capable of producing damage may be missing from the analysis of seismicity. If the exceedance of the number of earthquakes above the minimum magnitude were to increase by a factor of two, the probabilistic ground motions might increase by somewhat less than a factor of 1.4.

IX.B.2.e. Low values of p^A in EPRI/SOG methodology

Recall that the EPRI/SOG methodology assigns a p^A value to the likelihood that a candidate tectonic feature is active as a source zone (see section IV.C.1). We have hypothesized that the effect of using p^A would be to decrease the

effective seismicity acting near a site in the vicinity of active seismicity, but possibly to increase it in the vicinity of sites far from active seismicity (section VI.B.5 and Perkins and others, 1988). Recapitulating the argument, the value of p^A is affected by whether there is much or little historical seismicity in the vicinity of the proposed feature. Because the rate of seismicity assigned to a feature as a candidate source zone also depends on the historical seismicity, the result is an effective seismicity lower than that observed in the zone, because the low p^A value is the multiplier of the zonal seismicity in the hazard analysis (and the complement of the p^A value is the multiplier of the seismicity placed in the background zone). For sites near the feature, the calculated hazard would be lower than if there were no p^A multiplier (that is, if p^A were 1.0). For sites far from active seismicity the hazard could be higher, because the seismicity "removed" from the active source is added to that of the background. The evidence of the differences in results at nuclear power plant sites is that the lower the probabilistic ground motions, the lower a fraction the EPRI/SOG results are as a fraction of the LLNL results. This result agrees with the hypothesis for sites near seismicity, but disagrees for sites far from seismicity. In this section we test for the possibility that the p^A methodology could be the source for the observed LLNL vs EPRI/SOG difference at Portsmouth.

To test the possible effect at Portsmouth, we apply the p^A methodology to the USGS reference zones in the vicinity of Portsmouth. We assume that these zones have p^A values averaging about 0.2. The effect of p^A would be to decrease the effective seismicity of the active zones in the vicinity of the site by a factor of $1/0.2=5$. The remaining 80 percent of the former zonal seismicity would be dispersed into background. If this zone were the primary contributor to the hazard at the site (as, for instance, if the background zone had no

seismicity and was very large in area, thus diluting the seismicity placed into background, and if no other zone were close enough to be an effective contributor, the result of a factor of 5 decrease in effective local seismicity would be to decrease the probabilistic ground motion by about a factor of 2.5 (estimated using the relationship between log exceedance rate and log ground motion derived from curves from section V.B).

We have modeled this case, using the USGS reference model with no source-zone boundary smoothing. The results are shown in table IX-4. The first row gives probabilistic ground motion results for the reference model. The next row shows the results when all the seismicity is placed into a single background zone, with the center maximum magnitude remaining the same as for the sources of the reference model (6.1). The hazard results do not change much, indicating that the areal rate of seismicity of the background zone has not increased or decreased significantly. The third row shows the results when the reference model is given a probability of 0.2 (which models the effect of a p^A value of 0.2), and the

all-background model is given a probability of 0.8. The fourth line shows the results of the all-background model when the maximum magnitude is decreased to 5.5. Now the probabilistic ground motion has decreased by a factor of about 2. This is a profound effect. We should expect that when we again invoke the p^A model, this effect will be seen. And the fifth line shows this to be so.

Finally, comparing the first and last (sixth) rows, we find that using a p^A value of 0.2 for the local sources and *excluding* the contribution of the background zone produced a decrease in probabilistic ground motion of a factor of about 2, depending on return period, as we had predicted. We see, however, the mediating role of the background zone in contrasting this result with that of third line. When the zonal seismicity is added to the background seismicity as a probabilistic alternative, and the background receives a complementary p^A of 0.8, *and the background maximum magnitude is maintained at the same level as that of the active zones*, the net decrease in probabilistic ground motion was less than 25 percent or less (depending upon return period).

Table IX-4. Probabilistic response velocity (cm/sec) at Portsmouth at 1-sec period: Comparison of USGS reference model with one having simulated $p^A=0.2$.

Model Used	Return Period (yr)		
	100	1,000	10,000
USGS Reference model	4.1	12.7	31.6
All seismicity in background, with center $M_{\max} = 6.1$	3.2	11.0	31.1
$P(\text{ref})=0.2$; $P(\text{b.g.})=0.8$	3.4	11.4	31.2
All seismicity in background, with center $M_{\max} = 5.5$	1.9	6.3	16.6
$P(\text{ref})=0.2$; $P(\text{b.g.})=0.8$	2.5	8.1	21.1
Active zones only, but $P(\text{ref})=0.2$; $P(\text{b.g.})=0.0$	1.5	5.9	17.0

Clearly the role of the background zone is important here. At these return periods and ground-motion levels, the background seismicity (when treated as an alternative source with the seismicity which would otherwise be associated with an active zone dispersed into it) contributes significantly to the probabilistic ground-motion hazard.

The importance of the treatment of the background zone can be appreciated when we review the results when the maximum magnitude of the background zone is decreased. The table shows that the decrease in probabilistic ground motion is no longer negligible but rather a substantial 40 to 30 percent. This decrease is the result of assuming that there is no unknown tectonic source present in the background (which, when treated as an alternative, is the entire area around the site) capable of large magnitudes. This low background maximum magnitude is a frequent assumption in the EPRI/SOG methodology.

The effect, on the probabilistic ground motion for a site, of a small p^A for an active source can vary over a wide range, depending on whether the site is within an active source zone, merely near one, or definitely in background. For the example given here, we can see that even a p^A value as small as 0.0 for the active zones could be important or unimportant, depending on the maximum magnitude of the background zone. (Examine the second and fourth lines of the table to see the results of an effective p^A of 0.0.)

The area of the background zone plays a role as well, because it governs the extent to which local seismicity can be dispersed. Also the period of the ground motion makes a difference: short period ground motions tend to be more dependent on local sources and less dependent on maximum magnitude. Hence the effect we have seen here would be expected to be less for peak acceleration than for one-second response. At longer periods, and at low

ground-motion values, the contribution of distant sources and maximum magnitude are more important.

Because it is very difficult to reconstruct what the effective background size and seismicity is for the EPRI/SOG zonations in the vicinity of Portsmouth we cannot be sure of the actual role of p^A in accounting for the difference between the EPRI/SOG and LLNL results, but we find this experiment very telling, and we think p^A , particularly in combination with generally low maximum magnitudes for background zones, is very likely a major contributing factor to that difference.

IX.B.2.e. Most Likely Sources of Methodological Biases.

At this point we summarize our judgments as to the likely sources of methodological biases accounting for the differences in probabilistic ground motions at Portsmouth between LLNL and EPRI/SOG.

Choice of attenuation function has a clear effect when considering only individual attenuation functions. At Portsmouth the far-field ground-motion values seem to be driving the results. Using USGS source zones and $m_b(Lg)$ rates observed in these sources, we determine that the Toro McGuire attenuation function produces slightly higher uniform-hazard spectral ordinates than does the Atkinson-Boore attenuation function. This direction of effect is opposite to that observed in the EPRI/SOG and LLNL short-period, uniform-hazard spectral ordinates. The Nuttli-based spectral attenuations produce much higher spectral ordinates at long periods. The combination of several attenuation functions in the two methodologies should be such as to give little net difference in results for the short-period uniform-hazard spectral ordinates between EPRI/SOG and LLNL, though it should be a large contributor to the difference at long-periods)

The contribution of distant sources which may have been excluded in the EPRI/SOG methodology appears to be capable of accounting for a significant fraction of the difference between EPRI/SOG and LLNL long-period spectral ordinates. In its final report, Risk Engineering did use the more distant sources which we were concerned about, and their long-period spectral levels for the EPRI/SOG methodology have increased. It is still possible that some residual difference between LLNL and EPRI/SOG can result use of differences in maximum magnitude, seismicity, zone configuration for those distant sources.

The use of different magnitude conversions in the vicinity of the minimum magnitude may be capable of accounting for the approximately 30 percent difference in seismicity rates obtained by the EPRI/SOG and LLNL methodologies. However such a minor change in rate is not capable of accounting for the observed differences in spectral ordinates. Our study does point up the importance of the effect of minimum magnitude for short-period spectral ordinates, a point we shall return to in subsection IX.B.3.

In general, for certain configurations of site and local seismicity, use of low p^A values could account for factors of 2 difference in probabilistic ground motions. In the Portsmouth case, using the USGS reference model, we find that the use of (1) a p^A value of 0.2, together with (2) a low maximum magnitude for the background zone, can account for approximately a factor of 1.7 difference between methodologies which do and do not use these two features.

We conclude that the use of (1) low p^A -values and at the same time (2) low maximum magnitudes can account for the differences between the EPRI/SOG and LLNL short-period, uniform-hazard spectral ordinates. In addition to this cause, (3) the possible

exclusion or difference in treatment of distant sources in the EPRI/SOG methodology and (4) the use of the Nuttli-based spectral attenuations in the LLNL methodology can account for differences between the reported LLNL and EPRI/SOG long-period results.

IX.B.3. Use of Epicentral Intensity

We have found that the observed differences in LLNL and EPRI/SOG results can be explained by certain features of the respective methodologies. We now go on to investigate the difference of the USGS results from that of LLNL and EPRI/SOG as a feature of the USGS methodology.

The USGS reference estimates used a conversion of catalog epicentral intensity to moment magnitude calibrated in the western United States in order to guarantee that near-field ground motions associated with a given epicentral intensity in the eastern U.S. would be comparable to those of the west. The relationship used was

$$M_w = M_L, M_S = 1.3 + 0.6 I_o,$$

over the appropriate ranges of M_L and M_S .

However $m_b(Lg)$ is found to be implicitly related to epicentral intensity in the catalog according to the equation

$$m_b(Lg) = 0.7 + 0.6 I_o.$$

A relationship between M_w and $m_b(Lg)$ is observed from the horizontal ground motions obtained in the attenuation function derived from the Boore-Atkinson (1987) earthquake moment models for the eastern U.S. (see section VIII.B.4). The relationship is quadratic; the result is that the difference $M_w - m_b(Lg)$ ranges from about -0.5 to about +0.2 over the range of $m_b(Lg)$ from 3.5 to 7.5. The result is that the difference in M_w values associated with epicentral intensity between the USGS reference conversion and that implicit in the

Boore-Atkinson attenuation ranges from 1.1 to 0.4.

Either it is necessary to assert that moment magnitudes in the eastern U.S. do not have the same meaning as moment magnitudes in the western U.S., or else it is necessary to explain why a given epicentral intensity in the eastern U.S. is associated with a lower moment magnitude than the same epicentral intensity in the western U.S. Said another way, why does a given moment magnitude in the eastern U.S. produce a higher epicentral intensity than does the same moment magnitude in the western U.S.?

We suggest three possible explanations. First, perhaps eastern earthquakes have a higher stress drop for a given moment. This would mean that near-field ground motions, particularly high-frequency ground motions, would be higher in the eastern U.S. In the far field, ground motions, particularly long-period ground motions would be about the same as in the western U.S.

If this first hypothesis is true, it is necessary to construct different random-vibrations models for the attenuation of ground motion, based on moment magnitudes in which higher stress drops play a part. These attenuations should produce higher ground motions, at least at short distances and high-frequencies, perhaps by a factor of 2 to 3, than earthquakes of similar magnitudes in the western United States for some average site condition. In this case, the USGS peak acceleration and high-frequency response reference results would be approximately correct for rock sites comparable to California "soft rock/stiff soil" sites.

A second explanation is that the stress drops are the same east and west, but the site condition which produces epicentral intensities is such as to provide higher site amplification in the central and eastern U.S. The higher observed intensity would thus be a consequence of site condition rather than higher

stress drop. Modeled theoretical site amplifications for sites in the west produce factors of 2 to 2.5 increase in peak acceleration (see, for instance, Rogers and others, 1991). In order to account for a factor of 2 or 3 higher ground motion in the central and eastern U.S. than in the western U.S., site conditions capable of producing amplifications in peak acceleration of 4 to 8 would be required. We are not sure that such conditions exist.

(Systematic studies of the areal distribution of intensities might shed light on this situation. An increase of intensity of about 1 unit corresponds to an increase of ground motion of about a factor of 2; the site effect of the site condition controlling epicentral intensity in the east would have to be about one intensity unit higher than that in the west. Studies of site intensity amplification in the western U.S. (Eduard Arnold, oral communication) suggest site conditions corresponding to 1 and 2 intensity units increase. Similar studies in the central and eastern U.S. ought to indicate site intensity increase of 2 to 3 units.

If this second hypothesis is true—that the difference in epicentral intensity vs moment magnitude is due to a predominance of a greater contrast in rock to surface site amplification in the eastern U.S.—then rock ground motion at Portsmouth may not be underestimated by EPRI/SOG and LLNL, and the USGS estimates may represent ground motions on standard eastern surface site condition other than rock, say low velocity rock or stiff soils. However, if the site condition produces greater surface ground motions for a given moment magnitude in the East than in the western U.S., *the minimum magnitude used in a hazard analysis should be lowered in order to account for the proper number of earthquakes that can produce a given damaging, low-to-moderate ground motion at a surface site.* (Our discussion in section IX.B.2.c has already suggested lowering the minimum magnitude, for a different reason.)

Figures IX-5, IX-6, and IX-7 show the effect of changing minimum magnitude on the calculated Portsmouth spectra for rock. There is a significant increase in 1000-yr probabilistic response for periods less than 0.6 seconds for the Atkinson-Boore and Toro-McGuire attenuation functions. The effect is not of significant importance for response at periods of 1 second or longer. Note that any amplification for site effect over rock would have to be applied to these higher ground motions. An increase of a factor of 2 to 3 on the lower minimum magnitude spectra of figures IX-5 and IX-6 would produce values close to those of the USGS spectrum at Portsmouth (see, for instance, figure VII-13).

The effect shown is just that of including lower magnitude events. If because of the use of different magnitude conversion equations, some intensity VI and VII events would be assigned higher magnitudes, the effect would be experienced at somewhat longer periods than those shown in the figures.

A third explanation for the different relation of moment magnitude to epicentral intensity in the eastern and western U.S. would be to impeach moment magnitude determinations in the eastern U.S., asserting some regional bias. However, in our conversations with colleagues we are assured that moment-magnitudes derived from far-field, wave-form matching methods, for earthquake data having good quadrantal distributions, are as reliable as the similar moment magnitude determinations performed in other regions. In this method source duration and, hence, corner-frequency and stress drop, are not assumed, but rather come from the fitting. On the other hand, moment magnitudes derived from other methods, may be considerably less well determined, depending upon assumptions about distance attenuation, etc. (Steve Hartzell, oral communication). Our investigations into catalog comparisons of moment magnitude

with other magnitudes (see again section VIII) suggest that eastern U.S. moment magnitudes do not differ from moment magnitudes determined elsewhere in the world sufficiently to account for the large difference observed with respect to epicentral intensity.

IX.B.3.a. Testimony of Historical Intensities

In this section we attempt to assess whether the USGS probabilistic peak acceleration hazard estimate, which is 2 and 3 times higher than that of LLNL and EPRI/SOG, respectively, is consistent with the historical intensity of shaking at Portsmouth.

In section II, we noted the experience at Portsmouth of several events suggesting intensity VI or higher in the vicinity of Portsmouth. Four of these were from the 1811-1812 sequence. Although damage was not reported at Portsmouth for these events, the fact that the site could be placed within intensity VI or VII isoseismals suggests the likelihood of damaging ground motions at Portsmouth from these earthquakes.

The role of duration in causing damage makes it difficult to transform these intensities confidently to peak ground motions. In the near field of an earthquake in the western United States, intensity VII may correspond to approximately 0.12 g and intensity VI to 0.06 g (see Table 6 in Barosh, 1969, derived from Neumann, 1954). A rule of thumb from Neumann is that these ground motions hold within about 25 km from the epicenter, while at 100 kilometers distance from a larger earthquake, peak ground motions half these values could cause the same intensity, and at 200 km, one-quarter these values. In the eastern United States, these distances could be greater.

Three other earthquakes not of the New Madrid 1811-1812 sequence also produced intensity VI or higher at the site (section II). For one of

these, it is reasonable to place the site in the near field of the event, that of May 17, 1901. Intensity VII is interpretable from the damage experienced for that event, and it is not unreasonable to assign a peak acceleration of about 0.12 g for the site, *at the surface at the existing geologic site condition*. Thus, even discounting the 1811-1812 sequence, and assuming, under hypothesis one (previous section), a site amplification of 2, it is not unreasonable to assign a return period of 200 years to 0.06 g at the Portsmouth site vicinity, on rock. Peak accelerations of 0.03 g could reasonably be assigned return periods of 100 years or less. Accelerations having these return periods can be extrapolated, using the rate-translated shape of the reference sensitivity curve, to accelerations about 0.15 g at 1000-yr return periods. If, to be liberal, we double the above estimated return periods for 0.06 and 0.03 g, we arrive at an extrapolated acceleration of about 0.08 g at 1000-yr return period.

Thus, if site intensities of VI and VII mean the same thing in terms of near-field peak acceleration at the surface in the eastern U.S. as in the western U.S., the USGS 1000-yr return period value of 0.082 g is consistent with the historical intensities experienced at the site.

IX.B.4. Conclusions

The sensitivity studies results suggest that a systematic difference in the treatment of depth or maximum magnitude may produce at most a bias of plus or minus 25 percent. Choice of source zones and the dilution effect of multiple source zones can produce an effect believed to range at most plus or minus 40 percent. Although all these bias combined could conceivably result in differences approaching a factor of two, the nature of the methodologies is such that this total bias could occur between the EPRI/SOG and LLNL estimates but not between the LLNL and USGS estimates.

We believe that the range of median LLNL, EPRI/SOG, and USGS estimates is larger than a reasonable range attributable only to parameter bias. We suggest the sources of these discrepancies lie in systematic differences in methodology.

The most likely source of the short-period difference between the EPRI/SOG estimate at Portsmouth and that of LLNL lies in the difference in treatment of the background zone with respect to maximum magnitude combined with the use of the p^A methodology by EPRI/SOG. At longer periods we find additional sources of difference are the use of the Nuttli-derived spectral attenuations by LLNL and possibly the exclusion of, or difference in treatment of, distant sources by Risk Engineering using the EPRI/SOG methodology.

The likely source of the difference between the USGS estimate at Portsmouth and that of LLNL lies in the use of epicentral intensity to assign a western U.S.-like moment magnitude in order to guarantee corresponding near-field ground motions in the eastern and western U.S. Because there is a systematic difference in the relations of epicentral intensity to moment magnitude between the eastern and western United States, for those magnitudes between 4, 5, and 6 $m_b(Lg)$, the USGS estimate is larger than those of LLNL and EPRI/SOG by probably a factor of 2 or 3.

This difference, combined with reasonable inferences from the historical intensity experienced at Portsmouth, strongly suggests that moment magnitude attenuation functions constructed in analogy with western United States sources may underestimate, by a factor of two or more, low-level high-frequency probabilistic ground motions in the eastern United States.

Consideration of the historical seismicity at Portsmouth, and the near-field ground motions

associated with corresponding intensities in California indicate that the USGS results are not unreasonable, while the EPRI/SOG results may be too small.

Notice that the results obtained apply to the Portsmouth site situation, specifically, low probabilistic ground motions. Because the correspondence between epicentral intensity and moment magnitude for high magnitudes in the east is similar to that of the western United States, the above conclusions probably do not hold for high probabilistic ground motions where these are governed by proximity to high-rate, high-maximum magnitude sources, as would be the case at Paducah.

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Comparison of Atkinson Boore with Toro McGuire at a Spectral Period of 1 second

Figure IX-1. Comparison of Atkinson-Boore and Toro-McGuire $m_b(Lg)$ attenuation functions for response velocity at 1 Hz frequency (1 sec period).

Comparison of Atkinson Boore with Toro McGuire at a Spectral Period of 0.2 seconds

Figure IX-2. Comparison of Atkinson-Boore and Toro-McGuire $m_b(Lg)$ attenuation functions for response velocity at 5 Hz frequency (0.2 sec period).

Comparison of Atkinson Boore with Nuttli at a Spectral Period of 1 second

Figure IX-3. Comparison of Atkinson-Boore and Nuttli-derived $m_b(Lg)$ attenuation functions for response velocity at 1 Hz frequency (1 sec period).

Comparison of Atkinson Boore with Nuttli at a Spectral Period of 0.2 seconds

Figure IX-4. Comparison of Atkinson-Boore and Nuttli-derived $m_b(Lg)$ attenuation functions for response velocity at 5 Hz frequency (0.2 sec period).

**Toro-McGuire Attenuation comparing differences
in minimum magnitude and the contributions
of near and distant sources**

Figure IX-5. Uniform hazard spectra for Portsmouth site using Toro-McGuire spectral attenuation functions. Model uses USGS reference source zones with rates determined by catalog m_b or $m_b(Lg)$ earthquakes falling in zones. Short-period spectra show differing results according to change of minimum magnitude. Long-period results show effect of exclusion of distant sources.

Atkinson Boore attenuation Comparing differences
in minimum magnitude and contributions
of near and distant sources with EPRI-SOG

Figure IX-6. Uniform hazard spectra for Portsmouth site using Atkinson-Boore spectral attenuation functions. Model uses USGS reference source zones with rates determined by catalog m_b or $m_b(Lg)$ earthquakes falling in zones. Short-period spectra show differing results according to change of minimum magnitude. Long-period results show effect of exclusion of distant sources. For comparison we include the earlier EPRI/SOG spectrum (Risk Engineering, 1990) for which most sources beyond 200 km were excluded.

Nuttli Attenuation Comparing differences
in minimum magnitude and contributions
of near and distant sources

Figure IX-7. Uniform hazard spectra for Portsmouth site using Nuttli-derived spectral attenuation functions. Model uses USGS reference source zones with rates determined by catalog m_b or $m_b(Lg)$ earthquakes falling in zones. Short-period spectra show differing results according to change of minimum magnitude. Long-period results show effect of exclusion of distant sources.