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Seismic Hazard Assessment of the Paducah Gaseous Diffusion Plant

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Seismic Hazard Assessment of the Paducah Gaseous Diffusion Plant

Zhenming Wang[1] and Edward W. Woolery[2]

Abstract

Selecting a level of seismic hazard at the Paducah Gaseous Diffusion Plant for policy consideration and engineering design is not an easy task because it not only depends on seismic hazard itself, but also on seismic risk and other related environmental, social, and economic issues. Seismic hazard is the basis, however. There is no question that there are seismic hazards at the plant because of its proximity to several known seismic zones, particularly the New Madrid Seismic Zone. The issues in estimating seismic hazard are the methods being used and difficulty in characterizing the uncertainties of seismic sources, earthquake occurrence frequencies, and ground-motion attenuation relationships.

This report summarizes how input data were derived, which methodologies were used, and the resulting hazard estimates for the plant. Three seismic sources (the New Madrid Seismic Zone, the Wabash Valley Seismic Zone, and background seismicity) were identified and characterized. Four ground-motion attenuation relationships were used. Probabilistic seismic hazard analysis and deterministic seismic hazard analysis were performed. A panel of six members, who are experts in geology, seismology, earthquake engineering, and statistics, reviewed the report. Their review comments and responses are included as appendices.

In PSHA, seismic hazard is defined as the annual probability that a ground motion will be exceeded. The inverse of the annual probability of exceedance is defined as the return period. Therefore, seismic hazard is also defined as a particular ground motion being exceeded in a return period. PSHA calculates seismic hazard from all earthquake sources in consideration, and implicitly incorporates uncertainty in earthquake size and location and ground motion.

In DSHA, seismic hazard is defined as the ground motion or motions from a single or several earthquakes that are expected to produce maximum impact at a site. DSHA emphasizes ground-motion hazard from an individual earthquake (a scenario), such as the maximum credible earthquake or the maximum considered earthquake, and explicitly determines ground-motion hazard with a level of uncertainty. DSHA results show that the large earthquakes that have occurred in the New Madrid Seismic Zone dominate the hazard at the Paducah Gaseous Diffusion Plant.

The results from this project show that PSHA and DSHA could provide significantly different hazard estimates for the Paducah Gaseous Diffusion Plant. DSHA provides a ground-motion hazard with a level of uncertainty based on a large earthquake in the New Madrid Seismic Zone, whereas PSHA provides a range of ground-motion hazards based on all earthquakes being considered.

Introduction

Federal agencies such as the Federal Emergency Management Agency and the Environmental Protection Agency, State agencies such as the Kentucky Environmental and Public Protection Cabinet, and other government and private organizations such as the American Association of State Highway and Transportation Officials and the Building Seismic Safety Council (1998, 2004) use seismic-hazard maps produced by the U.S. Geological Survey (Frankel and others, 1996, 2002) for seismic safety regulations and engineering design. The maps currently being used show the ground mo-

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tions that have a 2 percent probability of being exceeded in 50 years. These maps predict very high ground motion in many counties in western Kentucky: peak ground acceleration (PGA) of 1.0 g or higher. These high ground-motion estimates affect everything in western Kentucky from building a single-family home to environmental clean-up of the Superfund site at the Paducah Gaseous Diffusion Plant. For example, it would be difficult for the U.S. Department of Energy to obtain a permit from federal and State regulators to construct a landfill at the Paducah Gaseous Diffusion Plant if the USGS maps with 2 percent probability of exceedance (PE) in 50 years are considered. The Structural Engineers Association of Kentucky (2002) found that if the International Residential Code of 2000, which was based on the 1996 USGS maps with 2 percent PE in 50 years, is adopted in Kentucky without revision, constructing residential structures in westernmost Kentucky, including Paducah, would be impossible without enlisting a design professional.

The International Building Code (International Code Council, 2000), based on the 1996 USGS maps with 2 percent PE in 50 years, requires a design PGA of about 0.6 g in Paducah and about 0.8 g at the Paducah Gaseous Diffusion Plant. In contrast, the highest building-design PGA used in California is about 0.4 g. These high design ground motions for western Kentucky are not consistent with the level of seismic activity (Fig. 1). Figure 1 compares seismic hazard for the New Madrid Seismic Zone with the hazard for southern California, over 100 years and 1,000 years (Stein and others, 2003). Although earthquakes are occurring in Kentucky and surrounding states, especially in the well-known New Madrid Seismic Zone, where at least three large earthquakes (magnitude 7.0–8.0) occurred in 1811-12, earthquake recurrence rates are much lower in the New Madrid region than in California, the Pacific Northwest, and Alaska. Table 1 compares the basic geologic and seismologic observations and design PGA for California and western Kentucky, and indicates that the higher design ground motion for western Kentucky may not be warranted.

Selecting a level of seismic hazard for policy consideration and engineering design is very complicated. It not only depends on seismic hazard itself, but also on seismic risk and other related environmental, social, and economic issues. Seismic hazard assessment is the basis, however. The objectives of this project were to gain a better understanding of the seismic hazard assessment for the Paducah Gaseous Diffusion Plant and its surrounding area, and to communicate the hazard information more effectively to the users and policymakers. In order to achieve these objectives, the following tasks were established:

1. Observe the microseismicity in the Paducah area
2. Conduct a thorough literature review
3. Characterize the seismic source
4. Conduct a probabilistic seismic hazard analysis
5. Conduct a deterministic seismic hazard analysis
6. Prepare a preliminary report

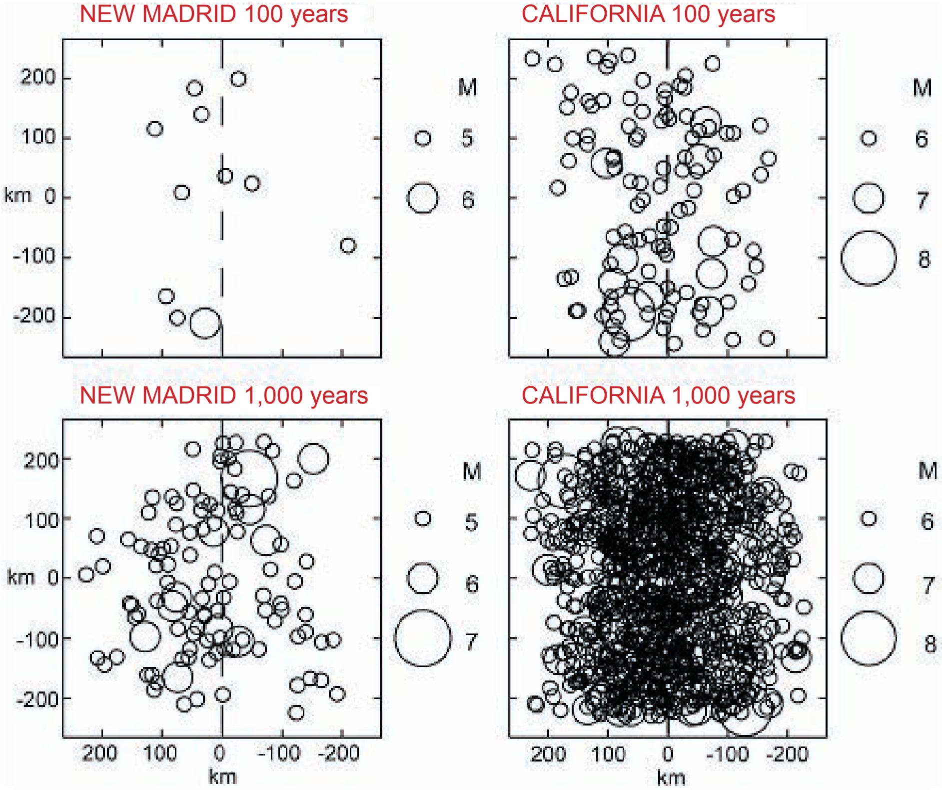

Figure 1. Schematic comparison of the seismic hazard for the New Madrid Seismic Zone and southern California. Circles mark area of shaking with acceleration greater than 0.2 g. From Stein and others (2003). Published with permission of the American Geophysical Union.

Table 1. Comparison of design ground motion, geology, and seismicity in California and western Kentucky.

	California		*Western Kentucky*	
Design PGA	≤ 0.4 g	≤ 0.7g	≥ 0.4 g	≥ 0.6 g
	(UBC97)	(CALTRAN)	(IBC-2000)	(bridge)
Geology	San Andreas Fault		New Madrid Fault	
	Displacement ≥ 20 mm/yr		Displacement ≤ 2 mm/yr	
Seismicity	High		Low	
	M 7–8: ~100 yr		M 7–8: ~500 yr or longer	
	M 6–7: ~20–50 yr		M 6–7: ?	

7. Conduct a panel review of the preliminary report
8. Prepare a final report.

The focus of this project is reviewing the methodology and data used by the U.S. Geological Survey because of the broad implications of the USGS's seismic-hazard assessments. This review was carried out in a series of workshops, professional conferences and publications, and private meetings and communications (Wang, 2003a, b, 2005 a–d, 2006a, b, 2007; Wang and others, 2003, 2004a, b, 2005; Cobb, 2004, 2006; Wang and Ormsbee, 2005).

A panel consisting of national and international experts on geology, seismology, engineering seismology, and engineering was formed to review the preliminary report that summarized the results from tasks 2 through 5. A statistician was added to the review panel in response to a suggestion of members of the panel. The panel was made up of:

- Roy B. Van Arsdale, University of Memphis
- Gail Atkinson, Carleton University
- James E. Beavers, consultant
- Kenneth W. Campbell, consultant
- Leon Reiter, consultant
- Mai Zhou, University of Kentucky Department of Statistics.

The review was divided into two parts: individual review (3 days) and panel review (1 day). The preliminary report was submitted to the panel in late February 2007 for their individual reviews. The panel's written comments and our responses are provided in Appendix A. Dr. Zhou's comments are contained separately in Appendix B. The panel met on April 30, 2007, in Lexington, Ky., to discuss the preliminary report, focusing on (1) the ground-motion attenuation relationship—uncertainty, dependency, and hazard calculation in PSHA, (2) seismic hazard analysis—temporal and spatial measurements, uncertainties, and quantification, and (3) seismic hazard assessment for the Paducah Gaseous Diffusion Plant—input parameters: sources, occurrence frequency, and ground-motion attenuation. Even though there was not enough time to fully discuss all issues, the panel reached some consensus, including:

- The ground-motion hazards with a 2,500-year return period estimated by the U.S. Geological Survey (Frankel and others, 1996, 2002) are conservative.
- Probabilistic seismic hazard analysis, as a methodology, is the common approach for seismic hazard assessment, but some improvements are needed.
- It is difficult to provide an estimate of seismic hazard for the Paducah Gaseous Diffusion Plant because a reasonable estimate is subjective.

The recommendations of the review panel were:

- Perform an improved probabilistic seismic hazard analysis.
- Perform a deterministic seismic hazard analysis.
- Revise the local source zone.

A draft final report was completed according to the above recommendations and sent to the panel for final review on May 11, 2007. The panel's comments on the draft final report are in Appendix C. Also included in Appendix C are our responses to the panel's comments.

Methodology

Two methods, probabilistic seismic hazard analysis and deterministic seismic hazard analysis, are commonly used for seismic hazard assessment. Both follow similar steps to estimate seismic hazard (Reiter, 1990; Kramer, 1996):

1. Determine earthquake sources.
2. Determine earthquake occurrence frequencies by selecting a controlling earthquake or earthquakes: the maximum magnitude, maximum credible, or maximum considered earthquake.
3. Determine ground-motion attenuation relationships.
4. Determine seismic hazard.

The differences between the two methodologies are in step 4, in how to define and calculate seismic hazard.

In probablistic analysis, seismic hazard is defined as the annual probability of a particular ground motion being exceeded at a site (National Research Council, 1988; Senior Seismic Hazard Analysis Committee, 1997; Frankel, 2004; McGuire, 2004). The reciprocal of the annual probability of exceedance is called the return period, and has been interpreted and used as "the mean (average) time between occurrences of a certain ground motion at a site" (McGuire, 2004). Therefore, seismic hazard can also be expressed as a ground motion being exceeded in a specific return period such as 500, 1,000, or 2,500 years. Probabalistic analysis calculates seismic hazard from all earthquake sources and considers the uncertainty in the number, size, and location of future earthquakes and ground motion (i.e., considers the possibility that ground motion at a site could be different for different earthquakes of the same magnitude at the same distance, because of differences in source parameters, path, and site conditions) (Cornell, 1968, 1971). The results of a probabilistic analysis are seismic hazard curves: a relationship between a ground-motion parameter (i.e., peak ground acceleration, peak ground velocity, and response acceleration at certain periods) and its annual probability of exceedance or return period.

In deterministic analysis, seismic hazard is defined as the ground motion or motions from a single or several earthquakes that have maximum impacts at a site (Reiter, 1990; Krinitzsky, 2002). Ground motion from an individual earthquake, such as the maximum credible or maximum considered earthquake, maximum probable earthquake, or design basis earthquake, is emphasized. Although determining a recurrence interval is not required and often not emphasized in deterministic analysis, it is equal to the recurrence interval of an individual earthquake (Wang and others, 2004b).

Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis was originally developed to derive theoretical ground-motion hazard curves at a site without enough observations or none at all (Cornell, 1968). Later, Cornell (1971) extended his method to incorporate ground-motion uncertainty (i.e., the possibility that ground motion at a site could be different for different earthquakes of the same magnitude at the same distance, because of differences in source parameters and path effects). According to Cornell (1968, 1971) and McGuire (1995, 2004), the heart of probabilistic analysis is

$$\begin{aligned}\gamma(y) &= \sum \nu P[Y \geq y] \\ &= \sum \nu \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}]\, d(\ln y)\} f_M(m) f_R(r)\, dm dr,\end{aligned} \tag{1}$$

where v is the activity rate, $f_M(m)$ and $f_R(r)$ are the probability density function of earthquake magnitude M and epicentral (or focal) distance R, respectively, and y_{mr} and $\sigma_{ln,y}$ are the median and standard deviation at m and r. The functions $f_M(m)$ and $f_R(r)$ were introduced to account for the uncertainty of earthquake magnitude and distance, respectively (Cornell, 1968, 1971; McGuire, 2004). The values y_{mr} and $\sigma_{\ln,y}$ are determined by the ground-motion attenuation relationship (Campbell, 1981, 2003; Joyner and Boore, 1981; Abrahamson and Silva, 1997; Toro and others, 1997; Electric Power Research Institute, 2003; Atkinson and Boore, 2006). Ground motion Y is generally modeled as a function of M and R with uncertainty E:

$$\ln(Y) = f(M,R) + E. \tag{2}$$

The uncertainty E is modeled as a normal distribution with a zero mean and standard deviation $\sigma_{\ln,Y}$ (Campbell, 1981, 2003; Joyner and Boore, 1981; Abrahamson and Silva, 1997; Toro and others, 1997; Electric Power Research Institute, 2003; Atkinson and Boore, 2006). Thus, the uncertainty of ground motion Y is modeled as a log-normal distribution. Therefore, equation 2 can be rewritten as

$$\ln(Y) = f(M,R) + n\sigma_{\ln Y}, \tag{3}$$

where n (a constant) is a number of standard deviations measured as the difference relative to the median ground motion $f(M,R)$ (Fig. 2).

According to Benjamin and Cornell (1970) and Mendenhall and others (1986), if and only if M, R, and E are independent random variables, the joint probability density function of M, R, and E is

$$f_{M,R,E}(m,r,\varepsilon)=f_M(m)f_R(r)f_E(\varepsilon). \tag{4}$$

where $f_E(\varepsilon)$ is the probability density function of E. The exceedance probability $P[Y \geq y]$ is

$$\begin{aligned} P[Y\geq y] &= \iiint f_{M,R,E}(m,r,\varepsilon)\,H[\ln Y(m,r,\varepsilon)-\ln y]\,dm\,dr\,d\varepsilon \\ &= \iiint f_M(m) f_R(r) f_E(\varepsilon)\,H[\ln Y(m,r,\varepsilon)-\ln y]\,dm\,dr\,d\varepsilon, \end{aligned} \tag{5}$$

where H[ln$Y$(m,r,ε)–ln$Y$] is the Heaviside step function, which is zero if lnY(m,r,ε) is less than ln$Y$, and 1 otherwise (McGuire, 1995). Because E follows a normal distribution, equation 5 can be rewritten as

$$\begin{aligned} P[Y\geq y] &= \iint \{\int f_E(\varepsilon)\,H[\ln Y(m,r,\varepsilon)-\ln y]\,d\varepsilon\} f_R(r)\,dm\,dr \\ &= \iint \{1-\int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y-\ln y_{mr})^2}{2\sigma^2_{\ln,y}}]\,d(\ln y)\} f_M(m) f_R(r)\,dm\,dr, \end{aligned} \tag{6}$$

where ln Y_{mr}=f(m,r). Therefore, we have equation 1, the heart of probabilistic seismic hazard analysis (Cornell, 1968, 1971; McGuire, 1995, 2004).

The return period (T_{rp}) is the inverse of the annual probability of exceedance (1/γ):

$$\begin{aligned} T_{rp}(y) &= \frac{1}{\gamma(y)} \\ &= \frac{1}{\Sigma \nu \iint \{1-\int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y-\ln y_{mr})^2}{2\sigma^2_{\ln,y}} d(\ln y)\} f_M(m) f_R(r)\,dm\,dr} \end{aligned} \tag{7}$$

If all seismic sources are characteristic, the return period is

$$T_{rp}(y) = \frac{1}{\Sigma \frac{1}{T}[1-\int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp(-\frac{(\ln y-\ln y_{mr})^2}{2\sigma^2_{\ln,y}} d(\ln y)]}, \tag{8}$$

where T is the average recurrence interval of the characteristic earthquake (M_c) at distance R_c. For a single characteristic source, equation (8) becomes

$$T_{rp}(y) = \frac{T}{1-\int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp(-\frac{(\ln y-\ln y_c)^2}{2\sigma^2_{\ln,c}} d(\ln y)}. \tag{9}$$

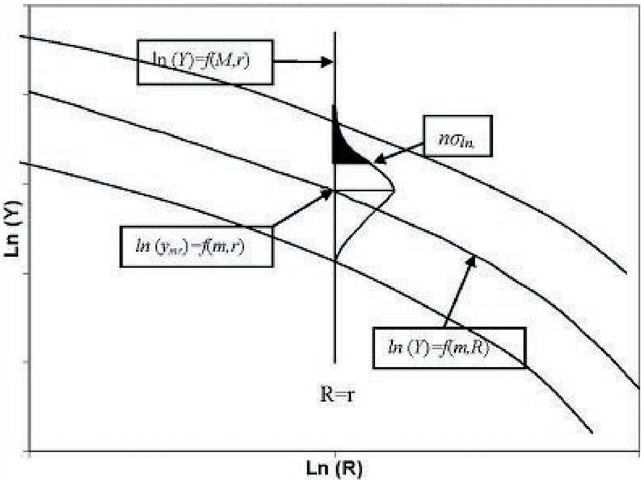

Figure 2. The ground-motion attenuation relationship.

Figure 3 shows how a PGA hazard curve is constructed for a site 40 km from the source with a single characteristic earthquake of magnitude 7.7 and a recurrence time of 500 yr in the New Madrid Seismic Zone.

Ground-motion uncertainty is implicitly incorporated into probabilistic assessment and becomes an integral part of it. Other uncertainties are incorporated explicitly through logic trees, by which different weights are assigned manually to a set of expert estimates for each input parameter (Senior Seismic Hazard Analysis Committee, 1997). There are advantages and disadvantages to these implicit and explicit incorporations of the uncertainty. One disadvantage, recognized by the first thorough review of probabilistic analysis by the committee chaired by Keiiti Aki (National Research Council, 1988), is that the significance of an individual earthquake (a single physical event) is lost "because the aggregated results of PSHA are not always easily related to the inputs." In other words, "the concept of a 'design earthquake' is lost; i.e., there is no single event (specified, in simplest terms, by a magnitude

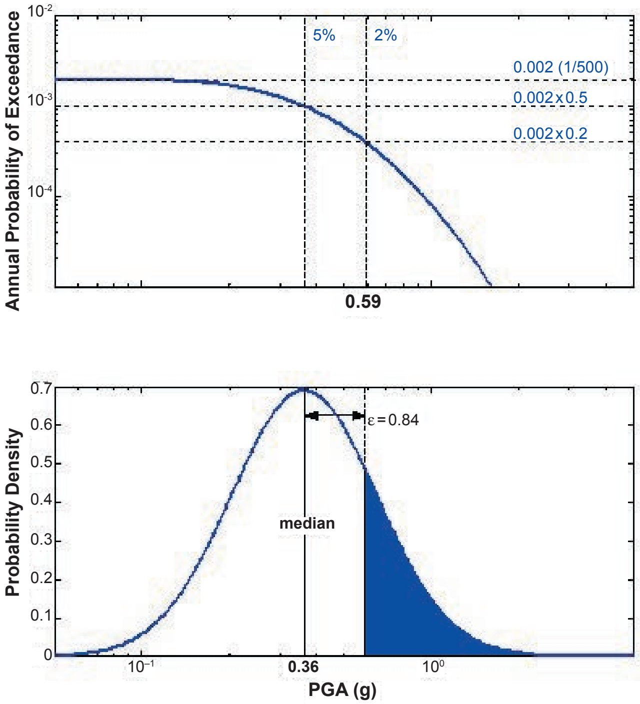

Figure 3. Hazard curve for a site 40 km from the source for a characteristic earthquake of magnitude 7.7 with a recurrence time of 500 years in the New Madrid Seismic Zone. The median ground motion (μ) is 0.36 g, and the standard deviation ($\sigma_{\ln}$) is 0.60; ε=(ln y –ln μ)/$\sigma_{\ln}$. From Wang and others (2005). Published with permission of Seismological Society of America.

and distance) that represents the earthquake threat at, for example, the 10,000-yr ground-motion level (which we call the 'target ground motion')" (McGuire, 1995). McGuire (1995) also proposed a methodology (called deaggregation) to seek the "design earthquake."

Another disadvantage of PSHA is that uncertainty, ground-motion uncertainty in particular, becomes a controlling factor in PSHA. This can be seen clearly in recent studies (Frankel, 2004; Wang and others, 2003, 2005; Bommer and Abrahamson, 2006), at low annual frequencies of exceedance (less than 10^{-4}) in particular. Figure 4 shows how the computed hazard varies with truncation of standard deviation (Bommer and Abrahamson, 2006). This is the reason that PSHA could result in extremely high ground motion (PGA of 10 g or higher) if a long return period (100 million yr) is considered for facilities at the nuclear waste repository site in Yucca Mountain, Nev. (Stepp and others, 2001; Abrahamson and Bommer, 2005; McGuire and others, 2005; Musson, 2005). As shown in Figure 5, a PGA of 11 g would be the result at the Yucca Mountain, Nev., nuclear waste repository if a return period of 100 million yr is considered (Abrahamson and Bommer, 2005). A significantly higher ground motion would have to be considered if Swiss nuclear power plants were reevaluated using a return period of 10 million to 100 million years (Klügel, 2005; Scherbaum and others, 2005). Bommer and Abrahamson (2006) attributed these high ground-motion estimates directly to the way the ground-motion uncertainty is treated in PSHA (Fig. 4).

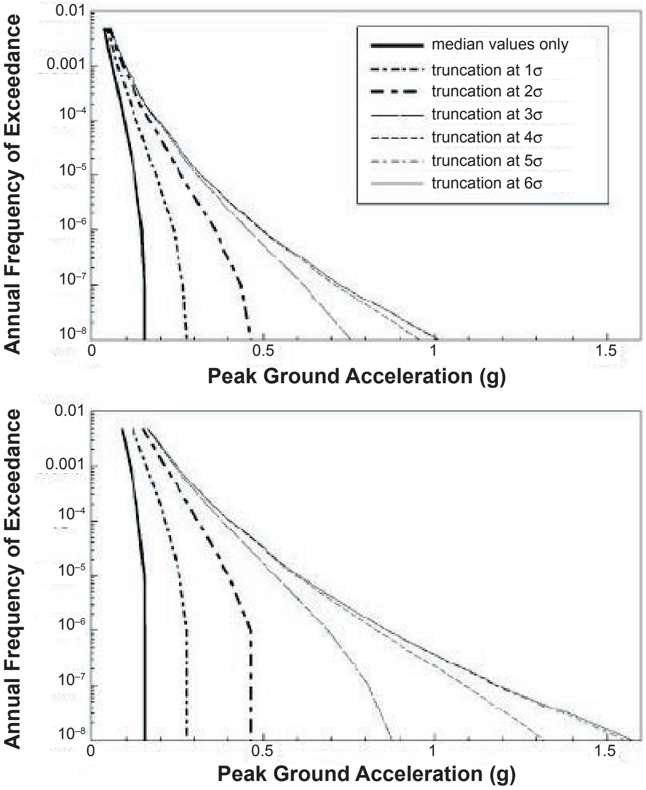

Figure 4. PGA hazard curves showing the effect of ground-motion uncertainty. From Bommer and Abrahamson (2006). Published with permission of the Seismological Society of America.

Deterministic Seismic Hazard Analysis

As discussed earlier, there is a fundamental difference between probabilistic and deterministic analysis in defining and calculating seismic hazard. DSHA emphasizes the ground motion from an individual earthquake, such as the maximum credible earthquake or the maximum probable earthquake. We used the steps outlined in Reiter (1990) and Krinitzsky (1995, 2002) to derive ground motions at the Paducah Gaseous Diffusion Plant. The advantage of DSHA is that ground motion is directly related to an earthquake, specified by a magnitude and distance. The uncertainty, including ground-motion uncertainty, is explicitly expressed in DSHA results. The advantages of DSHA are "an easily understood and transmitted method of estimating seismic hazard" and results that are "clear to the analyst (earth scientist), the user (engineer) and those elements of the general public who are interest-

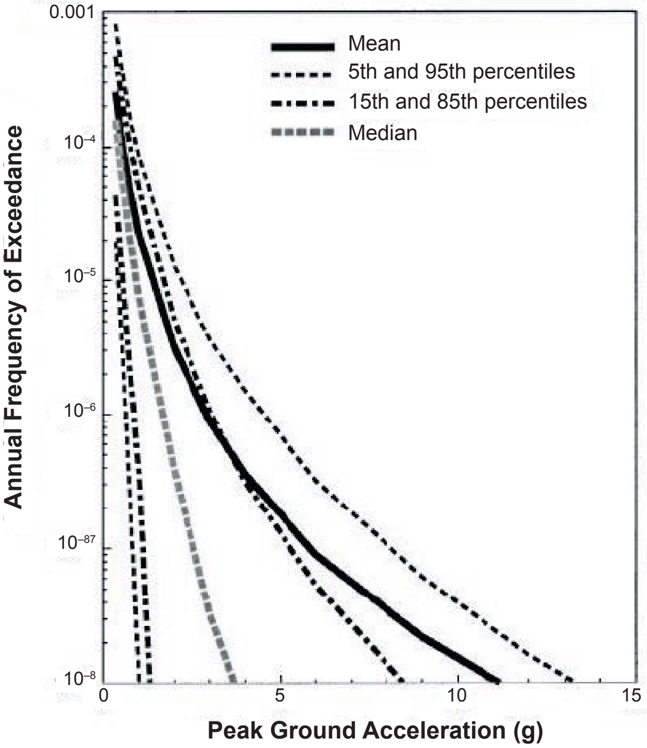

Figure 5. PGA hazard curves from the Yucca Mountain project. From Abrahamson and Bommer (2005). Published with the permission of the Earthquake Engineering Research Institute.

ed in nuclear power plant safety or earthquake related problems" (Reiter, 1990).

DSHA also has disadvantages. One such disadvantage is that "it (DSHA) does not take into account the inherent uncertainty in seismic hazard estimation" (Reiter, 1990). Another disadvantage is that "frequency of occurrence is not explicitly taken into account" (Reiter, 1990). In other words, DSHA is not reported in units of time. As pointed out by Hanks and Cornell (1994), however, "it is generally possible to associate recurrence interval information with plausible deterministic earthquakes." Plausible deterministic earthquakes are always associated with a recurrence interval, so in this sense DSHA actually is associated with a unit of time (Wang and others, 2004b).

Seismic Sources

The causes of intraplate earthquakes in the central United States are not well understood (Braile and others, 1986; Zoback, 1992; Newman and others, 1999; Kenner and Segall, 2000). Two hypotheses have been proposed to explain this seismicity: (1) selective reactivation of preexisting faults by local variations in pore pressure, fault friction, and/or strain localization along favorably orientated lower-crustal ductile shear zones formed during earlier deformation (Zoback and others, 1985) and (2) local stress perturbations that may produce events incompatible with the regional stress field (Zoback and others, 1987). In the central and eastern United States, the regional stress field is reasonably well known from well-constrained focal mechanisms (see, for example, Herrmann and Ammon, 1997), yet the link between the stress field and the contemporary seismicity remains enigmatic. In fact, many dramatically different seismic source zones have been proposed and used in the seismic hazard estimates for the central United States (Electric Power Research Institute, 1988; Bernreuter and others, 1989; Risk Engineering Inc., 1999; Geomatrix Consultants Inc., 2004). Seismic source zones considered in this study are discussed below.

New Madrid Seismic Zone

New Madrid Faults. The New Madrid Seismic Zone is a tightly clustered pattern of earthquake epicenters that extends from northeastern Arkansas into northwestern Tennessee and southeastern Missouri (Fig. 6). Earthquakes along the northeast-trending alignment of earthquakes in northeastern Arkansas and events in southeastern Missouri between New Madrid and Charleston are predominantly right-lateral strike-slip events. The earthquakes along the northwestern trend of seismicity extending from near Dyersburg, Tenn., to New Madrid, Mo., are predominantly thrust events. Focal depths of the earthquakes in the New Madrid Seismic Zone typically range between 5 and 15 km (Chiu and others, 1992). Even though they have been well studied, the locations and maximum magnitude of the New Madrid faults are still uncertain. This is demonstrated in the USGS national hazard maps (Frankel and others, 1996, 2002).

According to Frankel and others (1996),

> to calculate the hazard from large events in the New Madrid area we considered three parallel faults in an S-shaped pattern encompassing the area of highest historic seismicity. These are not meant to be actual faults; they are simply a way of expressing the uncertainty in the source locations of large earthquakes such as the 1811-12 sequence. The extent of these fictitious faults is similar to those used in Toro and others (1992). We assumed a characteristic rupture model with a characteristic moment magnitude M of 8.0, similar to the estimated magnitudes of the largest events in 1811-12 (Johnston, 1996a, b). A recurrence time of 1000 years for such an event was used as an average value, considering the uncertainty in the magnitudes of prehistoric events.

These parameters for the New Madrid Seismic Zone were used in the 1996 USGS national hazard maps (Frankel and others, 1996). In the 2002 USGS national hazard maps, quite different parameters for the New Madrid Seismic Zone were used, however (Frankel and others, 2002):

> The 2002 update incorporates a shorter mean recurrence time for characteristic earthquakes in New Madrid than was used in the 1996 maps, as well as a smaller median magnitude than that applied in 1996. A logic tree was developed for the characteristic magnitude (M_{char}) and the configuration of the sources of the characteristic earthquakes, where the uncertainty in location is described by using three fictitious fault sources as in the 1996 maps. A mean recurrence time of 500 years for characteristic earthquakes is used in the calculations (Cramer, 2001). This was based on the paleoliquefaction evidence of two to three previous sequences prior to the 1811-12 events (Tuttle and Schweig, 2000).

As shown in Figure 7, the northern extension of the New Madrid faults has a significant effect on seismic hazard estimates at the Paducah Gaseous Diffusion Plant. Although many researchers have postulated that the New Madrid faults probably extend northeast into the Jackson Purchase Region in western Kentucky, even into southern Illinois (Wheeler, 1997; Risk Engineering Inc., 1999), consistent geologic and seismologic evidence indicates that a northwest-trending structure separates the Southern Illinois Seismic Zone from the New Madrid zone (Braile and others, 1997; Wheeler, 1997). This is evident in Figure 8, which shows the Bouguer gravity anomaly and 1974–94 earthquake epi-

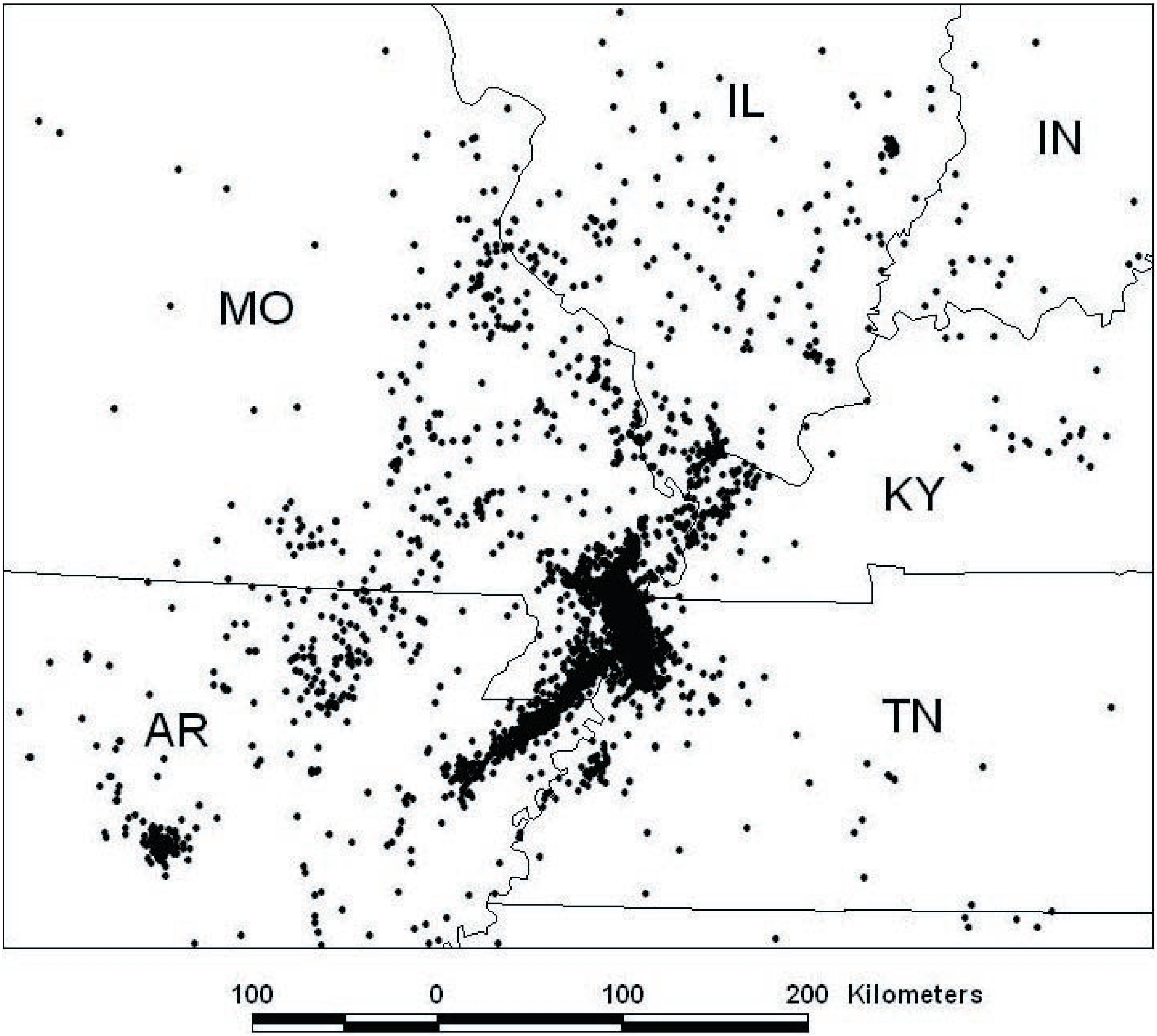

Figure 6. Seismicity between 1974 and 2005 in the central United States.

centers in the New Madrid region (Braile and others, 1997).

As suggested by Wheeler (1997), the northeast extensions of the New Madrid faults can be substantiated by further seismic network monitoring. Recent studies (Wang and others, 2003a; Anderson and others, 2005; Horton and others, 2005) indicate that the New Madrid faults may not extend northeast into the Jackson Purchase Region. A dense seismic network of nine stations was installed in the Jackson Purchase Region (Fig. 9) in late 2002 (Wang and others, 2003b). Table 2 lists the earthquakes recorded by the dense seismic network between January 2003 and June 2005 (Anderson and others, 2005). The focal depths of these earthquakes are all less than 10 km. The June 6, 2003, Bardwell, Ky., event (M_w4.0) is extremely shallow, only about 2 km, with southeast-northwest maximum compression (Horton and others, 2005). These short-period and dense-network observations suggest that the characteristics of earthquakes in the Jackson Purchase Region are different from those of earthquakes in the central New Madrid Seismic Zone. Thus, there is no evidence (microseismicity) to support the northeastern extension of the New Madrid faults into the Jackson Purchase Region.

The study by Baldwin and others (2005) showed that the New Madrid North faults are coincident with

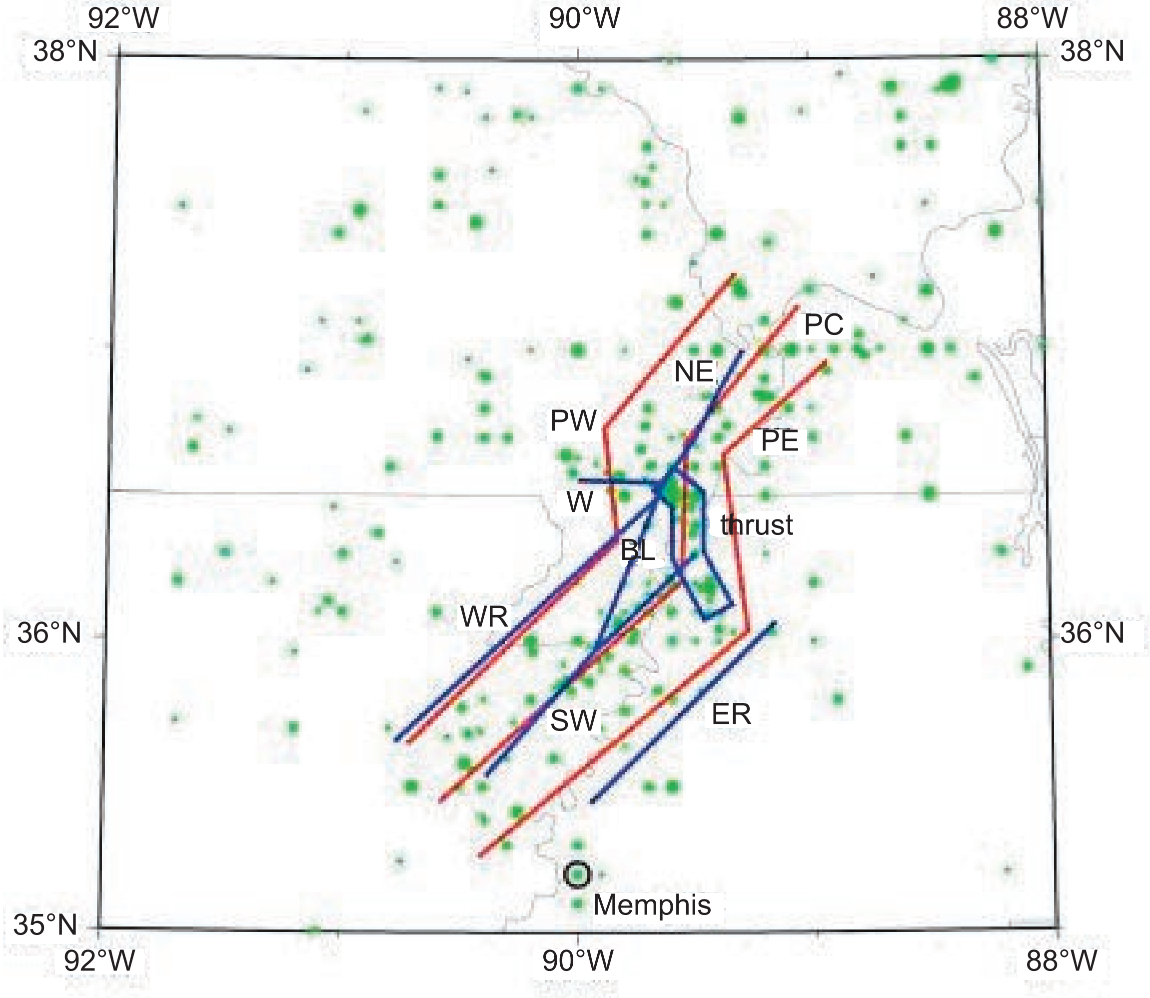

Figure 7. New Madrid faults. Pseudo-faults (lines in red) were used in the 1996 and 2002 USGS seismic hazard maps (Frankel and others, 1996, 2002). Blue=actual faults; red=pseudo-faults; green=earthquakes. From Cramer (2004). Published with permission of the author and the University of Memphis–Center for Earthquake Research and Information.

current seismicity in southeastern Missouri, which is consistent with the findings of Johnston and Schweig (1996). In addition, detailed coring data collected near the Paducah Gaseous Diffusion Plant show no evidence for Holocene (less than 11,000 years) displacement along previously interpreted faults underlying the site (William Lettis & Associates Inc., 2006). Thus, no geologic evidence suggests that the New Madrid faults extend northeast into the Jackson Purchase Region, particularly near the Paducah Gaseous Diffusion Plant site.

For this project, we used the locations of the New Madrid faults determined by Johnston and Schweig (1996), which are consistent with more recent studies (Wang and others, 2003a; Anderson and others, 2005; Baldwin and others, 2005; Horton and others, 2005).

Maximum Magnitude. The other large uncertainty for the New Madrid Seismic Zone is the estimate of the maximum magnitude. A single moment magnitude of 8.0 was used in the 1996 national maps (Frankel and others, 1996), whereas an M_{char} logic tree was used in the 2002 national maps for the New Madrid Seismic Zone: M 7.3 (0.15 wt), M 7.5 (0.2 wt), M 7.7 (0.5 wt), M 8.0 (0.15 wt) (Frankel and others, 2002). More recent studies (Hough and others, 2000; Mueller and Pujol, 2001; Bakun and others, 2003) suggest that the magnitude is about 7.2 to 7.5. GPS observations also suggest a similar magnitude (approximately 7) (Newman and others, 1999; Calais and others, 2006).

Scientists generally agree that the location of the New Madrid faults outlined by Johnston and Schweig (1996) is more appropriate than other locations, such as those used in the national hazard mapping (Frankel and others, 1996, 2002), for seismic hazard assess-

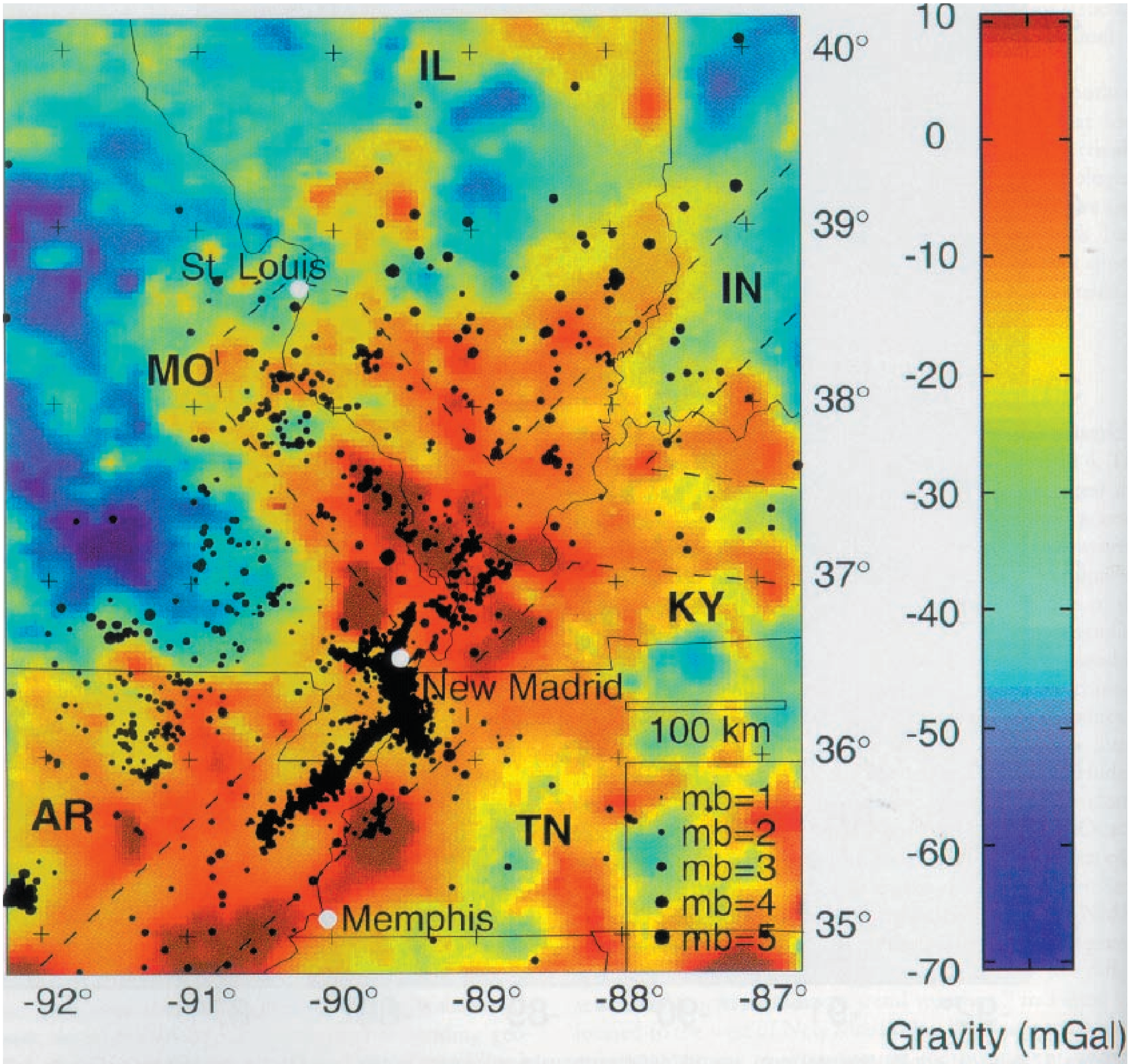

Figure 8. Bouguer gravity anomaly and 1974–94 earthquake epicenters and the New Madrid Rift Complex. From Braile and others (1997). Published with permission of the Seismological Society of America.

ment (Cramer, 2004; Geomatrix Consultants Inc., 2004; Windeler, 2006). Recent studies also suggest that the maximum magnitude for the New Madrid Seismic Zone should be lower M 7 (Newman and others, 1999; Hough and others, 2000; Mueller and Pujol, 2001; Bakun and others, 2003). In this report, we used the location of the New Madrid faults given by Johnston and Schweig (1996) (Fig. 7) with a mean maximum magnitude of M 7.5. As shown in Figure 7, the distance between the Paducah Gaseous Diffusion Plant and the New Madrid faults (indicated by blue lines) is much shorter than the distance used in the national hazard maps (indicated by red lines) (Frankel and others, 1996, 2002).

Wabash Valley Seismic Zone

Nuttli and Herrmann (1978) first proposed the Wabash Valley Seismic Zone on the basis of (1) the number of earthquakes, (2) the occurrence of five earthquakes greater than 5 $m_{b,Lg}$ occurring in the area between 1875 and 1975, and (3) the presence of the

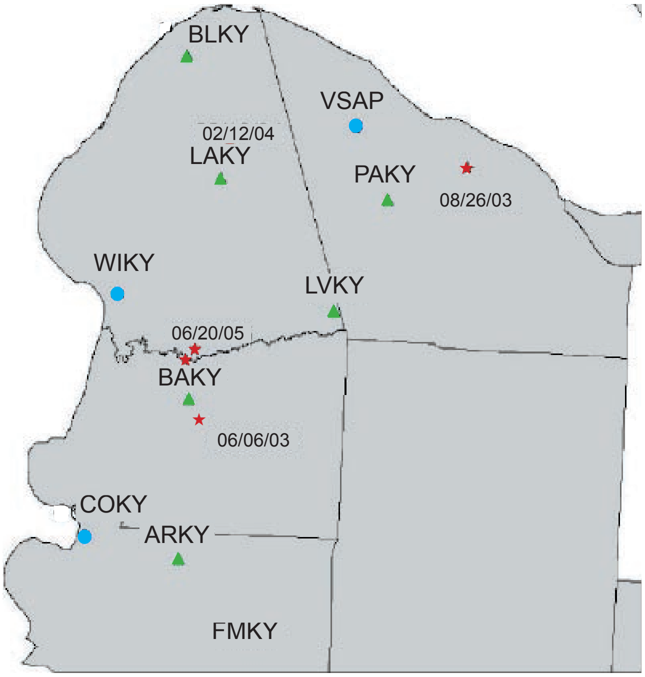

Figure 9. Seismic network and earthquakes (stars) recorded between January 2003 and June 2005 in the Jackson Purchase Region (Anderson and others, 2005). Triangle—short-period seismic station; circle—strong motion station.

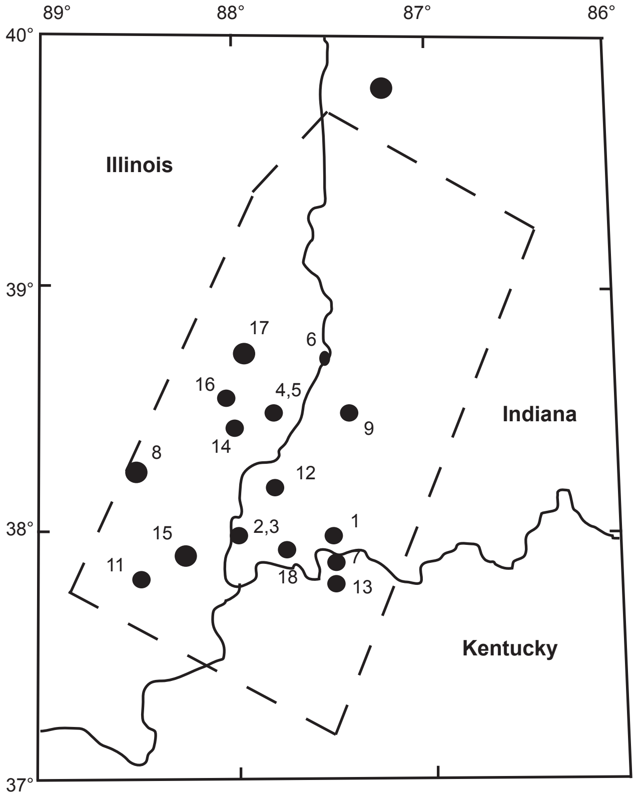

Figure 10. Epicentral locations of the felt earthquakes in the Wabash Valley Seismic Zone.

Wabash Valley Fault Zone. The boundaries of the Wabash Valley Seismic Zone as drawn by Wheeler and Frankel (2000) are shown in Figure 10. Also included in Figure 10 are the epicentral locations of the damaging earthquakes (modified Mercalli intensity greater than or equal to VI) in the seismic zone (Stover and Coffman, 1993) and the location of the 5.1 $m_{b,Lg}$ September 27, 1909, earthquake that occurred just north of the seismic zone (earthquake 10). Dates, times, and epicentral locations of the damaging earthquakes whose locations are shown in Figure 10 are listed in Table 3. Unlike the seismicity in the New Madrid Seismic Zone, where there is a well-defined pattern, seismicity in the Wabash Valley Seismic Zone is diffuse over a broad area.

Despite the number of damaging earthquakes in the Wabash Valley Seismic Zone, the number of permanent seismic stations in the zone is inadequate to derive well-constrained focal depths or focal mechanisms. As previously indicated, of the 18 events listed in Table 3, the only events for which well-determined focal depths and focal mechanisms have been estimated are events 15 through 18. These four earthquakes were large enough to generate sufficient surface-wave data to estimate their focal depths and focal mechanisms using the radiation pattern of their Rayleigh and Love waves (Herrmann and Ammon, 1997).

The largest instrumentally recorded historical earthquake in the Wabash Valley Seismic Zone occurred on November 9, 1968 (event 15 in Table 3). McBride and others (2002) believed that this earthquake was the result of reactivation of a fault plane within a series of moderately dipping lower-crustal reflectors that are decoupled from the overlying Paleozoic structure. The June 18, 2002, Darmstadt, Ind., earthquake (M 4.6) was well locat-

Table 2. Parameters of earthquakes (Anderson and others, 2005).

Date	*Time*	*Lat.*	*Long.*
Depth	*Magnitude*	*Depth*	
		(UK)	
06/06/03	12:29:34	36.870	–88.980
2.6	4	1.5	
08/26/03	2:26:58	37.100	–88.680
1.9	3.1	2.0	
02/12/04	6:49:49	37.110	–88.960
27.2	2.4	9.8	
06/20/05	2:00:32	36.930	–88.990
9.8	2.7	8.7	
06/20/05	12:21:42	36.920	–89.000
21.0	3.6	8.9	

Table 3. Damaging earthquakes in the Wabash Valley Seismic Zone.

Event	*Date*	*Time*	*Lat/Long*	*Magnitude*		*Depth*[3]
No.	*(Mo-Day-Yr)*	*(GMT)*	*(°N/°W)*	$m_{b,Lg}$[1]	M_w[2]	*(km)*
1.	July 5, 1827		38.0/87.5	4.8	4.4	
2.	Aug. 7, 1827	4:30	38.0/88.0	4.8	4.4	
3.	Aug. 7, 1827	7:00	38.0/88.0	4.7	4.3	
4.	Sep. 25, 1876	6:00	38.5/87.8	4.5	4.1	
5.	Sep. 25, 1876	6:15	38.5/87.8	4.8	4.4	
6.	Feb. 6, 1887	22:15	38.7/87.5	4.6	4.2	
7.	July 27, 1891	2:28	37.9/87.5	4.1	3.7	
8.	Sep. 27, 1891	4:55	38.25/88.5	5.5	5.3	
9.	Apr. 30, 1899	2:05	38.5/87.4	4.9	4.6	
10.	Sep. 27, 1909	9:45	39.8/87.2	5.1	4.8	
11.	Nov. 27, 1922	3:31	37.8/88.5	4.8	4.4	
12.	Apr. 27, 1925	4:05	38.2/87.8	4.8	4.4	
13.	Sep. 2, 1925	11:56	37.8/87.5	4.6	4.2	
14.	Nov. 8, 1958	2:41	38.44/88.01	4.4	4.0	
15.	Nov. 9, 1968	17:01	37.91/88.37	5.5	5.3	22
16.	Apr. 3, 1974	23:05	38.55/88.07	4.5	4.3	14
17.	June 10, 1987	23:48	38.71/87.95	5.1	5.0	10
18.	June 18, 2002	18:37	37.98/87.78	4.9	4.5	17–19

1. Magnitudes ($m_{b,Lg}$) are from Stover and Coffman (1993) except for events 8 and 15. The 5.5 $m_{b,Lg}$ for event 17, the November 9, 1968, southern Illinois event, is more generally accepted than the 5.3 $m_{b,Lg}$ given by Stover and Coffman (1993). The $m_{b,Lg}$ magnitude, seismic moment, and epicentral location for event 18 are preliminary estimates based on data from the University of Kentucky Seismic and Strong-Motion Network and R. Herrmann at St. Louis University (personal communication).
2. Except for events 15, 16, and 17, moment magnitudes (M_w) were derived using the m_b to seismic moment (M_o) to moment magnitude conversion. Moment magnitudes of events 17, 18, and 19 were calculated using the seismic moments given in Herrmann and Ammon (1997).
3. Focal depths are from Herrmann and Ammon (1997), except for event 18, which is based on a personal communication from R.B. Herrmann.

ed (Table 3). Kim (2003) believed that this earthquake was also the result of reactivation of a fault within the Wabash Valley Fault System (Fig. 11).

The Wabash Valley Fault System (Fig. 11) is a series of north–northeast-trending normal faults with right-lateral offsets across the Herald-Phillipstown and New Harmony Faults. The locations and extent of faulting are well known from the extensive set of drill logs and seismic-reflection lines acquired for oil and gas exploration purposes. Between the Albion-Ridgeway and New Harmony Faults is the Grayville Graben, so named by Sexton and others (1996) and shown by Bear and others (1997) to exhibit Cambrian extensional slip. Based on Bear and others' (1997) interpretation of the fault movement, Wheeler and Cramer (2002) identified the Grayville Graben as Iapetan and considered the graben and the Wabash Valley Fault System to be nonseismogenic. Woolery (2005) found that the Hovey Lake Fault (one of the faults in the Wabash Valley Fault System) moved as late as approximately 37,000 years before the present.

Because there is no clear evidence directly linking any of the earthquakes in the Wabash Valley Seismic Zone to a specific fault, the Wabash Valley Seismic Zone was treated as an areal source in the USGS seismic hazard analyses (Frankel and others, 1996, 2002; Wheeler and Frankel, 2000). A maximum magnitude of 7.5 was assigned to the zone in these maps (Frankel and others, 1996, 2002; Wheeler and Frankel, 2000), based on the magnitude estimates from paleoliquefaction studies by Obermeier and others (1991, 1993), Munson and others (1995, 1997), and Pond and Martin (1997). Recent studies by Street and others (2004) and Olson and others (2005), however, suggest that the best estimates of the magnitude of those paleoearthquakes are in the range of 6.2 to 7.3. The Tri-State Seismic Source Zone, one of the alternative source zones suggested by Wheeler and Cramer (2002) for the Wabash Valley Seismic Zone, was used in this study. We assigned a mean maximum magnitude of 6.8 to the Wabash Valley Seismic Zone (Fig. 12) based on these studies (Street and others, 2004; Olson and others, 2005).

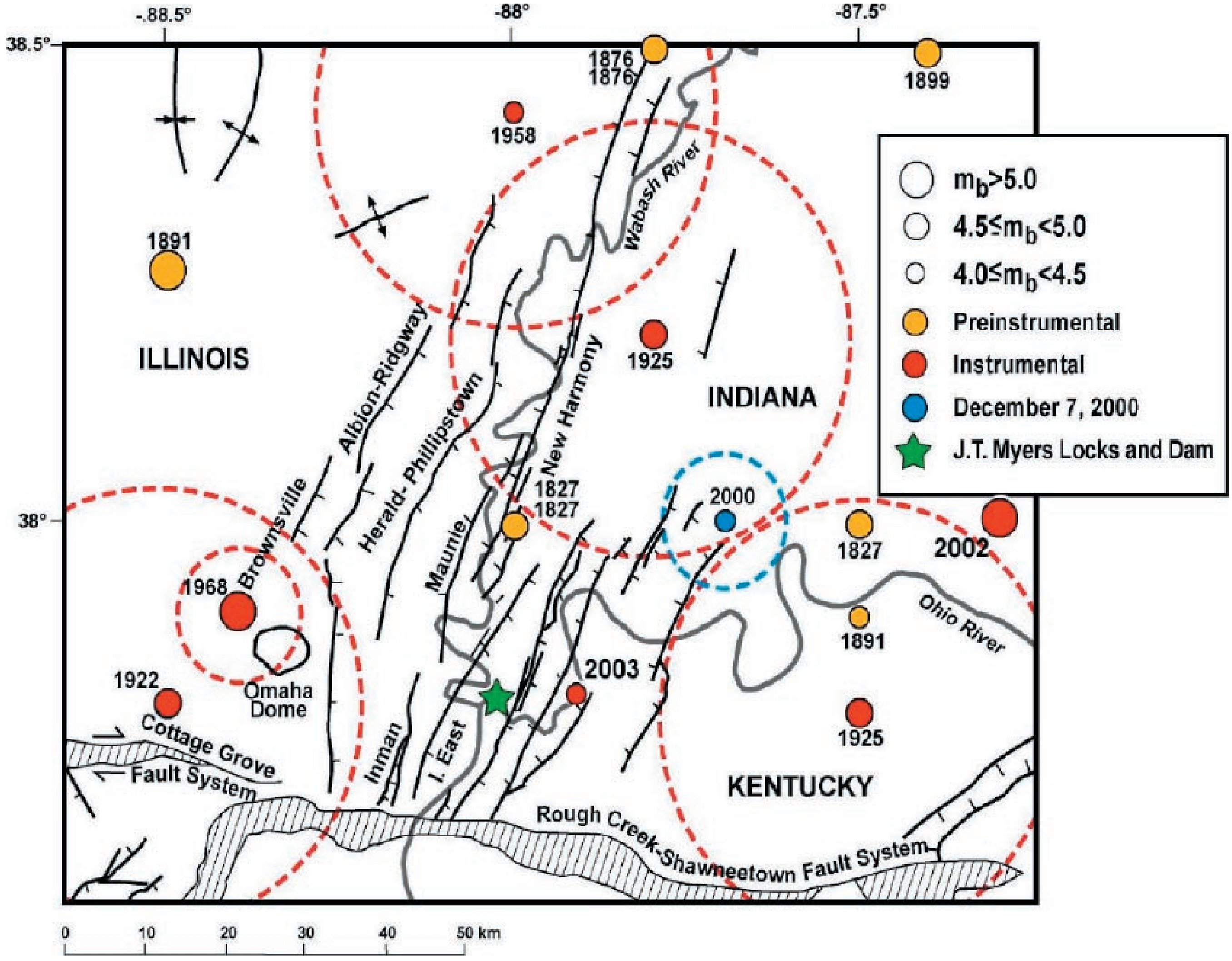

Figure 11. Earthquakes and faults in the lower Wabash Valley.

Background Seismicity

Earthquakes have occurred throughout Kentucky and surrounding states, many of them not associated with any known seismic zone or geologic/tectonic feature. For example, the February 28, 1854, earthquake (4.0 $m_{b,Lg}$) in central Kentucky is not associated with any known seismic zone. Many earthquakes have been recorded by the University of Kentucky Seismic and Strong-Motion Network since 1984 (Street and Wang, 2003), and designated background seismicity (Street and others, 1996). Background seismicity's contribution to seismic hazard was considered by means of smoothed spatial seismicity at grid points in the central and eastern United States (Frankel and others, 1996, 2002) (Fig. 13). A uniform background zone (Fig. 14) was also considered to account for large earthquakes in the central and eastern United States (Frankel and others, 1996, 2002). Although their magnitude is large (7.0 and 7.5), the large background earthquakes do not contribute to the seismic hazard because of (1) a large source zone and (2) a longer recurrence interval (more than 10,000 years) used in the national seismic hazard maps (Wang, 2003). Therefore, the use of these large background earthquakes in national seismic hazard maps is not necessary (Wang, 2003).

In this study, we adopted a method used by Street and others (1996). Based on historical and instrumental records, Street and others (1996) proposed a mean maximum magnitude of 5.3 $m_{b,Lg}$ (M 5.0) for the background seismicity (Fig. 15) in Ballard, Carlisle, Fulton, Graves, Hickman, Livingston, Marshall, and McCracken Counties of western Kentucky. This magnitude is based on moderate-size historical events and occasional events that have been recorded by the University of Kentucky Seismic and Strong-Motion Network, such as the June 6, 2003, Bardwell, Ky., earth-

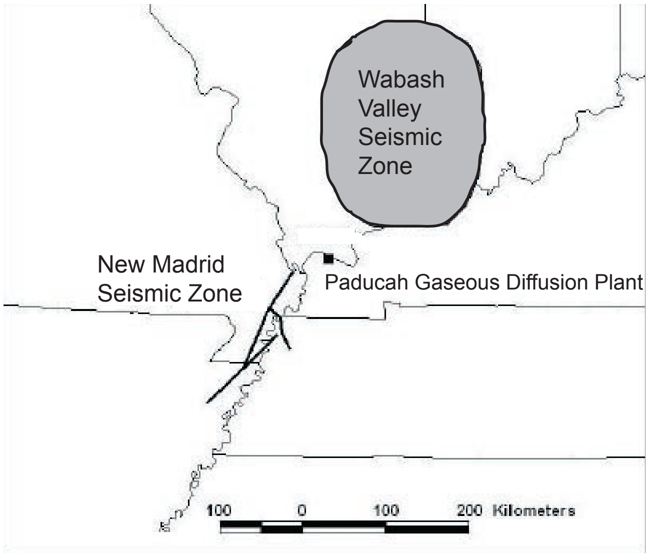

Figure 12. New Madrid faults and Wabash Valley Seismic Zone.

quake (Wang and others, 2003a). Within these counties, many earthquakes measuring 3.0 $m_{b,Lg}$ or larger have been recorded, such as the Bardwell earthquake (M 4.0), which caused some damage in Bardwell. The focal depths for the small earthquakes in the area are generally in the range of 5 to 20 km. Assuming an epicentral distance of 10 km and focal depth of 10 km, the shortest distance from the Paducah Gaseous Diffusion Plant is 14 km. For this project, the shortest distance of 15 km was used. We used an M 5.0 earthquake at a distance of 15 km for a point source to account for hazard contribution from the background seismicity.

Magnitude-Recurrence Relationship

In the central United States, the rate of seismicity is relatively low compared with that in California, and there are no instrumental recordings of strong and large earthquakes. Only two strong events (magnitude between 6.0 and 6.5) have occurred in the central United States since the 1811-12 New Madrid earthquakes: the 1843 Marked Tree, Ark., and the 1895 Charleston, Mo., earthquakes, both with a magnitude of 6.0. Bakun and others (2003) recently suggested that the Charleston earthquake was actually located in southern Illinois, about 100 km north of Charleston (not in the New Madrid Seismic Zone), however. The 1811-12 New Madrid earthquakes were great events (magnitude between 7.0 and 8.0) and recurrence of events of this magnitude are a safety concern for the area. Because

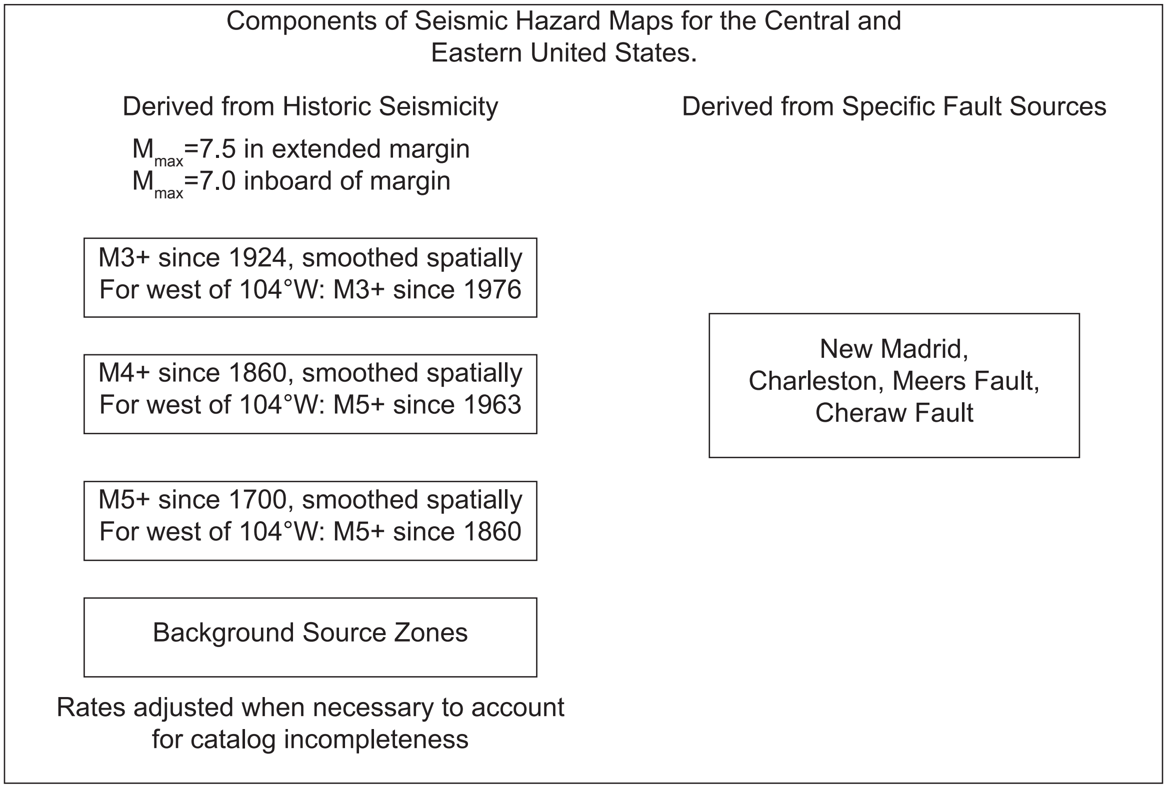

Figure 13. Seismic sources that were considered in the national seismic hazard maps (Frankel and others, 2002).

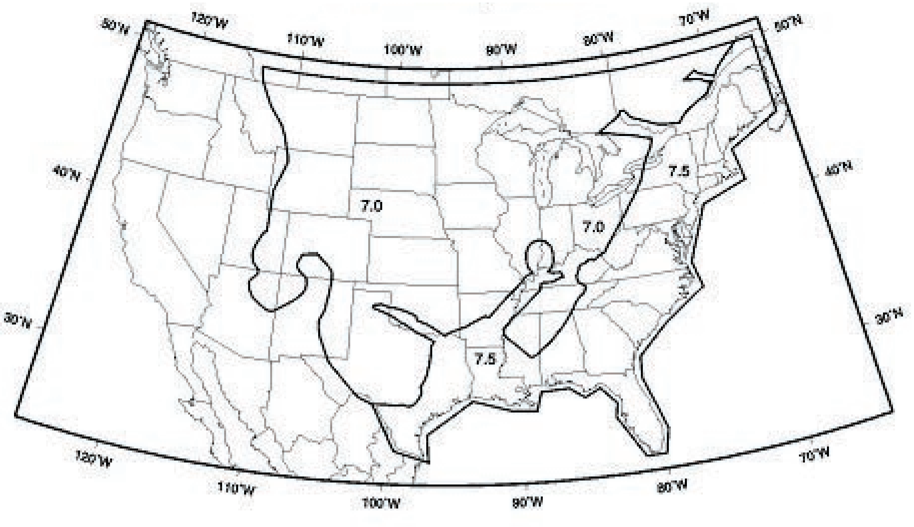

Figure 14. Background earthquakes (M_{max}) used in the national seismic hazard maps. From Frankel and others (2002).

the instrumental and historical records are insufficient to construct the magnitude-occurrence relationships for the central United States, prehistoric paleoliquefaction records (Tuttle and others, 2002) had to be used (Frankel and others, 1996, 2002). Figures 16 through 18 show the magnitude-occurrence relationships for the New Madrid Seismic Zone (Frankel and others, 1996) and Wabash Valley Seismic Zone (Wheeler and Cramer, 2002) based on instrumental, historical, and paleoliquefaction records.

New Madrid Seismic Zone

As shown in Figure 16, the annual rate of occurrence derived from instrumental and historical earthquakes is not consistent with that derived from paleoliquefaction records. Figure 16 also shows that there is an earthquake deficit (lack of strong earthquakes) in the New Madrid Seismic Zone. A *b* value of 0.95 was used in the USGS national seismic hazard mapping for the central United States (Frankel and others, 1996, 2002). Based on the *a* and *b* values determined from instrumental and historical records, the annual occurrence rate of a magnitude 7.5 earthquake in the New Madrid Seismic Zone is less than 0.0001 (meaning that the recurrence interval is longer than 10,000 years) (Fig. 16). Paleoliquefaction records reveal an annual occurrence rate of about 0.002 (recurrence interval of about 500 years), however (Tuttle and others, 2002). A recent study by Holbrook and others (2006) suggests that earthquakes may be temporally clustered on millennial scales. These large earthquakes have been treated as characteristic events (Frankel and others, 1996, 2002; Geomatrix Consultants Inc., 2004).

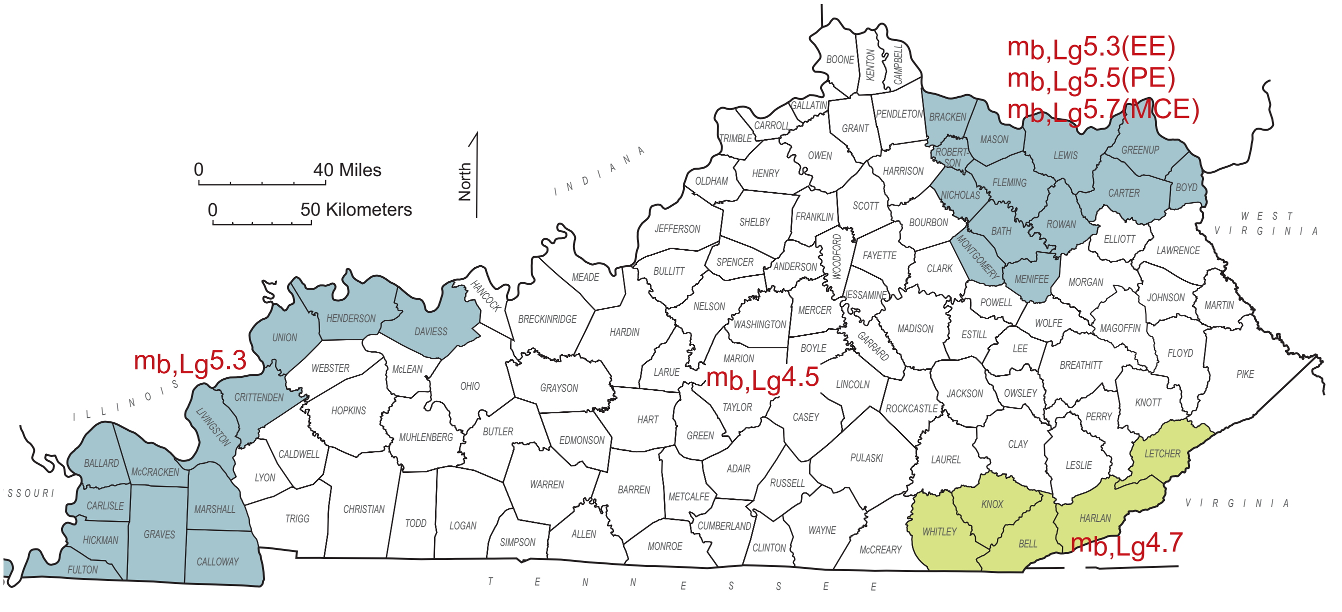

Figure 15. Maximum background earthquakes in Kentucky. From Street and others (1996). Published with permission of the University of Kentucky–Kentucky Transportation Center.

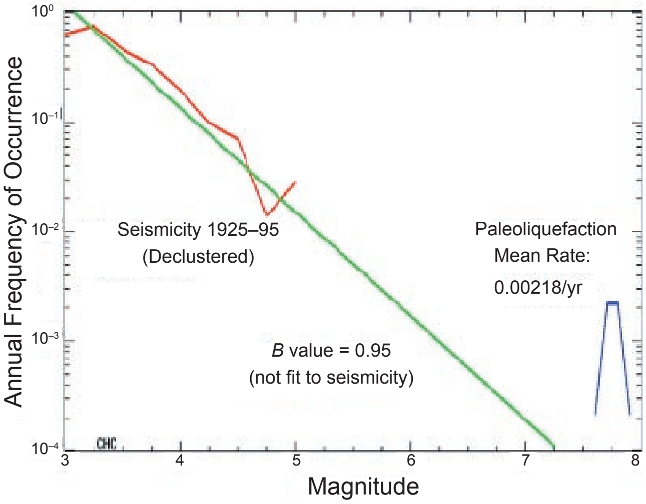

Figure 16. Magnitude-frequency relationship in the New Madrid Seismic Zone. From Frankel and others (1996).

Table 4 lists instrumental and historical earthquakes known to have occurred in the New Madrid Seismic Zone with magnitude equal to or greater than 4.0 (Bakun and Hopper, 2004). Figure 17 shows the Gutenberg-Richter curve for these earthquakes. The *a* and *b* values are about 3.15 and 1.0, respectively, for earthquakes with magnitudes between 4.0 and 5.0 (Fig. 17). The *b* value of 1.0 is consistent with that used in the national seismic hazard maps (Frankel and others, 1996, 2002) (Fig. 16). As shown in Figures 16 and 19, if the *a* and *b* values are used to extrapolate recurrence intervals for large earthquakes in the New Madrid Seismic Zone, they would be quite long: about 700 years for M 6.0, 7,000 years for M 7.0, and 70,000 years for M 8.0 earthquakes. This is why large earthquakes ($M \geq 7.0$) in the New Madrid Seismic Zone are treated as characteristic. We assigned a magnitude of 7.5 with a mean recurrence interval of 500 to 1,000 years for the characteristic event along the New Madrid faults, based on geological studies (Tuttle and others, 2002; Holbrook and others, 2006).

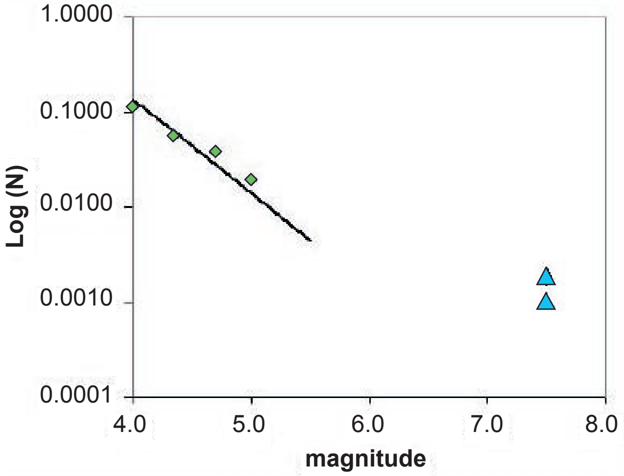

Figure 17. Magnitude-frequency (Gutenberg-Richter) curve for the New Madrid Seismic Zone. Diamond=historical rate; triangle=geological rate.

Wabash Valley Seismic Zone

Paleoliquefaction studies by Obermeier and others (1991, 1993), Munson and others (1995, 1997), and Pond and Martin (1997) suggest a mean recurrence interval of about 5,000 years for the large prehistoric earthquakes in the Wabash Valley Seismic Zone. As shown in Figure 18, this recurrence interval is consistent with the intervals projected from the seismicity of small and moderate earthquakes ($\leq$ M 5.0) (Wheeler and Cramer, 2002). Figure 19 shows the Gutenberg-Richter curve for the Wabash Valley Seismic Zone based on data from Bakun and Hopper (2004) (a=3.0, b=1.0). We derived a mean recurrence interval of about 4,000 years for an earthquake with a magnitude of 6.8 or greater, using Figure 19. This recurrence interval is consistent with geologic data (Obermeier and others, 1991, 1993; Munson and others, 1995, 1997; Pond and Martin, 1997) and was used for the Wabash Valley Seismic Zone in this report.

Background Seismicity

The occurrence frequency of the maximum background earthquake was determined based on earthquakes with magnitude greater than 2.5 in the area surrounding the Paducah Gaseous Diffusion Plant (Fig. 20). This is similar to the smoothed seismicity that

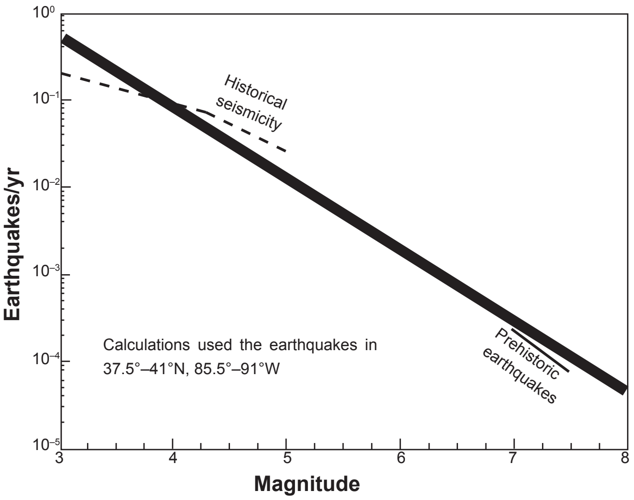

Figure 18. Magnitude-frequency relationship in the Wabash Valley Seismic Zone. From Wheeler and Cramer (2002). Published with permission of the Seismological Society of America.

Table 4. Earthquakes with magnitude equal to or greater than M 4.0 in the New Madrid Seismic Zone. From Bakun and Hopper (2004). Published with permission of *Seismological Research Letters*.

Date	*Latitude*	*Longitude*	*M*
1811-12-16	36.00	–89.96	7.6
1811-12-16 “dawn”	36.25	–89.50	7.0
1812-01-23	36.80	–89.50	7.5
1812-02-07	36.30	–89.40	7.8
1843-01-05	35.90	–89.90	6.2
1843-02-17	35.90	–89.90	4.2
1865-08-17	35.54	–90.40	4.7
1878-11-19	35.65	–90.25	5.0
1883-01-11	36.80	–89.50	4.2
1903-11-04	36.59	–89.58	4.7
1923-10-28	35.54	–90.40	4.1
1927-05-07	35.65	–90.25	4.5
1938-09-17	35.55	–90.37	4.4
1962-02-02	36.37	–89.51	4.2
1963-03-03	36.64	–90.05	4.7
1970-11-17	35.86	–89.95	4.1
1976-03-25a	35.59	–90.48	4.6
1976-03-25b	35.60	–90.50	4.2
1991-05-04	36.56	–89.80	4.1
2003-04-30	35.920	–89.920	4.0
2003-06-06	36.87	–88.98	4.0

was used in the national seismic hazard maps (Frankel and others, 2002). The *a* and *b* values were estimated to be 2.56 and 0.97, respectively (Fig. 21). The mean recurrence interval is projected to be about 200 years for an M 5.0 earthquake.

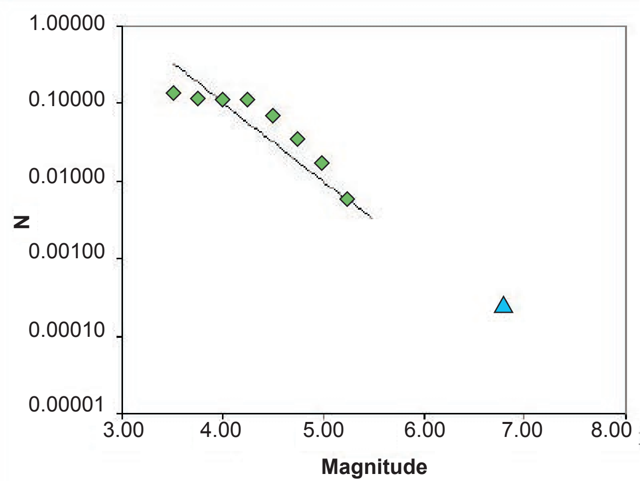

Figure 19. Magnitude-frequency (Gutenberg-Richter) curve for the Wabash Valley Seismic Zone. Diamond=historical rate, triangle=geological (paleoliquefaction) rate.

Ground-Motion Attenuation Relationship

As shown in Figure 2, the ground-motion attenuation relationship describes a spatial relationship between a ground-motion parameter (i.e., peak ground acceleration, peak ground velocity, modified Mercalli intensity, or pseudo-response acceleration at different periods) and earthquake magnitude and source-to-site distance with uncertainty (equation 2 or 3). This can be demonstrated through the following example of how the ground-motion attenuation relationship is modeled. Figure 22 shows horizontal uncorrected PGA versus distance to the fault (R_{RUP}) and five ground-motion attenuation relationships for the Parkfield earthquake of September 28, 2004 (Shakal and others, 2006). Figure 23 shows the locations of strong-motion stations and accelerograms recorded for the east-west component of the 2004 M 6.0 Parkfield earthquake (Shakal and others, 2006). Source-to-site distance is measured as the shortest distance to the fault rupture (R_{RUP}), not the epicentral distance (R_{EPI}). Figure 23 also shows that the epicentral distances are quite different from the rupture distances: R_{RUP} is about 4 and 2 km for stations FZ11 and FZ16, and R_{EPI} is about 10 and 15 km, respectively. As shown in Figure 22, a different set

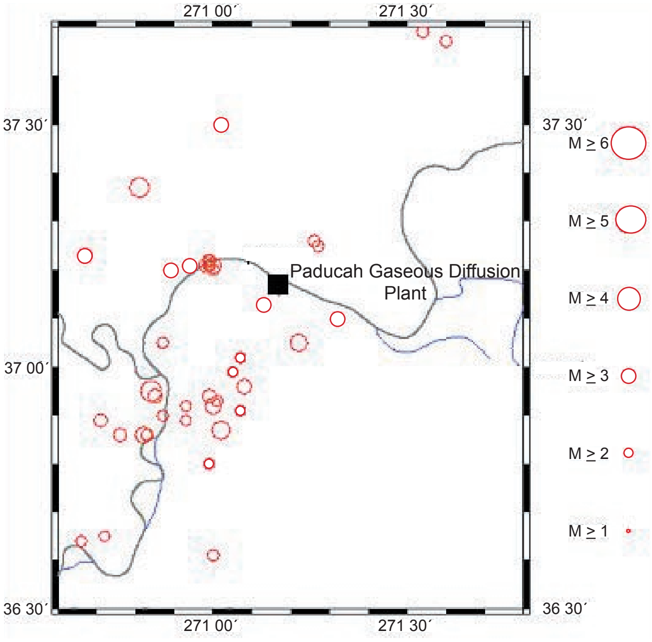

Figure 20. Recorded earthquakes with magnitude greater than 2.5 surrounding the Paducah Gaseous Diffusion Plant between 1978 and 2006.

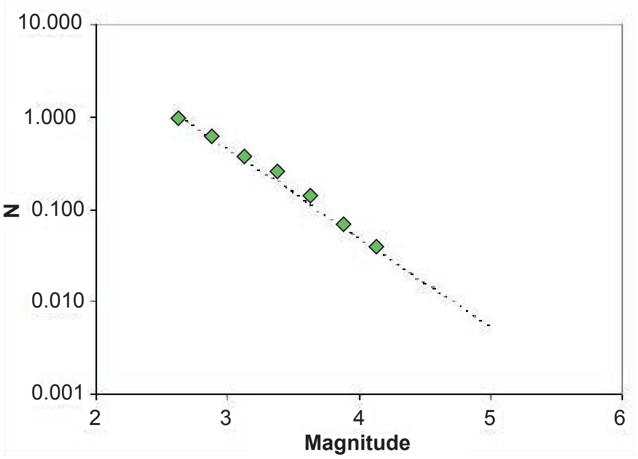

Figure 21. Magnitude-frequency (Gutenberg-Richter) curve for the background seismicity.

of parameters (i.e., $f(M,R)$ and $\sigma_{ln,Y}$) would result if the epicentral distance was used (represented by the blue diamond). This shows that the ground-motion attenuation relationship, equation 2 or 3, depends on how earthquake source (i.e., point versus finite), source-to-site distance (i.e., R_{RUP}, R_{JB}, R_{EPI}, or R_{HYP}), and site conditions (i.e., rock versus soil) are considered. In addition, many different functional forms are being used by different modelers. For example, Atkinson and Boore (2006) used the following functional form on hard rock of the central and eastern United States:

$$\log(PSA) = c_1 + c_2M + c_3M^2 + (c_4 + c_5M)f_1 + (c_6 + c_7M)f_2 + (c_8 + c_9M)f_0 + c_{10}R_{cd} + n\sigma_{\log,PSA} \tag{10}$$

where f_0=max (log(R_0/R_{cd}), 0);
f_1=min (log R_{cd}, log R_1);
f_2=max (log (R_{cd}/R_2), 0);
R_{cd}=the closest distance to the fault (R_{RUP});
R_0=10 km;
R_1=70 km;
R_2=140 km.

Silva and others (2002) used the functional form of

$$\ln(Y) = c_1 + c_2M + (c_6 + c_7M)\ln(R + e^{c4}) + c_{10}(M-6)^2 + n\sigma_{\ln,Y} \tag{11}$$

where R is the closest distance to the surface projection of the rupture surface (R_{JB}). Therefore, the ground-mo-

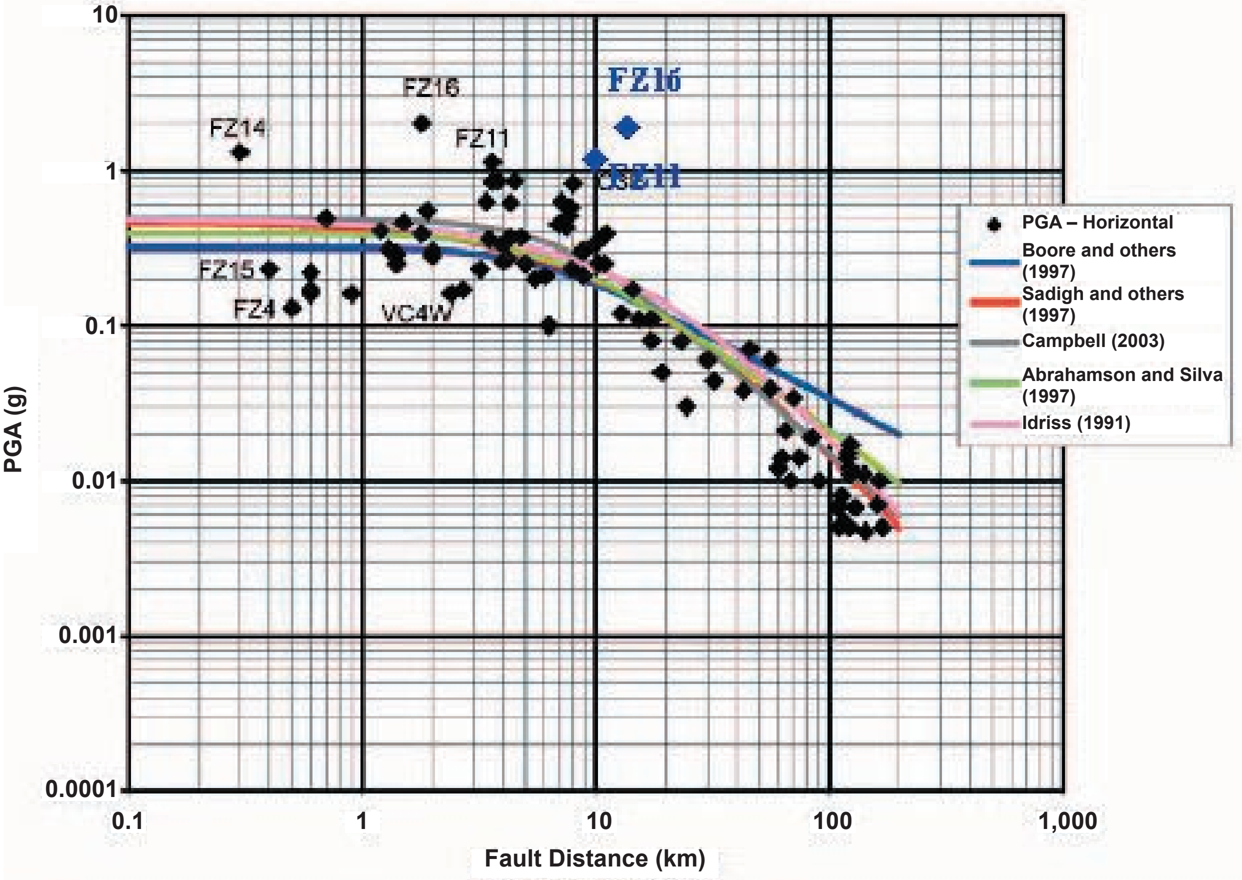

Figure 22. Horizontal uncorrected PGA versus distance to the fault for the Parkfield earthquake of September 28, 2004. From Shakal and others (2006). Blue diamonds are plots for stations FZ11 and FZ16 if the epicentral distance is measured. Published with permission of the Seismological Society of America.

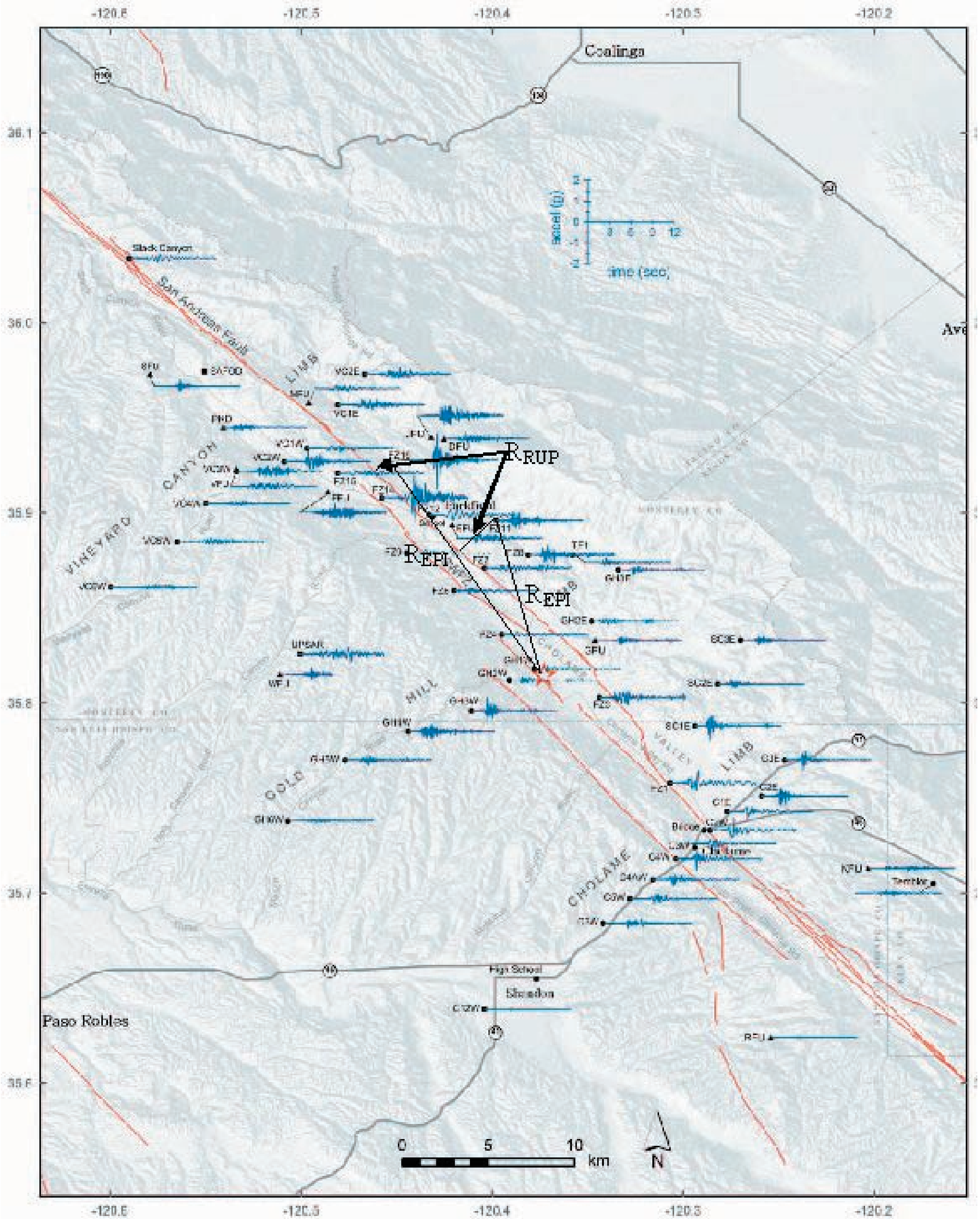

Figure 23. Strong-motion stations and accelerograms recorded in the 2004 M 6.0 Parkfield earthquake for the east-west component. From Shakal and others (2006). R_{RUP}=the closest distance to fault rupture; R_{EPI}=epicentral distance. Published with permission of the Seismological Society of America.

tion attenuation relationship depends not only on the functional form and associated constants being used, but also on how earthquake source (i.e., point or finite), source-to-site distance (i.e., R_{RUP}, R_{JB}, R_{EPI}, or R_{HYP}*)*, and site conditions (i.e., rock or soil) are considered. In other words, there may be a dependency between the statistical parameters (i.e., constants and standard deviation) and the variables (i.e., M and R*)*. In fact, many researchers (Youngs and others, 1995, 1997; Abrahamson and Silva, 1997; Sadigh and others, 1997; Toro and others, 1997; Campbell, 2003; Akkar and Bommer, 2007) have found that ground-motion uncertainty depends on M or R, or both. As discussed earlier, however, ground-motion uncertainty is treated as an independent random variable in PSHA (Cornell, 1968, 1971; McGuire, 1976, 1995, 2004). The dependency between the statistical parameters in the ground-motion attenuation relationship needs to be explored further, because it has a significant implication for hazard calculations (Carroll, 2003; Wang and Zhou, 2007).

One of the fundamental differences between assessing seismic hazard in the western and central United States is in the ground-motion attenuation relationship (Wang and others, 2005). The attenuation relationships developed for California are based on observations, such as those by Abrahamson and Silva (1997), Boore and others (1997), Sadigh and others (1997), Boore and Atkinson (2006), Campbell and Bozorgnia (2006), and Chiou and Youngs (2006). Figure 24 shows the worldwide data being used for development of the ground-motion attenuation relationship for the Next Generation Attenuation Models project by Chiou and Youngs (2006). In contrast, all the attenuation relationships currently available for the central United States are theoretical, based on very limited observations (Frankel and others, 1996; Toro and others, 1997; Somerville and others, 2001; Silva and others, 2002; Campbell, 2003; Electric Power Research Institute, 2003; Atkinson and Boore, 2006). Figure 25 shows the simulated data used for the ground-motion attenuation analysis by Atkinson and Boore (2006) for the central and eastern United States. 1

These significantly different attenuation relationships between the western and central United States result in differences in ground-motion uncertainties in both median and standard deviation in the two areas. As shown by Frankel (2004), the median ground motions for California vary only slightly between proposed attenuation relationships. For example, PGA ranges from 0.30 to 0.38 g between four attenuation relationships for a magnitude 7.8 earthquake at a distance of 15 km in San Francisco (Frankel, 2004). For comparison, Table 5 lists the median PGA for a magnitude 7.7 earthquake at 15 km from the New Madrid Seismic Zone from five attenuation relationships. The range of the median PGA in the central United States is between 0.69 and 1.20 g. Similarly, Frankel (2004) showed a large range of median ground motions, especially for near-source distances (less than 30 km). The theoretical models predict higher median ground motions (PGA and 5 Hz response acceleration) for the central United States than for similar earthquakes in the West. Thus, the theoretical models for the central United States predict not only higher median ground motion compared to the West, but also a greater uncertainty. Some theoretical models also predict higher standard

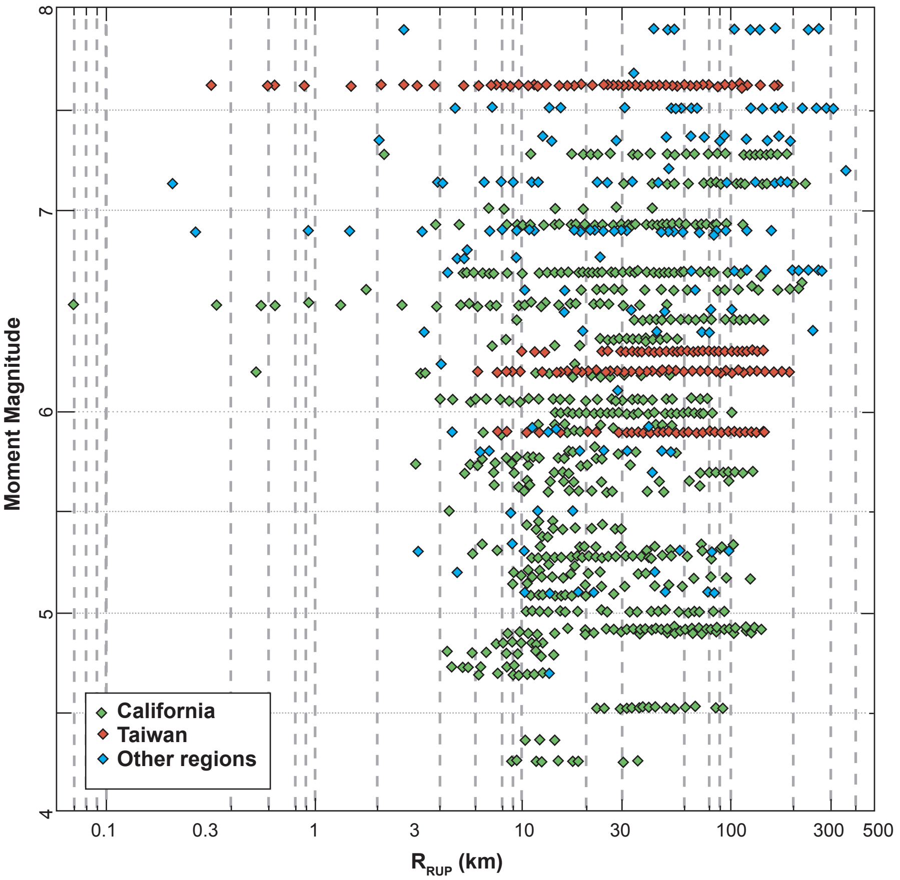

Figure 24. Magnitude-distance-region distribution of selected recordings. From Chiou and Youngs (2006).

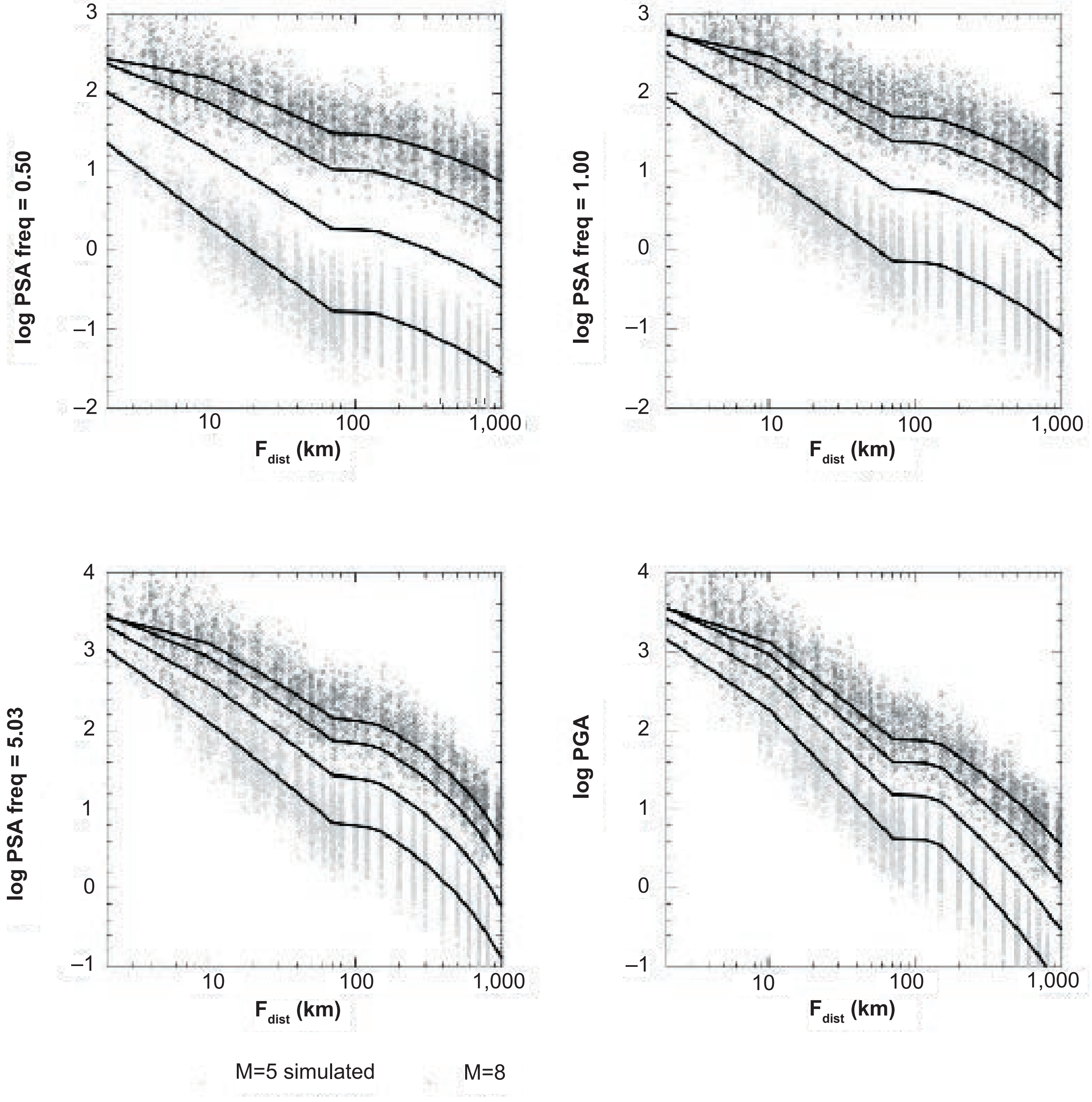

Figure 25. Log values of horizontal component 5 percent pseudo-acceleration at frequencies 0.5, 1, and 5 Hz, and PGA, for rock sites in eastern North America. Dots show PSA from simulations, including aleatory uncertainty, for M 5 (light) and M 8 (dark). Solid lines show predicted amplitudes from regression equations developed from a simulated database for M 5, 6, 7, and 8. From Atkinson and Boore (2006). Published with permission of the Seismological Society of America.

Table 5. Median ground motions for an M 7.7 New Madrid earthquake at 15 km for a hard-rock site from several attenuation relationships.

	Frankel and others (1996)	*Toro and others (1997)*	*Atkinson and Boore (1995)*	*Campbell (2003)*	*Somerville and others (2001)*
PGA (g)	1.20	0.90	0.90	0.91	0.69

deviations for the central and eastern United States than for the West, even though recent studies suggest that the standard deviation should be similar for the two regions (Atkinson and Boore, 2006).

Use of different attenuation relationships will result in different ground-motion estimates, for near-source distances (10 to 30 km) in particular. Frankel and others (2002, p. 6) said

> significant differences between the 1996 and 2002 maps are caused by the inclusion of additional attenuation relations in the 2002 maps. In 1996, we used the attenuation relations of Toro et al. (1997) and Frankel et al. (1996), which were assigned equal weight. For the 2002 maps we have added the attenuation relations of Atkinson and Boore (1995), Somerville et al. (2001) and Campbell (2003).

As the Senior Seismic Hazard Analysis Committee (1997, p. xv) concluded,

> one key source of difficulty is failure to recognize that 1) there is not likely to be "consensus" (as the word is commonly understood) among the various experts and 2) no single interpretation concerning a complex earth-sciences issue is the "correct" one.

There is no consistent or unique way to choose ground-motion attenuation relationships for seismic hazard analysis. Recent studies have indicated that ground motion at near-source distances (10–50 km) has been over predicted, however (U.S. Geological Survey/Nuclear Regulatory Commission Workshop, 2005; Atkinson and Boore, 2006), even for the West Coast, where ground motion was overly predicted at near-source distances (Abrahamson, 2006; Boore and Atkinson, 2006; Campbell and Bozorgnia, 2006; Chiou and Youngs, 2006). There is a consensus among researchers that many current attenuation relationships predict too high ground motion at near-source, particularly the relationship of Frankel and others (1996), for the central and eastern United States (U.S. Geological Survey/Nuclear Regulatory Commission Workshop, 2005). Figure 26 shows some of the ground-motion attenuation relationships for a magnitude 7.5 earthquake in the central United States. The attenuation relationship of Frankel and others (1996) predicts higher PGA at near-source distances between 10 and 50 km. Figure 27 shows some of the ground-motion attenuation relationships for a magnitude 5.0 earthquake in the central United States.

In this report, we used the ground-motion attenuation relationships of Somerville and others (2001), Silva and others (2002), Campbell (2003), and Atkinson and Boore (2006). These relationships represent

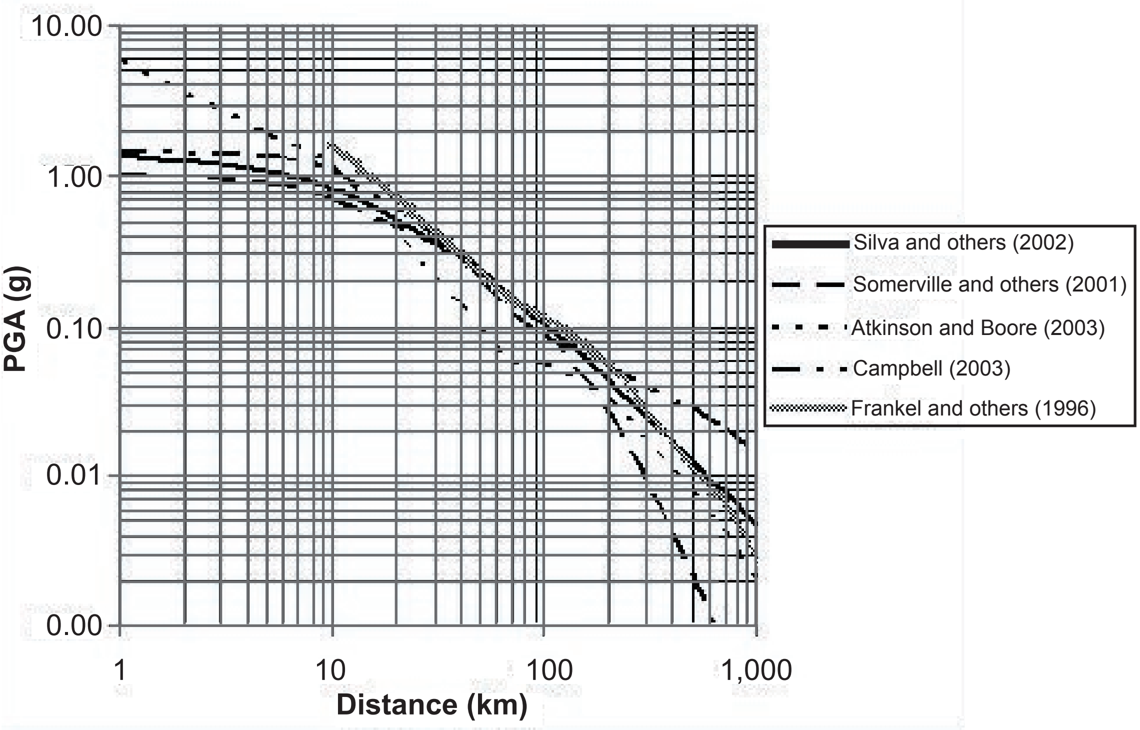

Figure 26. PGA attenuation relationships at hard rock for an M 7.5 earthquake in the central United States.

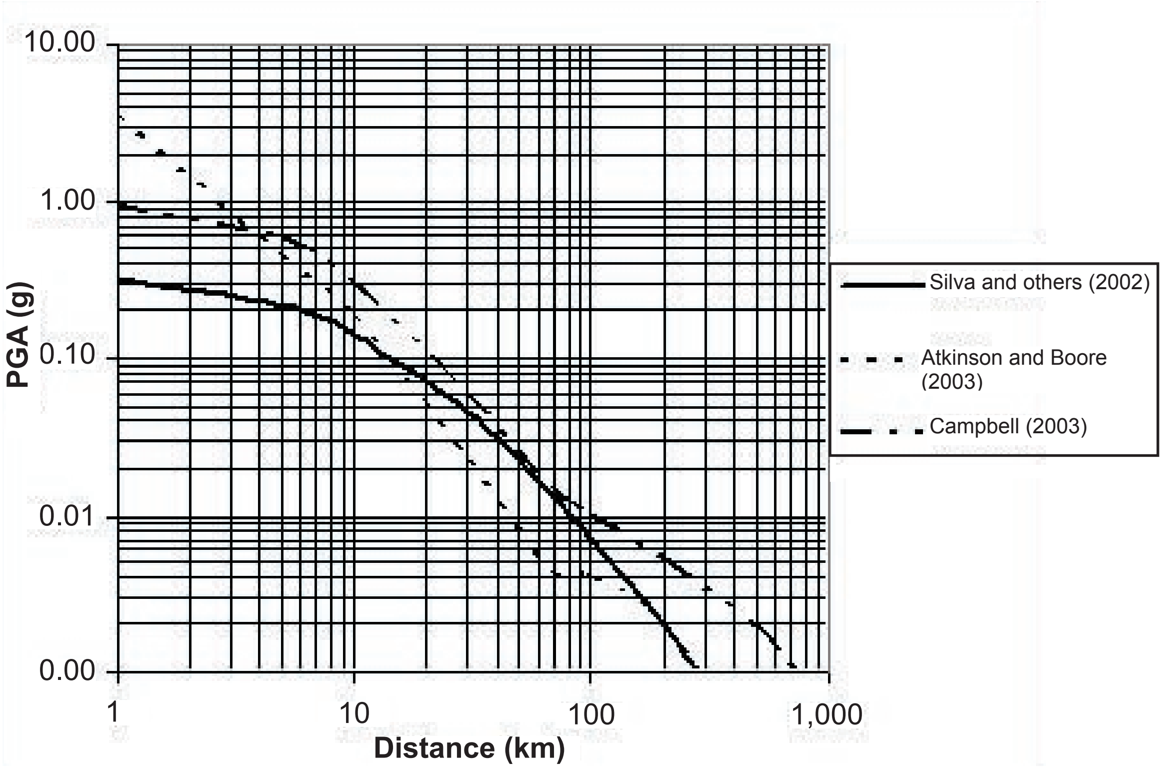

Figure 27. PGA attenuation relationships at hard rock for an M 5.0 earthquake in the central United States.

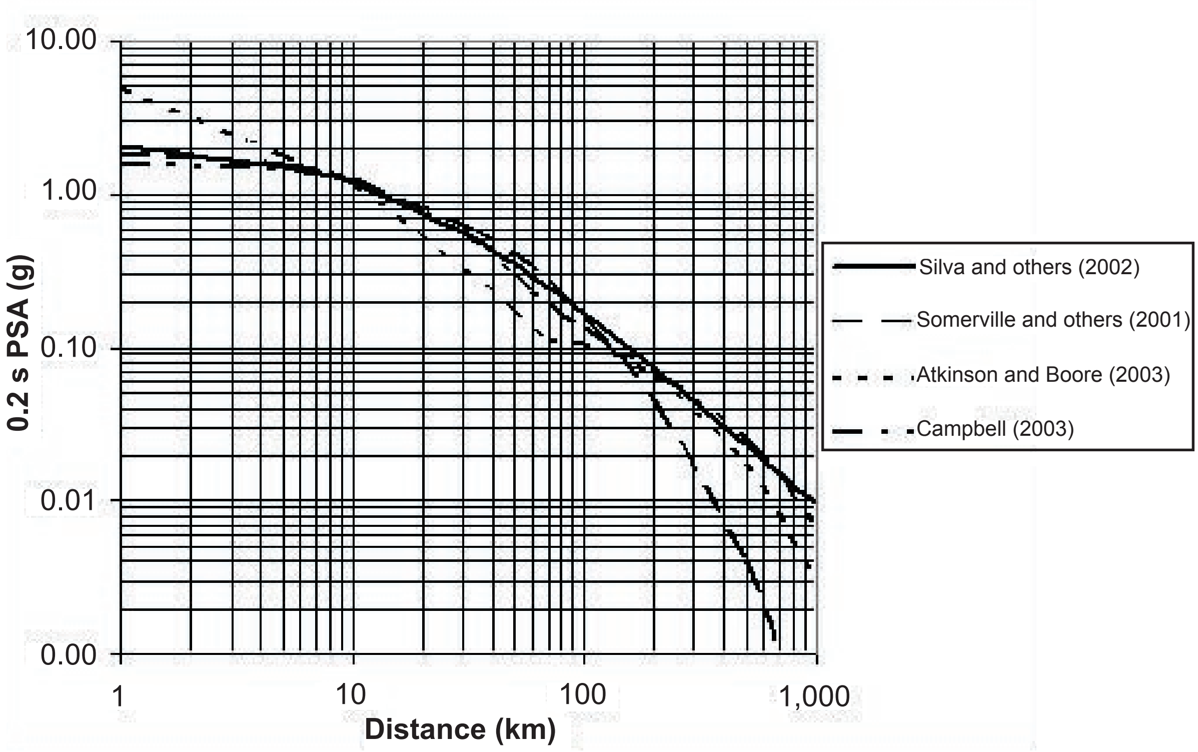

Figure 28. The 0.2 s PSA attenuation relationships used in this study at hard rock for an M 7.5 earthquake in the central United States.

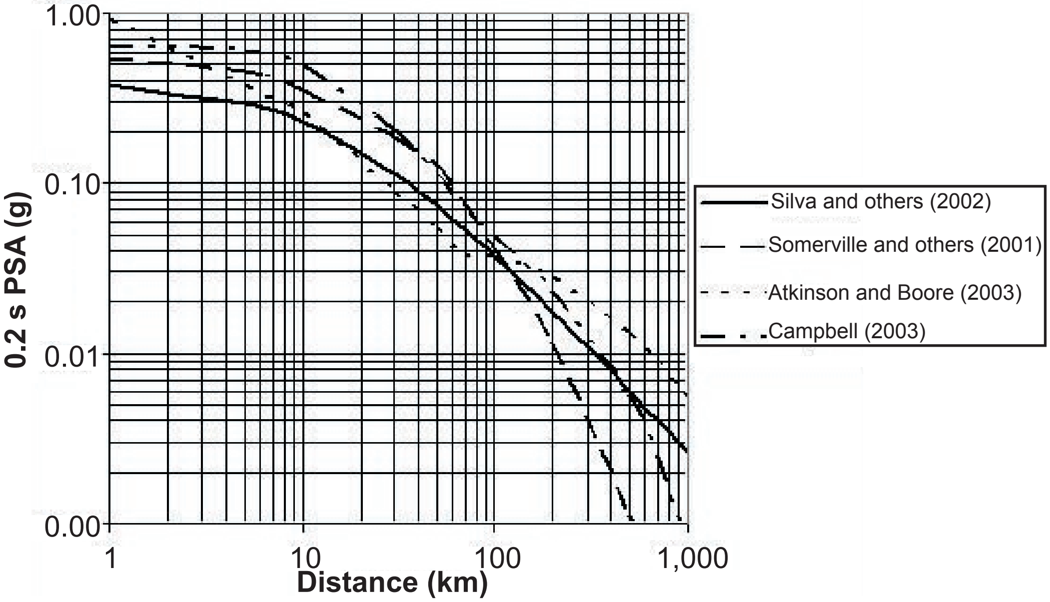

Figure 29. The 1.0 s PSA attenuation relationships used in this study at hard rock for an M 7.5 earthquake in the central United States.

different approaches (i.e., finite source/Green's function, double-corner, and hybrid methods). Figures 28 and 29 show 0.2 s and 1.0 s response accelerations of the four attenuation relationships for a magnitude 7.5 earthquake in the central United States. The rupture distance is used in all the attenuation relationships throughout this report.

Results

Three seismic sources affect the Paducah Gaseous Diffusion Plant: the New Madrid faults, Wabash Valley Seismic Zone, and small earthquakes nearby (Fig. 30). The mean distances from the plant to the New Madrid faults and Wabash Valley Seismic Zone are 40 and 60 km, respectively. The source-to-site distance from the New Madrid faults is treated as characteristic, and is similar to the characteristic source used in the national hazard mapping and other studies (Frankel and others, 1996, 2002; Geomatrix Consultants Inc., 2004). The Wabash Valley Seismic Zone is a large areal source. As shown in Figure 20, local earthquakes around Paducah may also contribute to the hazard. In this project, we used a point source at a distance of 15 km with a maximum magnitude of 5.0 (Fig. 30) to account for the background seismicity for the Paducah Gaseous Diffusion Plant.

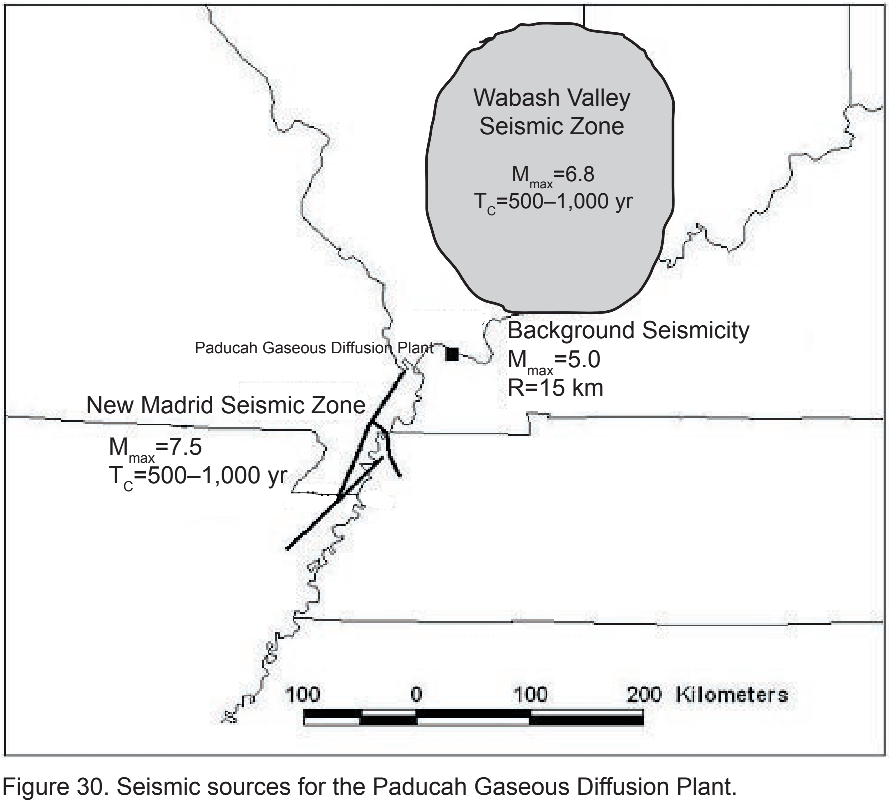

Figure 30. Seismic sources for the Paducah Gaseous Diffusion Plant.

PSHA Results

As discussed earlier, ground-motion uncertainty is inherently a part of PSHA, and other uncertainties, such as fault location, are treated with logic trees, which manually assign different weights to a set of expert estimates for each input parameter (Senior Seismic Hazard Analysis Committee, 1997). In this project, the weights shown in Table 6 were used to account for uncertainties in location, magnitude, recurrence interval, and attenuation relationship. Ground-motion hazard in the New Madrid Seismic Zone can be estimat-

Table 6. Input parameters and weights being used here in our PSHA for the Paducah Gaseous Diffusion Plant.

Source	*M_{MAX} (mean)*	*Recurrence interval (yr) (mean)*	*Distance (km) (mean)*	*Attenuation*
New Madrid Seismic Zone (characteristic)	7.5	500 (0.75) 1,000 (0.25)	40	Atkinson and Boore (2006) (0.25) Campbell (2003) (0.25) Silva and others (2002) (0.25) Somerville and others (2001) (0.25)
Wabash Valley Seismic Zone (areal)	6.8	4,000 (1.0)	60	Atkinson and Boore (2006) (0.25) Campbell (2003) (0.25) Silva and others (2002) (0.25) Somerville and others (2001) (0.25)
Background seismicity (point)	5.0	200 (1.0)	15	Atkinson and Boore (2006) (0.33) Campbell (2003) (0.33) Silva and others (2002) (0.33)

ed with a single equivalent earthquake of a specified magnitude and at a specified distance (Frankel, 2004). The deaggregation analysis also shows that ground-motion hazard in Paducah can be approximated by a single equivalent earthquake (Petersen, 2005). Although this analysis (Table 6) is not a standard PSHA, it can provide a good estimate (Frankel, 2004; Petersen, 2005) and is easy to understand. The hazard curves for PGA, 0.2 s PSA, and 1.0 s PSA are shown in Figures 31 through 33. Table 7 lists ground-motion values for the Paducah Gaseous Diffusion Plant on hard rock at several annual probabilities of exceedance.

DSHA Results

Table 8 lists the median PGA values for the three sources affecting the Paducah Gaseous Diffusion Plant (Fig. 30), using the attenuation relationships of Somerville and others (2001), Silva and others (2002), Campbell (2003), and Atkinson and Boore (2006). As shown in Table 8, the characteristic earthquake for the New Madrid Seismic Zone dominates the hazard determination for the plant. Tables 9, 10, and 11 list PGA and 0.2 s and 1.0 s PSA hazards for the Paducah Gaseous Diffusion Plant, using the characteristic earthquake for the New Madrid Seismic Zone and the ground-motion attenuation relations of Somerville and others (2001), Silva and others (2002), Campbell (2003), and Atkinson and Boore (2006). The return period for these ground motions is about 500 to 1,000 years, the same as the recurrence interval of the characteristic earthquake for the New Madrid Seismic Zone.

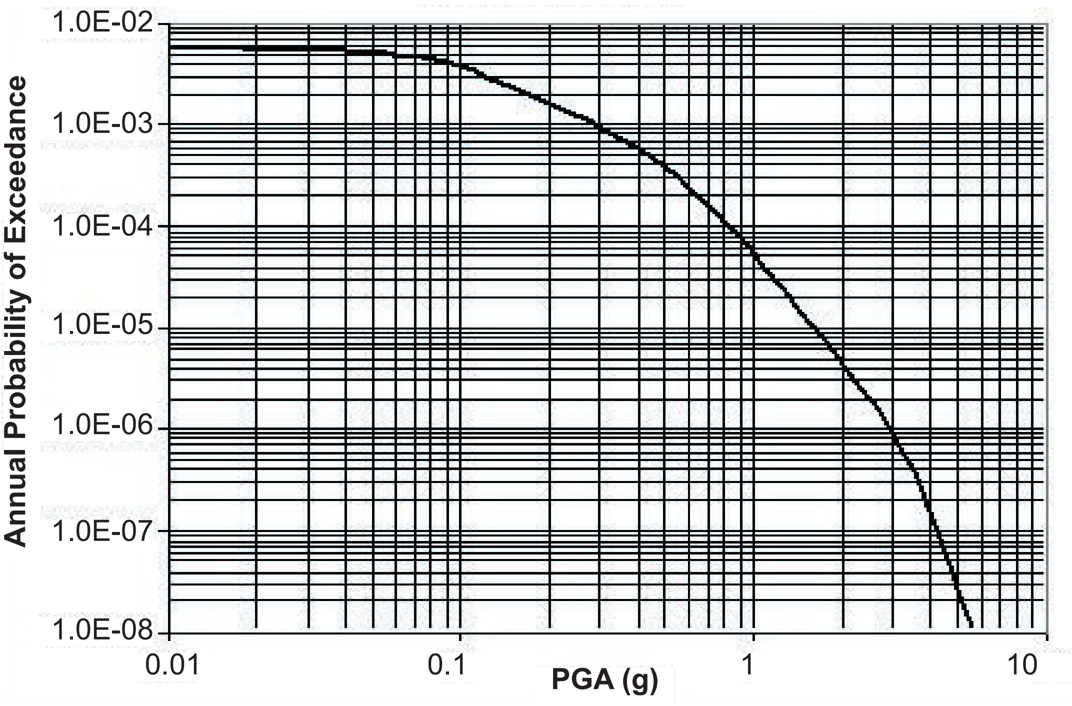

Figure 31. Mean PGA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant.

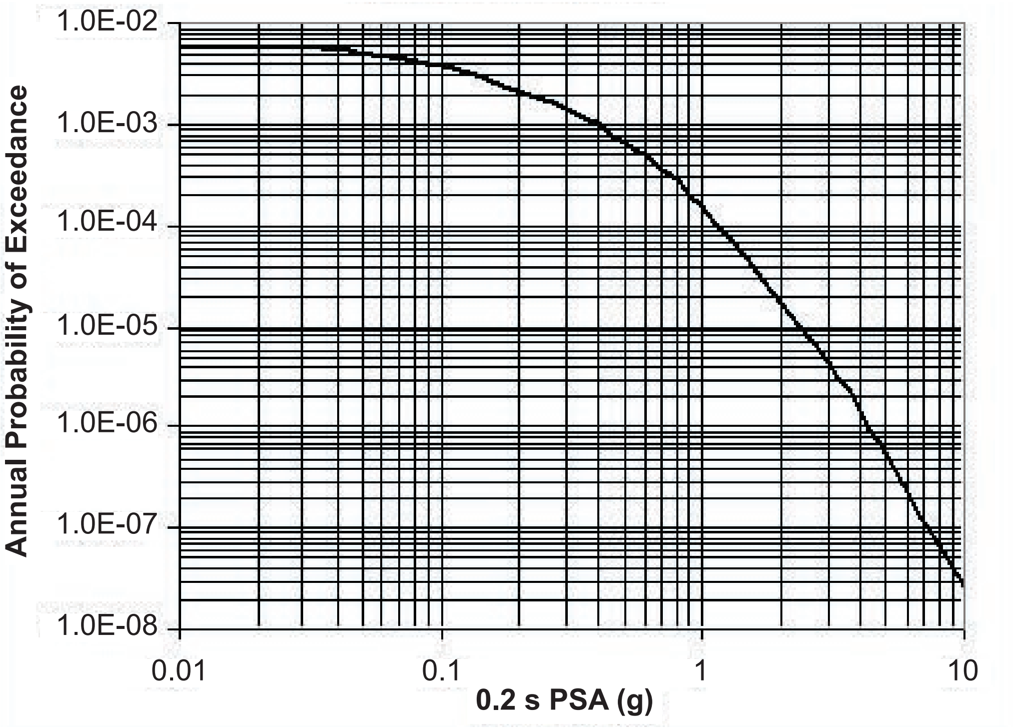

Figure 32. Mean 0.2 s PSA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant.

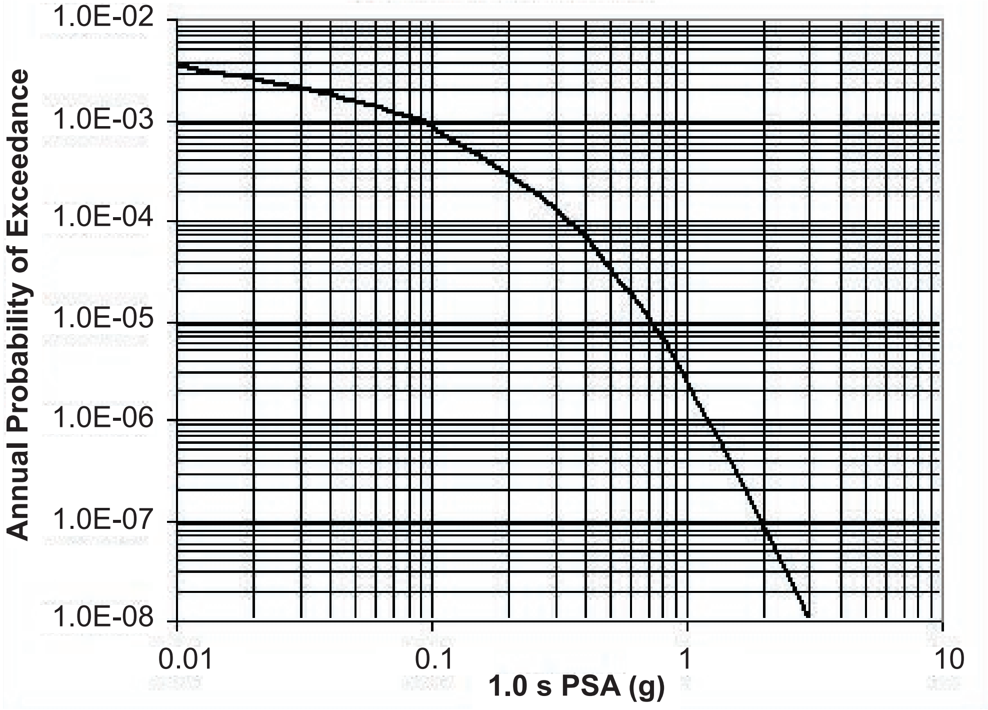

Figure 33. Mean 1.0 s PSA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant.

Table 7. Mean ground-motion hazards on hard rock at the Paducah Gaseous Diffusion Plant.

Annual Probability of Exceedance	*Return Period (years)*	*PGA (g)*	*0.2 s PSA (g)*	*1.0 s PSA (g)*
0.004	250	0.09	0.10	0.01
0.002	500	0.18	0.21	0.03
0.001	1,000	0.29	0.40	0.09
0.0004	2,500	0.49	0.68	0.16
0.0002	5,000	0.62	0.90	0.23

Conclusions and Recommendations

Estimating seismic hazard at the Paducah Gaseous Diffusion Plant is difficult because of a lack of instrumental ground-motion observations from large earthquakes in the region. Three seismic sources (New Madrid Seismic Zone, Wabash Valley Seismic Zone, and background seismicity) were characterized based on currently available information on geology and seismology in the central United States. Four ground-motion attenuation relationships were chosen and used for evaluating ground-motion hazard on hard rock at the plant. Probabilistic seismic hazard analysis and deterministic seismic hazard analysis were performed for the plant. Table 12 lists ground-motion hazards derived from PSHA using several commonly considered return periods. Table 13 lists ground-motion hazards and associated uncertainty derived from DSHA.

These results show that PSHA and DSHA use the same geologic and seismologic parameters, but pro-

Table 8. Median PGA (g) on hard rock at the Paducah Gaseous Diffusion Plant from the three seismic sources.

Source Zone	*Atkinson and Boore (2006)*	*Campbell (2003)*	*Silva and others (2002)*	*Somerville and others (2001)*
New Madrid	0.14	0.28	0.29	0.29
Wabash Valley	0.04	0.09	0.11	0.10
Background seismicity	0.11	0.17	0.10	n/a

Table 9. PGA (g) at the Paducah Gaseous Diffusion Plant from the characteristic earthquake in the New Madrid Seismic Zone.

	Median	*Median* $+1\sigma_{ln,y}$	*Median* $+2\sigma_{ln,y}$	*1.5 Median*
Atkinson and Boore (2006)	0.14	0.28	0.56	0.21
Campbell (2003)	0.28	0.55	1.08	0.42
Silva and others (2002)	0.29	0.67	1.55	0.44
Somerville and others (2001)	0.29	0.52	0.94	0.44
Average	0.25	0.51	1.03	0.38

Table 10. The 0.2 s PSA (g) at the Paducah Gaseous Diffusion Plant from the characteristic earthquake in the New Madrid Seismic Zone.

	Median	*Median* $+1\sigma_{ln,y}$	*Median* $+2\sigma_{ln,y}$	*1.5 Median*
Atkinson and Boore (2006)	0.23	0.46	0.92	0.35
Campbell (2003)	0.40	0.82	1.68	0.60
Silva and others (2002)	0.43	0.99	2.29	0.65
Somerville and others (2001)	0.51	0.93	1.71	0.77
Average	0.39	0.80	1.65	0.59

Table 11. The 1.0 s PSA (g) at the Paducah Gaseous Diffusion Plant from the characteristic earthquake in the New Madrid Seismic Zone.

	Median	*Median +1*$\sigma_{ln,y}$	*Median +2*$\sigma_{ln,y}$	*1.5 Median*
Atkinson and Boore (2006)	0.07	0.14	0.28	0.11
Campbell (2003)	0.15	0.31	0.65	0.23
Silva and others (2002)	0.09	0.21	0.51	0.14
Somerville and others (2001)	0.15	0.30	0.60	0.23
Average	0.12	0.24	0.51	0.18

duce quite different estimates of ground motion at the Paducah Gaseous Diffusion Plant. This is because in PSHA, seismic hazard is defined as the return period (or annual probability of exceedance) with a ground motion larger than a specific value, whereas in DSHA, seismic hazard is defined as the ground motion(s) from a single or several earthquakes that have maximum impact at a site. PSHA calculates seismic hazard from all earthquake sources in consideration, and implicitly incorporates uncertainty in earthquake size, location, and ground motion. DSHA emphasizes the ground motion from an individual earthquake, such as the maximum credible earthquake or maximum probable earthquake, and explicitly determines ground-motion hazard with a specified level of uncertainty.

What level of ground motion should be considered for engineering design of a facility at the Paducah Gaseous Diffusion Plant? The answer to this question is complicated and depends on many factors, such as which methodology is used, what type of facility is being considered, and what environment is being considered. There should be a scientific basis in selecting a design ground motion, however. It is well understood that large earthquakes in the New Madrid Seismic Zone similar to the 1811-12 events pose the biggest hazard in the central United States, at the Paducah Gaseous Diffusion Plant in particular. This study shows that the best estimate (mean) of PGA is about 0.25 g at the Paducah Gaseous Diffusion Plant from the New Madrid earthquakes (Table 13). This estimate is consistent with limited MMI data (Fig. 34). Figure 34 shows that modified Mercalli intensity at the plant site on February 7, 1812, was VIII, which is equivalent to a PGA of 0.20 to 0.30 g (Bolt, 1993; Atkinson and Kaka, 2007). This suggests that a PGA level of 0.25 to 0.3 g would be appropriate for engineering design of ordinary buildings and facilities at the site and surrounding areas. Therefore, the ground motion with 1,000-year return period, derived from PSHA (Table 12), would be appropriate for engineering design of ordinary buildings and facilities. This is why Structural Engineers Association of Kentucky (2002) selected ground motion with a 1,000-year return period (Frankel and others, 1996) as the basis for seismic design of residential buildings in

Table 12. Ground-motion hazards on hard rock at the Paducah Gaseous Diffusion Plant determined by PSHA.

Annual Probability of Exceedance	*Return Period (yr)*	*Exceedance Probability in 50 Yr (%)*	*PGA (g)*	*0.2 s PSA (g)*	*1.0 s PSA (g)*
0.004	250	18	0.09	0.10	0.01
0.002	500	10	0.18	0.21	0.03
0.001	1,000	5	0.29	0.40	0.09
0.0004	2,500	2	0.49	0.68	0.16
0.0002	5,000	1	0.62	0.90	0.23

Table 13. Ground-motion hazards (g) on hard rock at the Paducah Gaseous Diffusion Plant determined by DSHA.

	Average Median	*Average Median +1*$\sigma_{ln,\ y}$	*Average Median +2*$\sigma_{ln,\ y}$	*Average 1.5 Median*
PGA	0.25	0.51	1.03	0.38
0.2 s PSA	0.39	0.80	1.65	0.59
1.0 s PSA	0.12	0.24	0.51	0.18

western Kentucky. This ground motion has also been considered as the upper-level ground motion for seismic retrofit of highway structures in the central and eastern United States (Federal Highway Administration, 2006). The ground motion with one standard deviation (0.51 g PGA) derived from DSHA could be considered for critical facilities such as nuclear power plants (Table 13). This ground motion (0.51 g PGA) is similar to the ground motion (0.49 g PGA) with a 2,500-year return period derived from PSHA (Table 12). Table 14 lists our recommended ground motions for design consideration for facilities at the Paducah Gaseous Diffusion Plant.

The results from our PSHA are consistently lower than those from the national seismic hazard maps (Frankel and others, 2002) and the site-specific study by Risk Engineering Inc. (1999) at the same return periods (Table 15). These differences result from the difference of the input parameters, particularly the location of the New Madrid faults (Fig. 7), our use of a smaller mean magnitude (7.5) for the characteristic earthquake in the New Madrid Seismic Zone, and our use of lower ground-motion attenuation relationships.

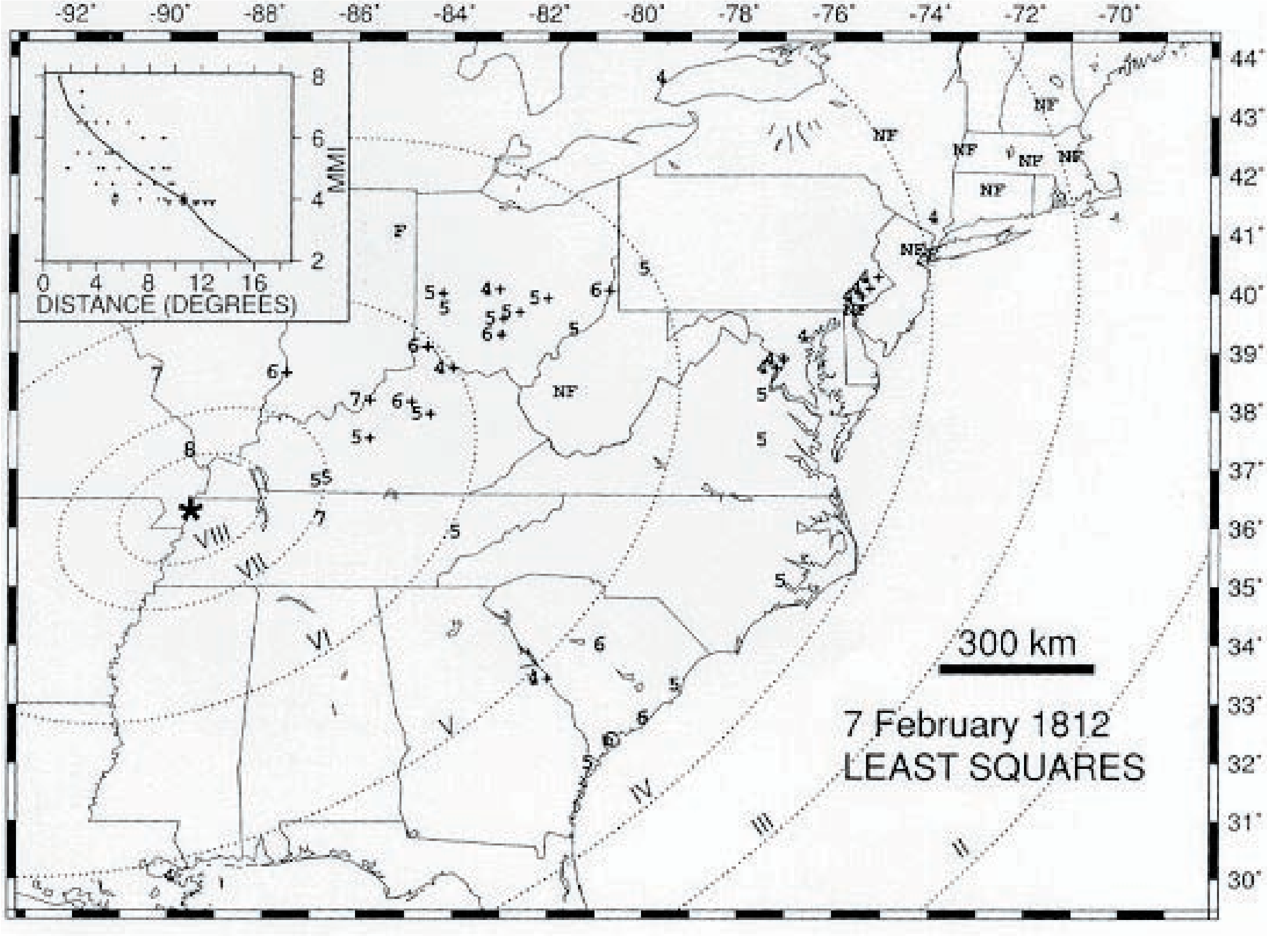

Figure 34. Isoseismal map of the February 7, 1812, New Madrid earthquake. From Hough and others (2000). Published with permission of the American Geophysical Union.

Table 14. Recommended ground motions on hard rock at the Paducah Gaseous Diffusion Plant.

Facility	*DSHA*	*PSHA*		*PGA (g)*	*0.2 s PSA (g)*	*1.0 s PSA (g)*
		Return Period (yr)	*Exceedance Probability in 50 Yr (%)*			
Ordinary	Median	1,000	5	0.27	0.40	0.10
Important	Median + one standard deviation	2,500	2	0.50	0.80	0.20

Table 15. Comparison of mean PGA (g) estimates on hard rock at the Paducah Gaseous Diffusion Plant determined from PSHA.

Return Period (yr)	*This Study*	*Frankel and others (2002)*[1]	*Risk Engineering Inc. (1999)*
250	0.09	0.08	0.10
500	0.18	0.24	0.20
1,000	0.29	0.55	0.38
2,500	0.49	0.95	0.78
5,000	0.62	1.24	1.15

[1] USGS values were converted from PGA for soft rock by a factor of 1.52.

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Appendix A:
Review Panel Comments on Draft Report

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
1.	Roy Van Arsdale	general	Although the work of Tuttle and others (2002) is the most recent to address earthquake recurrence in the New Madrid Seismic Zone, an earlier article came to the same conclusion. Kelson and others (1996) concluded that the recurrence interval on Reelfoot Fault earthquakes is in between 400 and 500 yr. This is significant because the earthquake recurrence interval is tied to a specific fault.	A recent study by Holbrook and others (2006) indicates earthquake recurrence interval of about 1,000 yr for the same fault. This is the reason that a range of recurrence intervals, 500 to 1,000 yr, is considered.
2.	Roy Van Arsdale	general	I did not see any treatment of multiple large earthquakes occurring on the New Madrid Seismic Zone like that which occurred in 1811-1812. Tuttle and others (2002) address this and there is also evidence for this clustering in Van Arsdale and others (1998). Does this clustering of large earthquakes not affect your results?	Seismic hazard is defined as an earthquake of magnitude M or greater (cumulative) or ground motion generated by the earthquake at a site versus mean recurrence interval (or return period for ground motion). Seismic risk is defined as the probability of at least one occurrence of M or greater earthquake (cumulative) or the ground motion at a site over a period. The clustering is considered, and will not have an effect on the results.
3.	Roy Van Arsdale	General	There is a large hole in our basement data at the north end of Reelfoot Rift. We really do not know how the Reelfoot Rift links with the Rough Creek Graben. I have a Ph.D. student (Ryan Csontos) who just completed his dissertation in which he took a stab at this. It appears that the Precambrian crystalline basement rises between the northern end of the Reelfoot Rift and the southern end of the Rough Creek Graben. Ryan interpreted the Reelfoot Fault to be a normal fault at depth, which forms a step up and out of the Reelfoot Rift. In his model, the Reelfoot Fault is an inverted normal fault. Another issue about the structure is the strike of fault in this transition zone. Do the faults continue N45°E or do they curve and merge with more easterly Rough Creek Graben faults? This should have a bearing on the stress on these faults from the N60°W regional maximum stress.	These are very good comments. The questions need to be addressed through future studies.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
1.	Gail Atkinson	general	This report deals with seismic hazards to the Paducah Gaseous Diffusion Plant and the methodology by which they should be assessed. The report is clearly written and easy to follow for the most part, but the reasoning used to propose an alternative methodology is flawed. The report does not actually provide a probabilistic seismic hazard assessment for the site. Rather, it is focused on providing arguments as to why PSHA may not be applicable. I did not find these arguments convincing. (1) PSHA is a well-accepted technique throughout the world, and the subject of many knowledgeable and definitive articles and textbooks by leading scientists and engineers over the last 40 years. In my view, it has a much sounder basis than the new methodology proposed here, which is a hybrid approach (elements of deterministic and probabilistic methodologies) that has been termed seismic hazard an assessment. (2) The proposed methodology (SHA) is seriously flawed, as discussed in the points below.	These general comments can be summarized into two questions: (1) Is PSHA appropriate even though it has been used for seismic hazard assessment for three decades? (2) Is the proposed methodology (SHA) seriously flawed? The answer to question 1 is clear: PSHA may not be appropriate for seismic-hazard assessment because it contains a mathematical error in its formulation: incorrectly treating ground-motion uncertainty as an independent random variable. Ground-motion uncertainty is an explicit or implicit dependent variable, as it is modeled in the ground-motion attenuation relationship. The mathematical error results in double/triple counts of uncertainties in earthquake magnitude and source-to-site distance. The mathematical error also results in mixing temporal measurements (occurrence of an earthquake and its consequences [ground motion] at a site) with spatial measurement (ground-motion variability due to source, path, and site effects). The results from a PSHA study are an artifact. The answer to question 2 is also clear: SHA is appropriate because (1) it was peer-reviewed (Wang, 2006b, 2007), (2) it is analogous to flood- and wind-hazard analyses for engineering design, and (3) it is similar to the Milne-Davenport approach (1969) and the approach of Stein and others (2005, 2006).

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
4.	Roy Van Arsdale	general	You do not address the large number of earthquakes that trend into western Kentucky illustrated in Figure 11.	The data quality, in terms of magnitude, location, and focal depth, for earthquakes before 2003 in western Kentucky is very poor due to the lack of seismic stations. Based on those earthquakes, Wheeler (1997) suggested the northeast extensions of the New Madrid faults, but also suggested that that can be substantiated by further seismic network monitoring. Recent studies by a more dense network (Wang and others, 2003a; Horton and others, 2005; Anderson and others, 2005) shows consistent differences between the earthquakes in the New Madrid zone and those in the Jackson Purchase Region, indicating that the New Madrid faults may not extend northeast into western Kentucky. There is no geologic evidence indicating the extension into the Jackson Purchase Region. On the other hand, there is geologic evidence showing the northeast extensions of the New Madrid faults on the Missouri side (see, for example, Baldwin and others [2005]).
5.	Roy Van Arsdale	Executive Summary	How can you have high seismic risk without seismic hazard?	In the report, we state "High seismic hazard does not necessarily mean high seismic risk, and vice versa." This means that low seismic hazard does not necessarily mean low seismic risk or there could be high seismic risk even though seismic hazard is low. If there is no seismic hazard, there is no seismic risk. This can be illustrated through the following examples: (1) The Mojave Desert has high seismic hazard (frequent large earthquakes, such as the Hector Mine earthquake), but has low seismic risk because of few exposures (people and property). (2) The San Simeon area has relatively low seismic hazard (compared to the Mojave Desert), but has higher seismic risk because of high exposure.
6.	Roy Van Arsdale	chapter 3, section 1, p. 21	The Reelfoot Rift–Rough Creek Graben–Rome Trough is commonly considered to be one large, perhaps discontinuous, Cambrian rift.	This is a good comment. The relationship between them in the Quaternary, particularly in the Holocene, is not clear, which has an impact on seismic hazard assessment.
7.	Roy Van Arsdale	chapter 3, section 1, p. 21	What about dense seismicity in western Kentucky in Figure 11?	See response to comment 4.
8.	Roy Van Arsdale	chapter 3, section 1, p. 21	True; also a black hole of no data.	See response to comment 3.
9.	Roy Van Arsdale	chapter 3, section 1	Why not through 2006?	All earthquakes up to March 2007 will be included.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
2.	Gail Atkinson	general	I also question why an entirely new methodology would be proposed in the context of a specific engineering project. For engineering projects, it is generally considered important to follow accepted practice. I appreciate that the motivation for such an approach arises from the consideration that PSHA suggests large ground motions at low probabilities for many regions of the central United States influenced by the New Madrid Seismic Zone and other nearby sources. However, I do not believe that the methodology proposed is a correct way to deal with these issues. Depending on the regulatory requirements that may apply, there could be other approaches to dealing with the site issues that would be more defendable. Just as an illustrative example (*not* a recommendation), it may be considered acceptable to find the probabilistic ground motions associated with each potential source separately (New Madrid, Wabash, background), for some target probability—one might then say, for example, that the facilities can accommodate the 2 percent/50 yr motions from each of the potential sources, while recognizing that this is not the total probability of receiving the ground motions. (The implicit rationale would be that the facility is not expected to be able to withstand a significant event from more than one potential source during its lifetime.) I emphasize that this is not a proposed solution, just a discussion point, and that this argument may not be applicable, depending on whether there are specific reliability targets for the project.	As shown in the report and response to comment 1, the results from a PSHA study are all artifacts, and may not be appropriate for seismic-hazard assessment. As demonstrated by Harris (2006), return period derived from PSHA is interpreted and used as mean recurrence interval, and compared with those of wind, snow, and other hazards. However, the return period is not equal or equivalent to mean recurrence interval. The proposed approach is not new, but a reintroduction of an old one (Milne and Davenport, 1969) with the addition of uncertainty. Return period derived from the proposed approach is identical to mean recurrence interval derived from wind, flood, and other hazard analysis.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
3.	Gail Atkinson	general	The proposed methodology is really a recasting of the concept of the "maximum credible earthquake," in which specific source scenarios (New Madrid, Wabash, background) are assigned in terms of a fixed distance and a subjective maximum magnitude. The casting of a recurrence relation for each source into a probabilistic ground-motion distribution only applies for the specific distance and maximum magnitude. In the case of background earthquakes and poorly understood sources (such as Wabash), the maximum magnitude and distance are arbitrary. The maximum magnitudes for the background (M_{MAX}=5) and Wabash (M_{MAX}=6.8) sources are not justified. The results of this proposed methodology will be very sensitive to the assigned maximum magnitude and distance. The derived ground-motion probabilities are not correct, as they do not consider that for each of the considered scenarios, there is a significant probability of a larger event at a closer location. They also do not properly account for the effect of sigma on ground-motion probability. The variability of actual ground motions about the predicted median increases the frequency of exceedance of any given ground-motion level. Thus, no probabilistic ground-motion distribution is actually obtained by this method.	These comments are really about how to treat temporal and spatial uncertainties (variability) of earthquakes. First, the temporal and spatial uncertainties are two intrinsic, but fundamentally different, measures, and must be treated separately. PSHA mixes the temporal uncertainty with the spatial uncertainty (this is the result of incorrect formulation of PSHA); i.e., using the ground-motion uncertainty to extrapolate the frequency (a temporal measure). The proposed approach treats the temporal and spatial uncertainties separately. The "maximum credible earthquake" is the best estimate (mean) of the maximum earthquake in a source zone, not a subjective estimate. The maximum magnitude for the Wabash source (M_{MAX}=6.8) is based on the most recent studies (Street and others, 2004; Olson and others, 2005). The maximum magnitudes for the background source (M_{MAX}=5) is somewhat subjective. The distances or source boundaries (Wabash) are more subjective. These subjective determinations of magnitude and boundaries are consistent with current practice in the region.
4.	Gail Atkinson	specific (p. 1.2)	It would be useful to discuss what regulatory requirements, if any, apply to the plant—Is there a specified target probability, for example? This is more relevant than the general issue of 2 percent in 50 yr maps and their possible implications for buildings and other projects in the region.	There is no specific target probability or regulatory requirement. This report has a general implication for engineering design and policy consideration in Kentucky.
5.	Gail Atkinson	specific (p. 1.6)	There is no need to discuss the USGS maps if they are not required by the applicable code—this is not really relevant and should be deleted.	Because they are universally referred to in government regulations, codes, and other relevant documents, the USGS maps have to be discussed. Revision will be done to reflect these documents and add more explanation.
6.	Gail Atkinson	specific (p. 2)	Figure 1 is not relevant, due to the very short time span (1 week)—if you want to illustrate the known seismicity of the country from a hazards viewpoint, plot something like all damaging earthquakes in the historic record.	Revised to use figure from Stein and others (2003).

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
7.	Gail Atkinson	specific (p. 3.3 and throughout)	The focus seems unbalanced—when performing an assessment of seismic hazard for a specific site, it would not be the appropriate venue to review the national seismic hazard maps of the USGS, nor to propose a new methodology.	As described in the responses to comments 4 and 5 (universally referred to in government regulations, codes, and other relevant documents, and general implications for engineering design and policy consideration in Kentucky), the USGS hazard maps have to be discussed and reviewed. As shown, PSHA is mathematically incorrect; an alternative needs to be developed.
8.	Gail Atkinson	specific (paragraph 5, throughout)	The definition of risk versus hazard used in this report does not follow the accepted convention. There was initial confusion between the terms "hazard" and "risk" in the early days of seismic hazard methodology. However, it is now nearly universal usage that seismic hazard refers to the likelihood of receiving seismic ground motions (or other seismic effects), while seismic risk is the product of the hazard and the consequence (exposure or vulnerability). Thus, a site with moderate seismicity but a hazardous or critical facility may pose a high seismic risk, while a site with high seismicity but few facilities may have low seismic risk.	The definition of hazard and risk used in this report follows the accepted convention, particularly in engineering applications (hydraulic, flood, wind, and snow). Seismic hazard describes phenomena, such as surface rupture, ground motion, ground-motion amplification, liquefaction, and induced landslides, generated by earthquakes that have potential to cause harm. Seismic risk, on the other hand, describes the likelihood (chance) of experiencing a specified level of seismic hazard in a given time exposure. These definitions are also consistent with those of McGuire (2004) and Reiter (1990). As defined by McGuire (2004, p. 7), seismic hazard is "a property of an earthquake that can cause damage and loss. A PSHA determines the frequency (the number of events per unit of time) with which a seismic hazard will occur." Seismic risk is "the probability that some humans will incur loss or that their built environment will be damaged. These probabilities usually represent a level of loss or damage that is equaled or exceeded over some time period" (p. 8). A similar definition was described by Reiter (1990): "Seismic hazard describes the potential for dangerous, earthquake-related natural phenomena such as ground shaking, fault rupture, or soil liquefaction; seismic risk is the probability of occurrence of these consequences" (p. 3).
9.	Gail Atkinson	specific (p. 6)	This page deals with hazard, not risk. A magnitude-recurrence curve is not on its own relevant to hazard, as events need to be associated with distances to determine ground motions.	As defined, seismic hazard is a property of an earthquake that can cause damage and loss, and a magnitude-recurrence curve is a hazard curve because an M 6.0 earthquake can cause damage and loss.
10.	Gail Atkinson	specific (p. 7)	The discussion of flood hazards is not relevant.	It is relevant because seismic hazard and risk analyses were developed based on an analogy to flood, wind, and other analyses.
11.	Gail Atkinson	specific (p. 8)	The description of seismic hazard versus risk is not a correct description of these concepts as they are used today. Furthermore, the discussion of seismic risk is not required here, as the report is dealing with seismic hazard.	The description of seismic hazard versus risk is consistent throughout this report. The discussion of seismic risk will help to understand why and how we do seismic hazard analysis.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
12.	Gail Atkinson	specific (p. 11)	The arguments presented regarding equation 4 are not convincing. The issue of E being independent of M and R is not central, in my view. Furthermore, E is in fact largely independent of M and R, as shown by recent ground-motion databases (Pacific Earthquake Engineering Research Center/Next Generation Attenuation of Ground Motions). The opposing references cited are largely taken out of context—there are many analyses, authored by the same sources cited on this page, to show that E does not depend strongly, if at all, on M and R. The conclusions reached on the validity of equations 4 and 9 are not justified.	R in equation 4 is focal distance (Cornell, 1968). In ground-motion attenuation relationships, R is measured as rupture, JB, or seismogenic distance. The ground-motion standard deviation will be different if a different R is used (R dependent). $f_R(r)$ in equation 4 is to account for the uncertainty of focal point (distribution). The uncertainty of focal point is accounted for in part by the uncertainty of ground motion, because R is measured as a single distance (rupture, JB, or seismogenic), regardless of focal distance. Equation 4 counts the distance uncertainty, at least some portion, twice. Similarly, $f_M(m)$ in equation 4 is to account for the uncertainty of magnitude (distribution). Also similarly, the ground motion standard deviation is dependent on M. Again, equation 4 counts the magnitude uncertainty, at least some portion, twice.
13.	Gail Atkinson	specific (p. 15.5)	There is no suggestion in the cited papers that ground motions *will* occur in 10^8 yr. The arguments advanced here are not correct, nor do they appear relevant.	As defined by McGuire (2004), return period is the mean (average) time between occurrences of a seismic hazard. The reciprocal of the return period is frequency. "PSHA determines the frequency (the number of events per unit of time) with which a seismic hazard will occur" (McGuire, 2004, p. 7). The same interpretation was also given by Frankel (2004, 2005) and Holzer (2005).
14.	Gail Atkinson	specific (p. 15.8)	This reasoning is not correct. PSHA is simply a compound probability, like any other compound probability. Space and time are both relevant in determining the likelihood of receiving strong ground motion at a site.	The temporal and spatial uncertainties are two intrinsic, but fundamentally different, measures, and must be treated separately.
15.	Gail Atkinson	specific (p. 16)	A hazard assessment for a critical facility is not the place to introduce a new trial methodology, in my view.	This report is not necessary for a critical facility. The main goal of this report is to conduct scientific research on the methodologies, geological and seismological parameters, and the results related to the Paducah Gaseous Diffusion Plant and the region.
16.	Gail Atkinson	specific (p. 18)	This SHA hazard curve is inherently limited in scope and applicability. It assumes a fixed distance to a single source, with no uncertainty in the location of a future event being considered. It is simply a transformation of the Gutenberg-Richter relation (Fig. 2), with a discontinuity imposed at M=5.5.	As shown earlier, ground-motion uncertainty is dependent on magnitude and distance. The uncertainty in the location of a future event is considered by confidence level.
17.	Gail Atkinson	specific (p. 20)	Include the location of Paducah on Fig. 11, 12. Note that this discussion highlights the fact that the location of a New Madrid event is uncertain, not fixed.	
18.	Gail Atkinson	specific (p. 24.8)	The reference to Figure 10 is incorrect (Figure 15?).	
19.	Gail Atkinson	specific (p. 26)	Include Paducah location on Figure 15.	

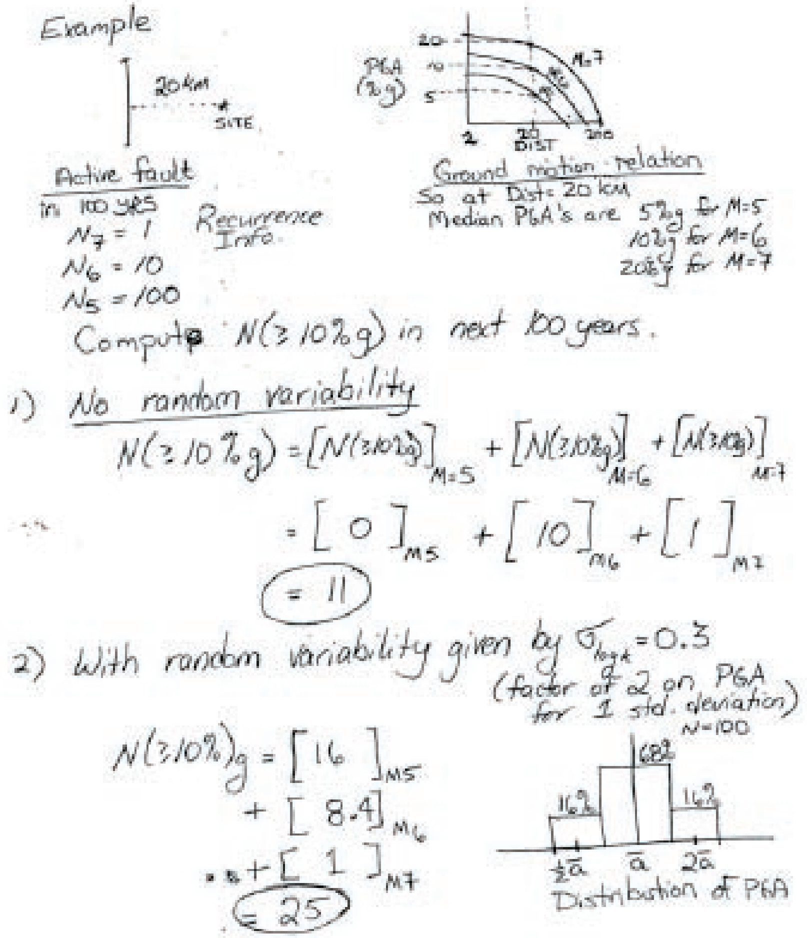
Comment Number	Reviewer	Part of Document Referenced	Comment	Response
20.	Gail Atkinson	specific (p. 28)	A maximum magnitude of M 6.8 cannot be arbitrarily assigned to the Wabash source in this way. This is a subjective "maximum credible earthquake" with an unknown exceedance probability. It has no physical basis as a limit on magnitude.	See response to comment 3.
21.	Gail Atkinson	specific (p. 28.5)	Add latitude, longitude to Figure 17.	
22.	Gail Atkinson	specific (p. 29)	A maximum magnitude of 5 cannot be credibly assigned anywhere in the world. This would imply we have identified all capable faults in the crust with spatial scales of about 1 km or more, and ruled out earthquake motion on any of them. There is no physical basis for such a claim. Worldwide experience has demonstrated time and again that large earthquakes happen, albeit with low recurrence rates, even in stable regions that appear to be nearly aseismic. Assigning M_{MAX}=5 to background seismicity is not justified.	See response to comment 3.
23.	Gail Atkinson	specific (p. 30)	Figure 20 demonstrates that the possibility of a large local earthquake (M 6 to 6.5) is not a negligible contributor to hazard. Why is there no contribution from M 5 to 5.5 shown on this figure?	This figure is from Petersen (2005), showing that there are earthquakes closer to the site.
24.	Gail Atkinson	specific (p. 33)	Is it possible on Figure 22 that we are seeing a temporary deficit of moderate events due to the after effects of the 1811-1812 sequence?	
25.	Gail Atkinson	specific (p. 36)	The data points for the Gutenberg-Richter relation for the background seismicity need to be shown. For all zones, the report should clearly show the zone boundaries that are associated with the magnitude recurrence relations. The completeness of the catalog used needs to be discussed. The conversions from local magnitude scales to moment magnitude need to be presented.	Will revise.
26.	Gail Atkinson	specific (p. 37.4)	Discuss why eastern North America ground motions are higher than California motions, and point out that this only applies at high frequencies.	Will revise.
27.	Gail Atkinson	specific (p. 37.5)	The differences in standard deviation are exaggerated. Most recent studies suggest that sigma should be similar in eastern North America and California (e.g., Electric Power Research Institute [2004]; Atkinson and Boore [2006])—about 0.25 to 0.30 in log(10) units (cite units when discussing sigma) in the general case.	The differences in standard deviation are in the range of 0.6 to 0.8 (in ln).

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
28.	Gail Atkinson	specific (p. 37.6)	The Atkinson and Boore (1995) and Frankel and others (1997) relations (and arguably also the Toro and others [1997] relations) do not apply well to large finite sources like New Madrid for which a point source is a poor model. You may wish to quote only finite-fault models. The recent Atkinson and Boore (2006) eastern North America model uses a finite-fault source. It predicts a PGA of approximately 0.7 g for the cited distance of 15 km from an M 7.7 event on hard rock. Thus, the relevant estimates of median PGA for hard rock, in my view, range from 0.7 g (Atkinson and Boore [2006] and Silva and others [2001]) to 0.6 g (Campbell [2003]).	Good comment. Will revise.
29.	Gail Atkinson	specific (p. 38)	Discuss distance measures used in the plots. Have they all been converted to one measure? Note that Atkinson and Boore (2006) is for distance to fault, so in the case of moderate events this is likely to always be greater than a few kilometers (e.g., an M 5.0 earthquake would likely correspond to about D_{fault}=10 km at the epicenter).	Will revise.
30.	Gail Atkinson	specific (p. 40)	The results are an incorrect assessment of the hazards from these sources, as they do not consider uncertainty in location, nor are the assumed maximum magnitudes for local sources reasonable. The local M 5.0 at 15 km is particularly arbitrary. The nearest location for both the New Madrid Seismic Zone and Wabash Valley Seismic Zone are subject to uncertainty, as are their maximum magnitudes (and recurrence intervals). Note that the combination does not consider the additive nature of the ground-motion probabilities.	The uncertainties in location and maximum magnitude are considered in the confidence level because uncertainty in ground motion is dependent on both of them. Otherwise, uncertainties will be counted twice or three times (in PSHA). Also see the response to comment 3 on M 5.0 and the distance.
31.	Gail Atkinson	specific (p. 42)	Figure 32 is not actually the probability of exceedance of the ground motions, as the given probabilities relate only to a specific subset (given distance). The effects of sigma on increasing expected ground motion are not included for a given probability. Effects of maximum magnitude on truncating the ground-motion estimates are apparent. Note that the likely importance of the background seismicity, if extended down to accommodate larger events than assigned M_{MAX}=5, is apparent.	The annual probability of exceedance (i.e., frequency by McGuire [2004]) is a temporal measure. Sigma (ground motion) is a spatial measure. Temporal and spatial measures should not be mixed together.
32.	Gail Atkinson	specific (p. 44.2)	The definition of seismic risk given is not correct.	See response to comment 8.
33.	Gail Atkinson	specific (p. 44.5)	The conclusion regarding PSHA is not correct.	See response to comment 1.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
34.	Gail Atkinson	specific (p. 45)	The suggested methodology is seriously flawed and will not result in a defendable estimate of seismic hazard. This could be demonstrated by a Monte Carlo simulation without resort to the PSHA equations.	See response to comments 1, 2, and 3.
35.	Gail Atkinson	specific (p. 46)	The ground motions presented can only be considered as judgmental scenario motions, without any associated probabilities. They are not a quantitative hazard calculation. The likelihood of exceeding the motions could be assessed by performing a PSHA using accepted methodologies. Note that the motions are for bedrock, and are likely to be significantly modified by site response.	The proposed approach considers separately the associated uncertainties (probabilities in time and space).
36.	Gail Atkinson	Appendix	See diagram on next page.	The example shows the problem associated with mixing a temporal measure with a spatial one. The examples you show are all of a "deterministic" interpretation. The probability that PGA exceeds 0.1 g is 84 percent if an M 7 event occurs. An event with 84 percent probability of occurrence will not necessarily occur (statistics), but is interpreted as being sure to occur (one event). Similarly, the probability that PGA exceeds 0.1 g is 50 percent if an M 6 event occurs. If earthquake occurrences follow a Poisson distribution, the probability that at least one PGA exceeds 0.1 g is about 99.3 percent if 10 M 6 events occur. This cannot be interpreted as 10 events (PGA exceeds 0.1 g). The probability that PGA exceeds 0.1 g is 16 percent if an M 5 event occurs. The probability that at least one PGA exceeds 0.1 g is about 99.99999 percent if 100 M 5 events occur. This cannot be interpreted as no event (PGA exceeds 0.1 g) will occur.

Appendix

Illustration of why random variability increases the probability of experiencing any given amplitude of ground motion. Compare the number of times that we would expect to get 10%g or more in the next 100 years at a site: 1) without any random variability; and 2) with typical random variability of about a factor of 2 (0.3 log units)



Example

Active fault

in 100 yrs

$N_7 = 1$

$N_6 = 10$

$N_5 = 100$

Recurrence Info.

Ground motion relation

So at Dist = 20 km

Median PGA's are 5%g for M=5

10%g for M=6

20%g for M=7

Compute $N(\geq 10\%g)$ in next 100 years.

1) No random variability

$$N(\geq 10\%g) = [N(\geq 10\%g)]_{M=5} + [N(\geq 10\%g)]_{M=6} + [N(\geq 10\%g)]_{M=7}$$

$$= [\ 0\ ]_{M5} + [\ 10\ ]_{M6} + [\ 1\ ]_{M7}$$

$$\boxed{= 11}$$

2) With random variability given by $\sigma_{\log k} = 0.3$

(factor of 2 on PGA for 1 std. deviation)

$$N(\geq 10\%)_g = [\ 16\ ]_{M5} + [\ 8.4\ ]_{M6} + [\ 1\ ]_{M7}$$

$$\boxed{= 25}$$

Distribution of PGA

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
1.	Jim Beavers	p. i, first paragraph	Line 7 states: "Seismic risk, on the other hand, describes the likelihood (chance) of experiencing a specified level of seismic hazard...." Comment: I do not think I would call this seismic risk. Risk is a concept that denotes a potential negative impact to an asset or some characteristic of value that may arise from some present process or future event. In everyday usage, "risk" is often used synonymously with the probability of a loss. What you are talking about here is frequency of occurrence. I have a risk of an earthquake causing my historic building in Urbana, Ill., to collapse. Thus, I passed this risk on to my insurance company.	In hydraulic engineering, risk can be defined as the probability of a peak discharge being exceeded in a period, such as 1 percent of 10,000 ft^3/s being exceeded in 1 yr (Gupta, 1989). Similarly, according to McGuire (2004, p. 7), seismic hazard is "a property of an earthquake that can cause damage and loss. A PSHA determines the frequency (the number of events per unit of time) with which a seismic hazard will occur." Because magnitude is a property of an earthquake, the larger magnitude, the higher potential to cause harm, a magnitude M or greater with an MRI) is seismic hazard. Similarly, MMI or ground motion at a site is a property of an earthquake, MMI of VIII (or PGA of 0.25–0.30 g) or greater with a specified return period is seismic hazard. MMI of VIII is described as causing considerable damage to ordinary buildings. Consequently, considerable damage or greater to ordinary buildings at a site with a return period is seismic hazard too. Therefore, measurements of seismic hazard can be different, from magnitude to damage (loss) level to buildings, and one measure can be converted to another through a statistical relationship (i.e., ground-motion and attenuation and fragility curve). As defined by McGuire (2004, p. 8), seismic risk is "the probability that some humans will incur loss or that their built environment will be damaged. These probabilities usually represent a level of loss or damage that is equaled or exceeded over some time period." A similar definition was described by Reiter (1990, p. 3): "Seismic risk is the probability of occurrence [in time] of these consequences." From these definitions, seismic risk is quantified by three elements: probability, a level of consequence (damage or loss), and time. Because damage or loss is also a property (measure) of an earthquake, the likelihood (probability) of its occurrence (M or greater) during a specific period is risk.
2.	Jim Beavers	p. i, paragraph 2	Last sentence states: "Temporal and spatial uncertainties are of different characteristics and must be considered separately in hazard assessment." I think I disagree with this statement.	
3.	Jim Beavers	p. i, starting in paragraph 3, line 16, continued through paragraph 4	It states: "There is a mathematical error in the...." Since this subject is quite controversial, I, as a reviewer, will be expecting to see considerable detail in the report about how this process is better than the PSHA process: sort of a one-on-one comparison.	This report has a detailed description and discussion of PSHA and SHA. There are also several references for each.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
4.	Jim Beavers	p. 1, paragraph 1	Line 13 states: “For example, it would not be feasible for the U.S. Department of Energy to obtain a permit from Federal and State regulators to construct a landfill at the Paducah Gaseous Diffusion Plant....” I do not believe you can say this, because we do not officially know that it is not feasible. Where is the feasibility study that says it is not feasible? In fact, the CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) cell report for site A had a peak ground motion design value of 0.48 g. The CERCLA cell project was stopped for political reasons, not technical.	This statement reflects the fact that the Kentucky Solid Waste Division refused to issue the permit by citing the USGS hazard estimate.
5.	Jim Beavers	p. 1, paragraph 2	Line 4 states: “Currently, the highest building design PGA used in California (UBC-97) is capped at about 0.4 g.” This is true; however, I believe that this capped value will be removed shortly because it truly underestimates the hazard in California. This cap was imposed by a bunch of engineers in the mid 1980’s.	With the deterministic cap and the NGA (Next Generation Attenuation of Ground Motions) attenuation relationships (near-source saturation), this cap (0.4 g) may still be valid.
6.	Jim Beavers	p. 1, paragraph 2	Line 12 states: “It clearly shows that the higher design ground motion in western Kentucky does not make sense scientifically.” This is where you are going to have to show why the PSHA is indeed the incorrect way to consider the uncertainties, to convince me and others. Comparing earthquake activity in California to the New Madrid Seismic Zone may make sense to the layman, but I can see where the PSHA approach might make sense, especially with the body of literature out there that continues to support PSHA, especially the Electric Power Research Institute and Lawrence Livermore National Laboratory methodologies. I really believe the DSHA does not consider all of the uncertainty. I have had a lot of discussion on this DSHA with Ellis Krinitzky and was not convinced that DSHA considered all of the uncertainty. However, in the 70’s and 80’s I would look at the PSHA approach to seismic hazard and then the DSHA approach and then make a judgmental decision on what the seismic design basis should be for a DOE facility.	As shown in this report, there is a mathematical problem: treating the ground-motion uncertainty as an independent random variable. As modeled in modern attenuation relationships, the ground-motion uncertainty is not an independent random variable. With this mathematical problem, PSHA is difficult to understand and use.
7.	Jim Beavers	p. 3, paragraph 1	This paragraph is right on target.	
8.	Jim Beavers	p. 3, paragraph 2	First line states: “Objectives of this project are....” I would think one objective would be to clearly show why the PSHA approach overstates the seismic hazard.	The PSHA approach may understate the seismic hazard. For example, the ground motion with 500-yr return period is considered to be low in the New Madrid area. The end result from PSHA is a hazard curve from which one could not tell if it was a high or low estimate.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
9.	Jim Beavers	p. 4, paragraph 4	First sentence states: "Two methods...." I currently do not believe that both PSHA and DSHA are commonly used today. I think the use of PSHA far outweighs the use of DSHA. In a recent correspondence with John Schneider (Geoscience Australia), he states: "I find it puzzling that there is still a debate over this issue. In my view PSHA is merely a means of formally accounting for uncertainty. I can't imagine why anyone would have any philosophical objection to that! In fact, in many instances, the deaggregation of a probabilistic analysis has been used to identify and justify specific scenarios, which are in effect deterministic solutions. In short, I don't know anyone apart from Ellis in the deterministic camp."	This is an interesting comment: "In fact, in many instances the deaggregation of a probabilistic analysis has been used to identify and justify specific scenarios, which are in effect deterministic solutions."
10.	Jim Beavers	p. 4, paragraph 4	Last sentence states: "Wang (2004)...." I assume Wang (2004) is Wang, Z. (in press) reference document at bottom of p. 53 or is it Wang and others (2004)? Also on p. 53 you have a Wang (2003) with no title or reference. In addition, I would suggest you list your references based on name and then earliest date; i.e., Wang (2003) would come before Wang (2004) in your reference list. The reference list needs to be verified; e.g., later in the report you reference Wheeler (1997) and cite *Seismological Research Letters* v. 63, which should be v. 68.	These errors will be corrected.
11.	Jim Beavers	p. 5, paragraph 2	Second sentence states: "The probability that no earthquake will...." Suggest that this say: "The probability that no such earthquakes will...."	Revised.
12.	Jim Beavers	p. 5, paragraph 2	Fourth sentence states: "Equation (3) shows the relationship between seismic risk, ... with X percent in PE in *Y* years, and seismic hazard, expressed...." In the introduction, I think you need to clearly state what is meant by seismic risk and seismic hazard and stick with that notation throughout the document. See comment 1. What you are calling seismic risk I still see as frequency because a 10 percent chance in 50 years has a frequency on the average over hundreds of thousands of years every 475 years. In addition, changing time interval notation in equation 3 from *t* to *Y* could leave the reader confused. Another example of using the words "seismic risk" is the Ohio Department of Natural Resources, where they state: "The brief historic record of Ohio earthquakes suggests a risk of moderately damaging earthquakes in the western, northeastern, and southeastern parts of the state" (Hansen, 2007). Here the risk is in terms of potential damage.	Seismic hazard and risk are two different concepts. They have been used interchangeably quite often. The attempt in this report is to distinguish and use them consistently.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
13.	Jim Beavers	p. 5, paragraph 2, continued on p. 6	Last sentence on p. 5 states: “Equation (3) also shows that the probability *p* shows ... and has no relation to spatial characteristics of the hazard....” This is true; however, we are only talking about PE of a magnitude M or greater in a certain source zone. However, to mitigate effects of the hazard’s occurrence, I must design my building for a peak ground acceleration or spectral value. Thus, I have to know where the earthquake is going to occur because of the attenuation factors, which are directly spatially related. Even in a DSHA, I still have to put the earthquake someplace to get my design values. In the old days, we put it right under our site.	
14.	Jim Beavers	p. 6, paragraph 2	I basically agree with this paragraph, assuming your Gutenberg-Richter curve represents the earthquake activity of the New Madrid Seismic Zone. However, when I got to p. 16–18, I realized that you had labeled Figure 2 wrong. The abscissa should be labeled N, not Log (N). See also Figure 23.	Corrected.
15.	Jim Beavers	p. 6, paragraph 2	Last sentence states: “The risk posed by....” This is still frequency to me.	By common definition, a frequency is used to describe how often an event occurs; it is not a probability of an event occurring over a period.
16.	Jim Beavers	p. 6, paragraph 3	First sentence states: “In practice....” To me, this is where the spatial aspects come into the equation.	Agree.
17.	Jim Beavers	p. 6, paragraph 3, continued on p. 7	Fifth sentence states: “From Figure 3 a mean annual....” There needs to be some definition of P_f before it is introduced here.	Revised.
18.	Jim Beavers	p. 6, paragraph 3, continued on p. 7	Seventh sentence states: “Similarly, the ground motions and their MRI’s at a site....” Here you are going from equation 3, which you justified on p. 5 as “the probability of earthquakes equal to or greater than a specific size *(M)* with *X* percent in *Y* years, and ...,” which I agree with, and now all of a sudden you are implying that it is equally compatible to replace *M* with ground motions. I do not think you can do this????	It is simple mathematics. From equation 6, $\ln(Y)=f(\mathrm{M,R})+n\sigma_{\ln,Y}$. We have equation 16: $M=g(R,\ln Y,nn\sigma_{\ln,Y})$. Combining equation 16 with equation 15: $\tau=\frac{1}{N}=e^{-2.303a+2.303M}$ resulting in equation 17: $\tau=\frac{1}{N}=e^{-2.303a+2.303bg(R,\ln Y,n\sigma_{\ln Y})}$.
19.	Jim Beavers	p. 6, paragraph 3, continued on p. 7	Seventh sentence states: “Similarly, the ground motions and their MRI’s....” The Milne and Davenport attenuation curves do consider only an estimated value and show no concept of the uncertainty in the ground motions. See Bommer and Abrahamson (2006).	This is true and is addressed in this report, in equation 17.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
20.	Jim Beavers	p. 6, paragraph 3, continued on p. 7	Eighth sentence states: "An empirical method, which is identical to the empirical flood-hazard analysis...." The Milne and Davenport paper is just that, an empirical paper that uses an attenuation equation that has no uncertainty and basically is a measured methodology using assumptions that most would not consider appropriate today. As a result, I think this approach may underestimate the seismic hazard.	The proposed approach is to consider the uncertainty. A similar approach has also been proposed by Stein and others (2005, 2006).
21.	Jim Beavers	p. 6, paragraph 3, continued on p. 7	The 11th sentence states: "For a building with an exposure...." This is correct if you use equation 3; however, I question using equation 3 for PGA, especially when you based your justification for equation 3 on probability of earthquakes equal to or greater than a specific size *(M)* with *X* percent PE in *Y* years. See comment 17.	See response to comment 17.
22.	Jim Beavers	p. 8, paragraph 1	Third sentence states: "Seismic risk, on the other hand, describes a probability of...." Again, I am having some trouble calling this seismic risk. I think of it as a frequency.	See response to comment 15.
23.	Jim Beavers	p. 8, paragraph 1	Fourth sentence states: "Seismic risk not only depends on seismic hazard ... used to describe the occurrences of earthquakes." I agree that seismic risk depends on seismic hazard, exposure, and model. My problem is the model where with the leap of faith from justifying the Poisson model (equation 3) based on the probability of earthquakes equal to or greater than a specific size *(M)* with *X* percent PE in *Y* years and then saying that is the same for ground motion. See comments 11, 12, and 17. To introduce the ground-motion parameter requires a spatial element, as noted in comments 12 and 15.	See response to comment 18.
24.	Jim Beavers	p. 8, paragraph 2	Second sentence states: "High seismic hazard does not mean high seismic risk...." I agree, but not for the same reasons. If there is a high-seismic-hazard geographic area and I build an important building in that area that costs $5 million, I have a high seismic risk. However, if I build a small cattle barn that costs $500 I do not have a high seismic risk. This is why there are no nuclear power plants within a 120-mile radius of the New Madrid Seismic Zone.	This is a good example showing that lower exposure (type of building) gives you lower risk, even though hazard is high.
25.	Jim Beavers	p. 8, paragraph 2	Third sentence states: "Moreover, the mitigation policy is mostly...." I agree, but I do not agree with your supporting logic, because you are only considering frequency of magnitude of events and not the uncertainty of ground motion.	The uncertainty of ground motion is considered by a level of confidence, as with flood risk.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
26.	Jim Beavers	p. 8, paragraph 2	Last sentence states: "That is why we have to spend more resources...." I agree with the statement, but disagree with the implied reasoning. We are spending more resources and effort to mitigate seismic hazard in San Francisco because they have a greater seismic risk as a result of the built environment and population density, and they understand their seismic hazard better than those in the New Madrid Seismic Zone.	The comparisons in the report are based on the same exposure. Higher exposure makes the comparison more valid.
27.	Jim Beavers	p. 9, Table 2, comparison of hazard and risk	This table is accurate with respect to the probabilities about MRI's of earthquakes having various magnitudes, but it doesn't stand up for considering ground-motion MRI's. In this respect, in the Wang and Ormsbee (2005) *Eos* paper it is stated: "Figure 2 shows that PGA with 2% PE in 50 years is 0.97 g." It is then stated: "This PGA (0.97 g) does not mean that it could occur in 2500 years; but rather that there are 0.0835, 0.0294, and 0.0086 probabilities that PGA will exceed 0.97 g if each of the three earthquakes occur" (p. 51). In my view, it means that the probability of exceedance of an 0.97 PGA will occur on the average once every 2,500 years over hundreds of thousands of years.	In the Wang and Ormsbee (2005, p. 51) *Eos* paper, it is stated: "Figure 2 shows that PGA with 2% PE in 50 years is 0.97 g." It is then stated: "This PGA (0.97 g) does not mean that it could occur in 2500 years; but rather that there are 0.0835, 0.0294, and 0.0086 probabilities that PGA will exceed 0.97 g if each of the three earthquakes occur. A probability of 0.0835, 0.0294, or 0.0086 that PGA will exceed 0.97 g if each of the three earthquakes occurs does not mean this will occur.
28.	Jim Beavers	p. 10, paragraph 3	This paragraph starts with: "According to Benjamin and Cornell...." While this is mathematically true, I currently believe that there is enough independence of the ground-motion uncertainty that E can be treated as an independent variable, like M and R.	No response.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
29.	Jim Beavers	p. 11, paragraph 2	This paragraph starts with: "As demonstrated above...." While this is true in the explicit sense, at the present state of knowledge, I do not see an alternative. Maybe this is why you have been having a hard time convincing others about your approach. Along those lines, it is very interesting to me that you reference Shakal and others' (2006) research on the M 6.0 Parkfield [earthquake] to position your justification that the ground-motion uncertainty is dependent on M and R or both and at the same time Bommer and Abrahamson (2006) in the *Bulletin of the Seismological Society of America* are using the M 6.0 Parkfield event to clearly show the uncertainty of ground motion for any earthquake. In reality, I know that ground motion is dependent on both M and R, because if you do not have M you do not have ground motion, and until you know R, you do not know what levels the ground motion will be. But it looks like to me that they (your nonbelievers) have a pretty good justification, so far, that the uncertainty is independent of M and R.	The key point here is that the distance being measured for a finite fault (modern attenuation) is compared with the distance being measured for a point source. We agree with "in reality I know that ground motion is dependent on both M and R, because if you do not have M you do not have ground motion, and until you know R you do not know what levels the ground motion will be." This will result in different formulation for hazard calculation. In other words, current PSHA has a mathematical problem.
30.	Jim Beavers	p. 11, equation 10	Below this equation you describe σ_{ource} and σ_{path} and do not describe $\sigma_{modeling}$. Is there a reason for this? I do not have Electric Power Research Institute (2003) to verify.	$\sigma_{modeling}$ describes modeling uncertainty.

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31.	Jim Beavers	p. 12, last paragraph	This paragraph starts with "Equations (11) through (13)...." It appears that you are using equations 11 through 13 to show that the PSHA result is an invalid formulation. But it is not clear to me what you are trying to say. At first brush, it looks like to me you are saying the following: "I have equation 13, which says $T_{RP}(y)$=T divided by the uncertainty of the ground motion and since $T_{RP}(y)$ is a return period and T is the characteristic earthquake return period, they are the same, so equation 13 is invalid." However, in your *Eos* paper you imply that if I have a characteristic earthquake of return period T at some distance R and probability of exceeding a certain ground motion, that the probability of the ground motion being exceeded at the site of interest is (1/T) x (probability of exceedance). For characteristic earthquakes, I believe this is the correct approach, if you know the distance to the site of interest. In my mind, I think equation 13 is still good because $T_{rp}(y)$ is the return period of (y) being exceeded, while T is the return period of the characteristic earthquake. See earlier comments 13, 18, 21, and 23.	These equations show the fundamental difference between the recurrence interval (T) of an earthquake and the return period (T_{RP}) of a ground motion that is generated by an earthquake at a site. Occurrence of a ground motion at a site must be associated with an earthquake. There would not be a ground motion at a site if there is no earthquake. However, PSHA could produce a range of return periods from a single recurrence interval.
32.	Jim Beavers	p. 12, last paragraph, last sentence	Here you use the term "ergodic assumption." This is also called "Chaos Theory." If you look at Bommer and Abrahamson (2006), you might call the uncertainty of ground motion that (Chaos Theory), because the spread is one order of magnitude, based on the M 6.0 at Parkfield.	The term "ergodic assumption" was defined by Anderson and Brune (1999).
33.	Jim Beavers	p. 15, first paragraph	Fifth sentence starts: "This interpretation fundamentally...." I agree that in the discussion above that it kind of gets ludicrous when we go talking about a 100-million-yr earthquake. However, I really do not think you are changing the physical and statistical meanings, except maybe to the layperson. We all know that this still remains a probability of occurrence. Going to a return period is just the nature of the beast, and we need to live with it whether we are talking about a 100-yr return period in flooding or a 100-million-yr return period in earthquakes. I guess a 100-million-yr return period in terms of magnitude would be an M_W of 12.0, which, as I recall, would split the earth in half.	Good comment.

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34.	Jim Beavers	p. 15, first paragraph, eighth and ninth sentences	Both sentences begin: "Figure 9 shows...." It is quite clear to me that if you have an M 7.7 [event] that has an MRI of 500 yr in the New Madrid Seismic Zone and the uncertainty does exist per Campbell (2003) that you will have the uncertainty shown in Figure 9, and if the median PGA is 0.36 g, then the probability of exceeding 0.36 g, given that the earthquake occurs, is (1/500) x 0.5 or 0.001 annual frequency or an event that has a return period of 1,000 yr [then] during the 50-yr life of a building there is a 5 percent chance the building will experience that kind of ground motion. In past designs, the rule was to design for a 10 percent chance in 50 yr, which is the "500-yr earthquake"; in better words (more accurate), an earthquake that might occur from the characteristic fault that could cause the building to experience PGA of 0.36 g or more in its lifetime.	Good comments. These show the differences between PSHA and the proposed approach.
35.	Jim Beavers	p. 15, first paragraph	Last sentence states: "In other words...." I think you are overstating the case when you say "... however, to mean that that ground motion *will* occur at least once in 2,500 years...." My question is, who has been interpreting a 20 percent probability of being exceeded in 500 yr as being the ground motion that occurs at least once in 2,500 yr? They should be interpreting it as on average, over hundreds of thousands of years, this ground motion will be exceeded once every 2,500 yr.	According to McGuire (2004, p. 8), return period is "the mean (average) time between occurrences of a seismic hazard—for example, a certain ground motion at a site, or a certain level of damage or loss." Frankel (2005) and Holzer (2005) interpreted it exactly that way.
36.	Jim Beavers	p. 15, second paragraph, first sentence	I think I disagree with this statement and do not support the logic you have used thus far that mixing temporal and spatial measurements is causing any kind of problem, especially your discussion in the first paragraph. See earlier comments 13, 18, 21, 23, 33, 34, and 35.	Temporal and spatial measurements are two of the most fundamental elements of the world. Mixing them one way or the other would cause problems.
37.	Jim Beavers	p. 15, second paragraph, second sentence	Sentence starts: "Temporal and spatial...." I am confused. Here, as you are saying, "the temporal measurements (M) and spatial measurements (ground motions) are two intrinsic independent characteristics of an earthquake ... and must be treated separately." If that is true, why can't I consider M, R, and ground motion as independent events for PSHA?	M, R, and ground motion at a site are not temporal measurements.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
38.	Jim Beavers	p. 15, second paragraph, last sentence	I think you are overstating the issue. I do not think of it as being inappropriate or confusing; only to the layperson or engineer who has no experience in seismic design. Based on the two DOE projects, one at Portsmouth and one at Paducah, in which I am the DOE site reviewer, there are a number of engineers in the Midwest and East who are not familiar with seismic design.	Unfortunately, it happens all the time.
39.	Jim Beavers	Section 2.2 (New Approach—Seismic Hazard Assessment), p. 16–18	When I started reviewing this report, especially when I saw your table in the Executive Summary, and knowing certain issues you have had with the USGS methodology and vice versa, I thought I would do a DSHA to see what I get and how it compares to your results. Based on the PSHA work that had been done for me at Paducah (McGuire, 1999; Risk Engineering Inc., 1999) and my use of the USGS methodology, I had access to the deaggregations. The deaggregations for both (McGuire [1999] and USGS) show that a magnitude M 7.5 or 8 was driving the PSHA ground motions 20 km from the Paducah Gaseous Diffusion Plant. The 20 km is based on Johnston and Van Arsdale's appendix to Risk Engineering Inc. (1999). So I said, "OK, let's have a DSHA earthquake of M 8.0 occur 20 km from the Paducah Gaseous Diffusion Plant and let's also be more realistic and have an M 8.0 occur 60 km from the Paducah Gaseous Diffusion Plant where the February 11, 1812, event occurred." After I did these, I decided to look at it from your perspective of 30 km.	Your analyses show how PSHA can derive different return periods for a single earthquake with a recurrence interval. If an earthquake occurs every 500 yr, the ground motion generated by the earthquake at a site must also occur every 500 yr.
40.	Jim Beavers	p. 22, last paragraph	In this paragraph it appears that you reference Wheeler (1997) in support of the New Madrid Seismic Zone extending northeastward toward the Paducah Gaseous Diffusion Plant and cite Wheeler (1997) in support of it not extending toward the Paducah Gaseous Diffusion Plant. This is confusing to the reader, unless you quote statements made by Wheeler showing his own uncertainty on the issue. As I recall, you have done this elsewhere in the document.	This will be clarified.
41.	Jim Beavers	p. 20, last paragraph, last sentence	As an engineer, when I look at Figure 13, it doesn't mean a thing to me. You need to explain what I am supposed to be seeing. Also, if I look at Figure 4 of Braile and others (1997) it looks to me like Johnston and Van Arsdale (Risk Engineering Inc., 1999) have a justification for the northeast extension.	Will revise.

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42.	Jim Beavers	p. 21, first paragraph, sixth sentence	States: "These short period and dense network...." In what way do these observations suggest that the characteristics of earthquakes in the Jackson Purchase Region are different from those of earthquakes in the central New Madrid Seismic Zone?	They are different in terms of stress field and focal depth.
43.	Jim Beavers	p. 21, second paragraph, last sentence	Starts with: "Thus, there is no evidence...." I think the jury is still out on this.	
44.	Jim Beavers	p. 21, last paragraph, last sentence	States: "In this report, we used the location...." I agree with using a maximum magnitude of M 7.5.	
45.	Jim Beavers	p. 24–28, section 3.2	I have read this section and am not going to comment as I feel it has little bearing on the Paducah Gaseous Diffusion Plant.	
46.	Jim Beavers	p. 29, first paragraph	I do not have a copy of Peterson (2005), although I was at the workshop.	It is a summary of a meeting between KGS and USGS in Lexington.
47.	Jim Beavers	p. 29, first paragraph, fourth sentence	Sentence starts: "The use of these large background earthquakes...." I believe they do, if you are doing a PSHA and are needed for completeness.	It has also been shown by Frankel (2004) and Petersen (2005).
48.	Jim Beavers	p. 32, first paragraph, last sentence	Sentence starts: "Figures 22 and 23 show...." In this sentence, you imply that Figure 23 is for the Wabash Valley Seismic Zone; however, this figure is labeled as magnitude-occurrence relationship of the New Madrid Seismic Zone.	Will correct it.
49.	Jim Beavers	p. 32, last paragraph, fifth sentence	Sentence starts: "A recent study by Holbrook and others (2006)...." Just before this sentence there seems to be some missing or misrepresenting text, because at the end of the fourth sentence it states "... New Madrid Seismic Zone, however (Fig. 22)."	Will revise.
50.	Jim Beavers	p. 37, last paragraph, ninth sentence, continuing on to p. 38	Sentence starts: "As shown in the figure, Frankel...." The figure actually shows Frankel's attenuation curve at near-source, similar to Campbell (2003). It is Atkinson and Boore (2006) that is higher in the near-source. Maybe Frankel and others did not get put on the graph, because the one I first thought was Frankel and others now looks like it is Silva and others (2002).	The comparison should be at a distance between 10 and 40 km. Frankel and others (1996) did not provide values less than 10 km.
51.	Jim Beavers	p. 40, last paragraph, first sentence	Sentence starts: "Figure 32 shows median PGA...." I am confused here. You talk about using Campbell (2003) attenuation equations in the earlier parts of the document, and all of a sudden here, for your detail work, you say you are going to use Atkinson and Boore (2006), which, in Figure 27, has the highest near-source attenuation values. But in Tables 7 through 8, you use all attenuation equations except Frankel.	In this report, we used the ground-motion attenuation relationships of Somerville and others (2001), Silva and others (2002), Campbell (2003), and Atkinson and Boore (2006). Figures 29 and 30 show 0.2 s and 1.0 s response accelerations of the four attenuation relationships for an M 7.5 earthquake in the central United States.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
52.	Jim Beavers	p. 40, last paragraph, last sentence	Sentence starts: "Tables 7, 8, and 9 list the PGA...." I am also confused as to how you got these numbers. The old building code process required seismic design of a building to be designed for an earthquake that had a 10 percent probability of being exceeded during its assumed life. The assumed life was 50 yr. A 10 percent probability of exceedance in 50 yr represents an event that occurs every 475 yr, to be exact, or 500 yr. This turns out to be the return period of the New Madrid earthquakes, as you have said, and you have called them characteristic earthquakes, and rightfully so. If the characteristic earthquake occurs, you showed in Figure 10, p. 18, that the mean PGA would be 0.44 g, so how could your mean PGA ground motions in Table 7 be below 0.3 g? You need to have more discussion in your report on how you got these numbers and the justification for it.	The PGA of 0.44 g is the median for a site at 30 km distance. Table 7 is for PGA's at a site of 45 km.
1.	Ken Campbell	general, hazard versus risk	I think that your narrow definitions of hazard and risk are not well supported in the literature. Hazard generally refers to the description (whether deterministically or probabilistically described) of a physical phenomenon, such as ground-motion amplitude, liquefaction, surface-fault rupture, landslide, etc. Risk generally refers to the description (whether deterministically or probabilistically described) of the consequence of hazard, such as the collapse of a building, the number of lives lost, the cost of repair, the insured loss, etc. I think that the distinction you are trying to make is more related to the difference between frequency and probability, although even this distinction can be blurred. For example, frequency is a measure of how often an event occurs within a given period of time. Probability is a measure of the likelihood of occurrence of an event relative to a set of alternative events. Frequency can be derived from observations, like your flood example, or it can be derived theoretically, from a probability distribution. These are both valid descriptions of frequency. Both frequency and probability need an exposure period. So, personally, I don't think that trying to distinguish between frequency and probability or hazard and risk in the way that you are is meaningful or will lead to change in the current paradigm.	Seismic hazard and risk are two fundamentally different concepts. We agree that "hazard generally refers to the description (whether deterministically or probabilistically described) of a physical phenomenon, such as ground-motion amplitude, liquefaction, surface-fault rupture, landslide, etc." But according to Reiter (1990, p. 3), "seismic risk is the probability of occurrence of these consequences (of hazard)." Frequency and probability are different. Frequency is a measure of how often an event occurs (temporal), whereas probability is a measure of the likelihood of occurrence of an event (temporal) or a physical measurement such as ground motion (spatial). In other words, probability can be used to describe temporal and spatial measurements. This can be demonstrated by throwing a dice. Every time throwing a dice is an event, and how many times being thrown in a minute is a frequency. At each throwing, the probability of getting number 1, 2, 3, 4, 5, or 6 is 1/6. The probability here is not related to time (or, not temporal). An earthquake and its ground motion at a site are analogous to throwing a dice.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
2.	Ken Campbell	temporal versus spatial	I think that the distinction between temporal and spatial descriptions is meaningful, but not necessarily as cut-and-dry as you have attempted to make it. The only purely temporal part of PSHA is earthquake recurrence frequency or probability, as described by, say, a magnitude-frequency distribution, such as the Gutenberg-Richter relationship, or by a probability-magnitude distribution, such as the truncated exponential distribution. In this sense, it is clear that one can describe the hazard in the equally meaningful terms of frequency, probability, and return period, where return period is the reciprocal of the annual probability of the event, defined as the expected value of the number of years to the first occurrence of an event. This concept can even be extended to ground motion at a specific site. If one were to measure ground motion at a site over a given period of time (exposure period), wouldn't the observed number of events (in this case defined as ground motion of a certain amplitude or higher) divided by the exposure period be a valid description of the frequency of such an event? Here the frequency is purely temporal (the number of events in a given period of time), but the event itself is influenced by both temporal and nontemporal factors. Isn't this the same as the flood example that you use as a valid example of PSHA? If so, can't this frequency also be calculated theoretically from a probability distribution that describes these same phenomena? If the answer is yes, and I don't see from the definitions of theoretical frequency or probability why that shouldn't be the case, then the basic concept of PSHA to calculate ground-motion hazard would seem to be valid.	Time and space are two of the most fundamental elements of the world. Mixing them one way or the other will cause problems. Any activity or event is always associated with a time and space. See response to comment 1 on frequency versus probability.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
3.	Ken Campbell	frequency versus probability versus return period	Whether from temporal or nontemporal causes, the ultimate result of observing (or calculating theoretically) the number of times an event (e.g., ground motion of a specified amplitude or greater) occurs at a specific site in a given exposure period is its frequency of occurrence. Distinctions between ergodic or non-ergodic processes don’t really seem to be meaningful. The observed or calculated frequency or probability will be impacted by such factors as the rate of occurrence of earthquakes of a specified magnitude on a given source, the locations of all possible sources in a region, the locations of all possible ruptures on a given source, the amplitude of ground motion from a given rupture on a given source from a given magnitude at a specified site, and the aleatory uncertainty (randomness) in these factors. To calculate this frequency theoretically, as is done in PSHA, one has to define the event in terms of a probability, which requires defining a probability distribution. Typically, a Poisson probability is used for assumptions of time-independence of the event or a log-normal distribution (or Brownian passage time, etc.) for assumptions of time-dependence of the event. Here is where a certain level of uncertainty is introduced, since we do not really know what the appropriate probability distribution should be. If the Poisson probability distribution is incorrect, then so too will be the theoretical frequency calculated from this distribution. However, I am not aware of the existence of an alternative probability distribution, although I can’t say that I have done a thorough literature search either. So the problem is not in the calculation of theoretical frequency of an event, but rather in determining what the appropriate probability distribution should be. Regarding return period, it is simply defined as the reciprocal of annual probability, however that probability is calculated, and, say for an annual probability 0.01 of, for example, a flood event, is often referred to as the 100-yr flood, where 100 is the return period. However, as Benjamin and Cornell (1970) have stated, “the term is somewhat unfortunate, since its use has led the layman to conclude that that there will be 100 years between such floods when in fact the probability of such a flood in any year remains 0.01 independently of the occurrence of such a flood in the previous or a recent year (at least according to the engineer’s model).” Although Benjamin and Cornell attribute such a misconception to laymen, it is one that has found widespread belief amongst earthquake engineers and scientists. As a result, I believe that the use of this term should be abandoned and that we should refer to probabilistic hazard by its probability of occurrence in a given period of time (usually 1 yr) or the theoretical frequency that corresponds to that probability.	First, frequency and probability are different (see response to comment 1) and cannot be compared. Return period is “the reciprocal of annual probability.” The annual probability defined in PSHA is a combination of frequency of earthquake (temporal) and probability of ground motion (spatial). Therefore, return period is also a combination of temporal and spatial measurements. Therefore, frequency, probability, and return period are different measures and cannot be compared.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
4.	Ken Campbell	aleatory uncertainty in ground motion	If the standard deviation associated with an estimate of ground motion from an attenuation relationship is truly and purely aleatory, then it seems that it should be used to calculate the probability or theoretical frequency of ground-motion exceedance at a site, even though it describes nontemporal uncertainty in the estimation of ground motion. However, this is not necessarily the case. As I see it, there are at least four major issues that arise in attempting to probabilistically quantify ground motion at a site from a given earthquake: (1) what is the probability distribution that should be used to describe the uncertainty in the predicted ground motion (this distribution is usually assumed to be log-normal), (2) should this distribution be truncated at its upper end (this truncation is usually taken as two to three sigmas independent of amplitude), (3) does the standard deviation only represent aleatory uncertainty (it usually is), and (4) does the attenuation relationship truly represent an estimate of median ground motion (it usually is). All of these factors can have a profound impact on the results of PSHA, especially at low values of probability, and especially in the central United States, where attenuation relationships are theoretically derived and not empirically constrained at the larger magnitudes and close distances of importance for sites located near the New Madrid Seismic and Fault Zones, such as Paducah. There is insufficient time to discuss each of these at length, so I will simply give you some general thoughts and wait until the meeting for a more thorough discussion.	These comments are excellent. Detailed discussions on these comments are beyond the scope of this project.
5.	Ken Campbell	probability distribution	The log-normal distribution has been shown to be a perfectly valid distribution in many statistical tests. However, if in fact there is a limit (physical or otherwise) to the amplitude of ground motion, another distribution (e.g., Beta) might be a better description of probability. At relatively low values of ground motion, it mimics the log-normal distribution. However, it becomes less long-tailed as the ground-motion limit is approached and will naturally place a limit on the value of ground motion that is predicted from this distribution at very low values of probability.	Excellent comments. Detailed discussions on these comments are beyond the scope of this project.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
6.	Ken Campbell	ground-motion truncation	There has to be a physical limit to ground-motion amplitude. This is a topic of intense research because of its issue at Yucca Mountain. I am not sure what progress is being made, but it still might make sense to apply a reasonable limit. The USGS used a limit of 1.5 g for the median value of PGA, although they did allow the truncated log-normal distribution to predict higher values (up to three sigmas above this value, or around 6 g or so). This doesn't seem reasonable. Using something like 1.5–2.0 g (solicited from expert opinion) as a true upper bound (i.e., the value at which the probability distribution is truncated) might be a more reasonable approach.	Ground-motion uncertainty is an integral part of PSHA. Statistically, applying a limit is arbitrary.
7.	Ken Campbell	aleatory versus epistemic uncertainty	All variability between the observations and the predicted values are currently assumed to be aleatory. This we know is not really the case. As the Next Generation Attenuation of Ground Motions project showed, as we added more parameters to the model, we were able to reduce the standard deviation. If it was all aleatory, then this would not have been possible. The current paradigm is to treat uncertainty as aleatory if it is otherwise not modeled as epistemic. Although this is not strictly true, it is in fact very hard to separate the two. In my view, aleatory uncertainty in eastern North America can be assumed to be the same as that in western North America, and my latest hybrid-empirical model reflects this. This helps to limit aleatory standard deviations to reasonable values. This might not be as big an issue if items 1 and 2 are implemented.	In reality, aleatory and epistemic uncertainties are difficult to separate, particularly in the central United States.
8.	Ken Campbell	biased median estimate	In my view, many of the theoretically derived attenuation relationships in eastern North America predict unreasonable median estimates of ground motion, especially at short periods. I have attempted to correct this in my latest hybrid-empirical model, but unfortunately, it might not be ready in time for the USGS to use it. The largest median estimates of PGA on NEHRP B–C site conditions in eastern North America from my latest hybrid-empirical model is around 1 g, which I believe is more reasonable. This compares to a PGA value of around 0.5 g from my NGA model for the same site conditions.	Excellent comments.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
1.	Leon Reiter	general	In general, I have found that the draft report is lacking in technical justification for a number of the methods used and the assumptions made. This is particularly true for the proposed approach called seismic hazard analysis and the definitions of seismic hazard and seismic risk. Some of my criticisms may be due to the draft report's lack of clarity in explaining and justifying what was done. A clearer explanation may alleviate some, but not all, of my concerns.	This report is not a typical site-specific seismic hazard assessment, but a summary of scientific research on geological and seismological conditions, the methodologies, and the seismic hazard assessment related to the Paducah Gaseous Diffusion Plant and the surrounding area. Therefore, it may be reviewed in a different way than a normal site-specific technical report. The proposed approach, SHA, is not really a new one, but an old one (Milne and Davenport, 1969) with inclusion of ground-motion uncertainty. A similar approach has also been proposed by Stein and others (2005, 2006). SHA is analogous to flood, wind, and other hazard analyses and is technically sound. The definition of hazard and risk used in this report follows the accepted convention, particularly in engineering applications (hydraulic, flood, wind, and snow). These definitions are also consistent with those of McGuire (2004) and Reiter (1990). A better explanation of the methods used and the assumptions made will be addressed.
2.	Leon Reiter	p. 1, second paragraph	How can Figure 1 show that that higher seismic design in western Kentucky doesn't make sense when the total recording period is only 1 week? During 1 week you could be seeing the effects of a swarm that could give you an atypical increase in seismicity or seismic quiescence that would show anomalous low seismicity. If you want to make this point, show a longer period of time.	Revised to use Stein and others (2003).
3.	Leon Reiter	p. 4, first paragraph	DSHA does not (as stated in step 2) require the determination of earthquake occurrence frequencies.	True.
4.	Leon Reiter	p. 4, last line	There is no Wang (2004) in the list of references. Is this Wang (2003), which is listed, but without a title?	It should be Wang and others (2004).

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
5.	Leon Reiter	section 2.1.1, p. 5	In this section and at other locations in the text, the authors introduce their definitions of seismic risk and seismic hazard. These definitions are unclear and cause confusion. The commonly accepted definitions of hazard and risk (e.g., Reiter, 1990; McGuire, 2002) define seismic hazard as those earthquake-related properties that have a potential to cause damage or loss. Seismic hazard may be described deterministically (DSHA) or probabilistically (PSHA). Seismic risk is the probability of occurrence of adverse consequences from seismic events to humans or their built environment. This fits in with the classic definition of risk (Kaplan and Garrick, 1981) stating that risk analysis answers three questions: what can go wrong, how likely it is to happen, and what are the consequences or outcomes. According to the authors (bottom of p. 5), "Equation (3) [the probability of at least one earthquake with magnitude equal to or greater than a specific size occurring in *t* years] shows the relationship between seismic risk, expressed in terms of an earthquake magnitude *(M)* with *X* percent PE in *Y* years, and seismic hazard, expressed in terms of an earthquake with a magnitude *M* or greater and its MRI [mean recurrence interval] in an area or along a fault." Thus, according to the authors, the magnitude of an earthquake (and its mean recurrence interval) represents the hazard, and the likelihood of its occurrence during a specific time period represents the risk. These are simply different ways of expressing the same information. Risk, in this case, assumes a Poisson model of earthquake occurrence.	Seismic hazard and risk are two fundamentally different concepts. Seismic hazard is a natural phenomenon generated by earthquakes, such as ground motion, and is quantified by two parameters: a level of hazard and its mean return interval or frequency. Seismic risk, on the other hand, describes a probability of occurrence of a specific level of seismic hazard over a certain time, and is quantified by three parameters: probability, a level of hazard, and exposure time. These definitions are consistent with those by McGuire (2004) and Reiter (1990). According to McGuire (2004), seismic hazard is "a property of an earthquake that can cause damage and loss. A PSHA determines the frequency (the number of events per unit of time) with which a seismic hazard will occur." Because magnitude is a property of an earthquake, and the larger magnitude, the higher potential to cause harm, a magnitude *M* or greater with an MRI is seismic hazard. Similarly, MMI or ground motion at a site is a property of an earthquake with an MMI of VIII (or PGA 0.25–0.30 g) or greater with a return period is seismic hazard. MMI VIII is described as having considerable damage to ordinary buildings. Consequently, considerable damage or greater to ordinary buildings at a site with a return period is seismic hazard too. Therefore, measurements of seismic hazard can be different, from magnitude to damage (loss) level to buildings, and one measure can be converted to another through a statistical relationship (i.e., ground-motion attenuation and fragility curve). As defined by McGuire (2004), seismic risk is "the probability that some humans will incur loss or that their built environment will be damaged. These probabilities usually represent a level of loss or damage that is equaled or exceeded over some time period." A similar definition was put forth by Reiter (1990): "Seismic risk is the probability of occurrence [in time] of these consequences." From these definitions, seismic risk is quantified by three elements: probability, a level of consequence (damage or loss), and time. Because damage or loss is also a property (measure) of an earthquake, the likelihood (probability) of its occurrence *(M* or greater) during a specific period is risk.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
6.	Leon Reiter		There is no mention of the critical issue of consequences, such as building damage or loss of life. Using their definitions, the same information is needed to define hazard and risk. The authors are using their definitions to make a point. Frankly, I am not sure why they chose these definitions and am not sure what point they are trying to make. If they insist on this approach they should systematically explain how they differ from the classic definitions of hazard and, particularly, risk, and why they are using these definitions. I have unsuccessfully attempted to find clearer definitions and rationales in some of the other papers the authors have written.	It is very important to mention the assumption of a Poisson model of earthquake occurrence (in time). The risk (probability) calculations throughout the report are based on this assumption. The probability will be different if a non-Poisson model of earthquake occurrence is assumed. This is one of the differences between seismic hazard and risk: in order to estimate seismic risk, we have to make an assumption on earthquake occurrence in time (Poisson or non-Poisson). Seismic hazard is estimated from observation (data). The other important parameter, exposure time, is also very important to mention here. Exposure time is a normal lifetime or considered time for something (building, dam, bridge, etc.) being exposed to the hazard. The exposure time and physical content (regular two-story house, concrete dam, etc.) are properties of something being exposed but not properties of an earthquake. Therefore, seismic risk is an interaction (or so-called product) of seismic hazard and something being exposed. Thus, seismic hazard and risk are different.
7.	Leon Reiter	Figures 2, 23	Vertical axis should be "N," not "Log (N)."	Will revise.
8.	Leon Reiter	p. 5, Figure 3	The authors give an example of flood hazard and say that they can convert this to risk by using equation 3. I did a quick foray into the Web looking at definitions of general, and flood, hazard, and risk. These definitions make use of the classic definition I mentioned above with respect to seismic hazard and risk: i.e., adding the component of consequences (e.g., building vulnerability and loss of life).	See response to comment 5.
9.	Leon Reiter	p. 9, Table 2	When MMI is used, an argument could be made that this is true risk because it considers the level of damage.	If MMI is OK, why not M? See response to comment 5.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
10.	Leon Reiter	p. 11, first full paragraph	The authors raise an important point here, that the uncertainties may not be independent. I am not sure whether they are correct, but it seems to me that even if they are correct, it may be a necessary evil that we try to work around, but can't get rid of completely. This is something I would be happy to hear discussed by my colleagues at the review panel meeting. The authors also claim that Bommer and Abrahamson (2006) attribute the large uncertainty in Figure 6 to the use of site-fault distance rather than epicentral distance. However, Bommer and Anderson (2006) argue that the large variability reflects the variability due to wave propagation from a finite fault that is characterized only by the distance from the station to the closest point on the fault.	In the ground-motion attenuation relationships, R is measured as rupture, JB, or seismogenic distance. The ground-motion standard deviation will be different if different R is used (R dependent). $f_R(r)$ in equation 4 is to account for the uncertainty of focal point (distribution). The uncertainty of focal point is accounted for in part by the uncertainty of ground motion, because R is measured as a single distance (rupture, JB, or seismogenic), regardless of focal distance. Equation 4 counts the distance uncertainty, at least some portion, twice. Similarly, $f_M(m)$ in equation 4 is to account for the uncertainty of magnitude (distribution). Also similarly, the ground-motion standard deviation is dependent on M. Again, equation 4 counts the magnitude uncertainty, at least some portion, twice. These issues will be fully discussed at the review meeting.
11.	Leon Reiter	p. 12, first full paragraph	I don't understand how "equations (11) through (13) demonstrate that the invalid formulation of PSHA results in extrapolation of the return period from the recurrence interval of the earthquake and the ground-motion uncertainty … or the so-called ergodic assumption (Anderson and Brune, 1999)." Anderson and Brune (1999) showed that when determining hazard for a specific scenario (e.g., *X* km from the San Andreas Fault), the use of generalized attenuation equations based on many earthquakes may overestimate the hazard when compared to ground-motion-like data (precarious rocks) that exist for that scenario. They argued that the aleatory uncertainty in the generalized attenuation equations included epistemic uncertainty that could be reduced when a specific scenario is being considered. Do the authors have any data like this that could be used to reduce the uncertainty in the Paducah hazard analysis? This could be another good topic for review panel discussion.	Ground-motion uncertainty has been separated into aleatory and epistemic parts. But it is difficult to do so, particularly in the central United States. This will be discussed at the meeting.
12.	Leon Reiter	p. 15, first paragraph, first sentence	The authors state that geologic records of earthquakes are limited to the past 11,000 yr (Holocene). This is not true. Many records go back much longer: e.g., the area around Yucca Mountain contains geologic records of earthquakes that go back many hundreds of thousands of years.	But not hundreds of millions of years.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
13.	Leon Reiter	p. 15, first paragraph, last line (see also statements in the middle of the first paragraph)	I can't find the statement in Frankel (2005) that says that ground motion with a 2,500-year return period *will* [authors' emphasis] occur at least once in 2,500 years. On the contrary, Frankel (2005) talks about the ground motion being exceeded once *on average* [my emphasis] over 2,500 years. Also, in a response to Wang and Ormsbee (2005), Holzer (2005) clearly states that the 2,500-year PGA is *not guaranteed* [my emphasis] to occur in 2,500 years. How important is this to the authors' criticism of PSHA?	Figures 1 and 2 in Frankel (2005) show that (which is the acceleration that will be exceeded). Frankel's explanation is a "deterministic" interpretation. An event with a 63 percent probability of occurrence may not occur, but was interpreted and shown to occur.
14.	Leon Reiter	p. 15, last paragraph	The authors' statement that PSHA is invalid because it inappropriately mixes temporal measurement (occurrence of an earthquake and its ground motion) and spatial variation (ground-motion uncertainty due to source, path, and site effects) appears to be a key point in this report that needs to be clarified. I don't understand how spatial variation (as defined above) cannot be taken into account (if that indeed is what the authors are stating) when describing the likelihood of exceeding a given ground motion over a period of time. If there were no spatial variation, every time an earthquake occurred we would more likely know what the ground motion would be. Because there is spatial variation (much of which is assumed to be random, based on current knowledge), the likelihood of reaching a certain ground motion when an earthquake of given size occurs has to be different, because of increased uncertainty, than if there were no spatial variation. Eventually, I assume we will increase our knowledge of spatial variations such that we will have a better idea of what the source, path, and site effects are and they won't be assumed to be random.	It was stated that "the invalid formulation causes PSHA to mix the temporal measurement (occurrence of an earthquake and its consequence [ground motion] at a site) with spatial measurement (ground-motion uncertainty due to the source, path, and site effects)." Temporal and spatial measurements are two intrinsic and independent characteristics of an earthquake and its consequence (ground motion) at a site, and must be treated separately.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
15.	Leon Reiter	p. 17, middle paragraph, and Figure 10	It's very important to understand what the authors' proposed SHA does and does not do. For example, Figure 10 shows that at a given distance (30 km) from the New Madrid faults, the earthquake with an average recurrence rate of 0.004/yr will produce ground motion whose median is 0.1 g (and whose 16th percentile is about 0.04 g and whose 84th percentile is about 0.22 g). Ground-motion contributions at 0.1 g from other earthquakes with smaller or larger recurrence rates are not considered in this statement and have to be addressed in terms of earthquakes with other average recurrence rates. The statement on p. 17 that "equation (17) describes a … hazard curve in terms of *ground motion and its MRI* [my emphasis] at a site" can be misleading. Thus, if one stated that the median ground motion associated with a recurrence rate of 0.004/yr was 0.1 g, it would be incorrect. A similar problem exists in the last paragraph on p. 17, although the last sentence is clearer. Both paragraphs should be reworded to make absolutely clear what SHA is and is not. The last paragraph on p. 17 also states that Figure 10 (SHA) is comparable to Figure 3 (flood hazard at Lock 4). How can this be so? I assume that the flood-hazard curve is derived from annual peak discharge recorded at the same place. This includes all the uncertainty and is much simpler than having to derive magnitudes, recurrence information, and attenuation equations to determine what the seismic ground-motion hazard at a given place (e.g., Paducah) is. Also, the database used for determining flood hazard includes floods of different sizes and is not comparable to the SHA curve in which the peak ground motion is only associated with a given-size earthquake.	In SHA, temporal and spatial measures (including associated uncertainties) are considered separately. Ground motions from earthquakes with different recurrence rates should not be considered all together, particularly in the way of PSHA. This can be demonstrated from Figure 10. Say there are only two characteristic earthquakes, M 5.5 and M 7.5, with 0.004/yr and 0.002/yr recurrence rates (Fig. 2), both at 30 km. At 0.22 g, the confidence level is 84 percent (16 percent PE) if M 5.5 occurs and 16 percent (84 percent PE) if M 7.5 occurs. Here, ground motion with a confidence level of 84 percent is compared with the one with a confidence level of 16 percent. This comparison may not be statistically correct. Comparison of two statistical data sets should be based on the same level of confidence. The statement "equation (17) describes a hazard curve in terms of ground motion and its MRI at a site" has a clear physical meaning. The hazard curve is directly converted from the Gutenberg-Richter curve (equation 15) and ground-motion attenuation (equation 16) (i.e., converting the source measurement [magnitude] to the measurement [PGA] at a site at 30 km). Figure 10 (SHA) is comparable to Figure 3 (flood hazard at Lock 4) in terms of the way the curves are constructed and used. In fact, PSHA was originally developed from the analogy of flood, wind, and snow hazards (Cornell, 1968). The problem with PSHA is that there is a mathematical error (dependency of variable) in the formulation.
16.	Leon Reiter	Figure 10	What would the mean seismic hazard be? In the caption to this figure the authors imply that the median is the same as the mean for the characteristic earthquake. This is not correct if the ground motion was derived from attenuation equations that assumed a log-normal distribution. Can SHA calculate the mean hazard, which is used extensively for many regulatory purposes?	This is a good point. Mean and median are different and need to be clarified. A mean curve will be added to Figure 10.
17.	Leon Reiter	p. 20, Figure 11, and other map figures following	It would be very helpful if the authors showed the location of the Paducah facility on these maps. I think it only appears on Figure 31 and possibly as a yellow dot on Figure 20.	Will revise.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
18.	Leon Reiter	p. 20, last paragraph	How specifically does Figure 12 show that the northeast extension of the New Madrid faults has a significant effect on seismic hazard estimates at Paducah? How much closer to Paducah are the New Madrid faults if one assumes that there is a northeast extension?	The distance will be less than 10 km from the faults (in red) to the site. Our measurement from the faults of Johnston and Schweig (1996) to the site is about 45 km.
19.	Leon Reiter	p. 21, first paragraph	As stated above, the authors believe that the northeast extension is a significant issue. They have cited some evidence against its existence; however, this evidence should be laid out carefully and systematically. For example, the authors could show the location of the Jackson Purchase Region with respect to the surrounding area (including the Paducah facility), the proposed extension of the New Madrid faults, the proposed northwest-trending structure, and discuss their significance. They could also show the plots of microseismicity (or modify the existing figures) that support the argument that the New Madrid faults don't extend into this region. A table comparing the aspects of earthquakes in the New Madrid zone, the northwest-trending structure, and the Jackson Purchase/northeast extension, along with other seismological and geological evidence (as stated on p. 20) would be useful. One can then judge whether the evidence supports the claim. Do other hazard maps (e.g., Frankel and others, 2002; Risk Engineering Inc., 1999) make the same assumptions that the authors of this report do about the Jackson Purchase, the northwest-trending structure, and the northeast extension of the New Madrid faults? If not, justify the choice.	Good comment. Will revise.
20.	Leon Reiter	p. 22, Figure 12	It is not clear what the blue lines represent and the basis for their definition. Do they represent faults as identified by the authors and Johnston and Schweig (1996)? Should they be the same as the New Madrid faults shown in Figure 31? What are the blue boxes trending north-northwest supposed to represent?	The blue lines represent New Madrid faults (southwest branch, Bootheel Lineament, northeast branch, west branch, and thrust-box) and rift boundaries (east ridge and west ridge) by Johnston and Schweig (1996). The faults in Figure 31 are the same as those of Johnston and Schweig (1996), except for the thrust fault presenting by the northern edge.
21.	Leon Reiter	p. 24, first paragraph	The authors refer to Figure 10. Do they mean Figure 15?	Yes, Figure 15.
22.	Leon Reiter	p. 27, top paragraph, Figure 16, and bottom paragraph	How old is "Iapetan"? What are the dotted circles in Figure 16? What is the significance of the J.T. Myers Locks and Dam shown on Figure 16? Can the Paducah facility be located on this figure and Figure 15? (See comment 16 above.) Do the authors mean to say "areal" rather than "aerial"? (See also "aerial" in paragraph 1 of p. 40.)	Figures 15 and 16 were taken from other reports. The references will be cited. It should be "areal."

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
23.	Leon Reiter	p. 28	What is the rationale behind the authors' use of the Tri-State Seismic Source Zone? How would the other alternative models affect the hazard calculations? I assume that a maximum magnitude of 6.8 was picked because it was midway between 6.2 and 7.3. Is this correct?	The zone has been called by different names, such as the Wabash Valley. I prefer the Wabash Valley Zone and will revise that. Different models (zone boundaries) surely affect the hazard calculations. A maximum magnitude of 6.8 was picked because it was midway between 6.2 and 7.3.
24.	Leon Reiter	p. 29, discussion of background seismicity	The authors contend that large earthquakes (M=7.0 to 7.5?) in the background zone do not make any contribution to the hazard (citing Figure 20 taken from Petersen, 2005), and they cause confusion. Figure 20 is not clear, but it looks like nearby (background?) magnitude 6 and 6.5 earthquakes (blue and green bars surrounding Paducah facility) are contributing to hazard. How is this consistent with the magnitude 4.7 to 5+ maximum background earthquakes shown in Figure 21? Also, how do large background earthquakes "cause confusion"?	As shown in Figures 18 and 19, large earthquakes (M=7.0 to 7.5) in the background zone were used in the national mapping. The recurrence interval of the large earthquake is 10,000 years or greater. In PSHA, these large earthquakes were distributed in large areas (Fig. 19) such that contributions from these large earthquakes to any site are negligible. This can be seen in Figure 20. In other words, the large earthquakes were introduced, but have no effect on hazard calculation. Some people, even seismologists, have used Figure 19 to generate ground-motion hazard maps to show the general public and policy-makers. This is clearly confusing. Figure 20 was used to show that there is no contribution to the hazard from large background earthquakes. Magnitude 6 and 6.5 earthquakes shown in Figure 20 were derived from the smoothed seismicity (Fig. 18) by Frankel and others (2002). The magnitude 4.7 to 5+ maximum background earthquakes shown in Figure 21 were derived from historical observations plus one standard deviation (~0.25 unit).
25.	Leon Reiter	Figure 21	The text states the Paducah facility is located in McCracken County, shown in Figure 21. I cannot locate McCracken County on this map because the print is too small.	A bigger map is needed to show county boundaries.
26.	Leon Reiter	p. 32, first paragraph	The magnitude-recurrence relationship for the Wabash Valley Seismic Zone is shown on Figures 24 and 25, not Figure 23 (as stated in the text).	Correct.
27.	Leon Reiter	p. 32, second paragraph	Make it clear that Figure 23 itself does not come from Bakun and Hopper (2004), but rather it is based on data from that source. Also, do the authors assume that the 1811-1812 events can be considered as a single, magnitude-7.5 earthquake? If so, how significant is this assumption?	Will revise. Yes, we assumed that the 1811-1812 events can be considered as a single magnitude-7.5 earthquake. In this report, seismic hazard is defined as an earthquake of magnitude M or greater (cumulative) or ground motion generated by the earthquake at a site versus mean recurrence interval (or return period for ground motion). The cluster events are considered through the cumulative effect.
28.	Leon Reiter	Figure 22	Is the red curve a line drawn through individual seismicity data points?	It should be, but is directly cited from Frankel and others (1996).

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
29.	Leon Reiter	p. 33, Table 5	What happened to event 6 in Bakun and Hopper (2004), the February 7, 1812, M=7.8 earthquake in the New Madrid Seismic Zone? Has this been left out of the authors' calculations? If so, justify this choice and estimate its impact.	That was a mistake. Will be added. The hazard calculations will be the same.
30.	Leon Reiter	Figure 26	Overlay the data mentioned on p. 34 that served as a basis for drawing the magnitude-frequency relationship for the background seismicity.	Will be added.
31.	Leon Reiter	p. 37, first paragraph	Contrary to what is stated, Table 6 contains five, not six, attenuation relationships, the lowest value of which is 0.69 g, not 0.46 g. Also, I am not clear what range of standard deviations the authors are assuming for the central United States. Is it 0.6 to 0.8?	Errors will be corrected. The range of standard deviation for all attenuations in the central United States is 0.6 to 0.8. Exact numbers used are based on each attenuation.
32.	Leon Reiter	p. 37, second paragraph	I look for my colleagues Ken Campbell and Gail Atkinson to confirm the statement that "There is a consensus that many current attenuation relationships predict too high ground motion at near source, particularly Frankel and others' attenuation relationship (U.S. Geological Survey/Nuclear Regulatory Commission, 2005)." I contacted someone from the Nuclear Regulatory Commission who was at the workshop and the USGS organizer of the workshop, and they do not remember this statement about a consensus.	There is a video CD for the workshop.
33.	Leon Reiter	Figure 27	I cannot see the symbol for the Frankel curve (referenced in the text on p. 38) on the figure. Is the high near-field curve from Atkinson and Boore (2006)?	Frankel and others (1996) did not provide attenuation equations, but only a table with cut-off distance at 10 km. The comparisons were made at 10 km.
34.	Leon Reiter	p. 39, first paragraph	Why did the authors choose these four attenuation relationships? Was Frankel and others' relationship left out only because they felt that there was a consensus to support leaving it out, or were there other reasons?	It was an "outlier."
35.	Leon Reiter	p. 40, first paragraph	In regard to background seismicity, what is the justification of using a 15 km distance to the source? Also, the contributions from background seismicity shown in Figure 32 (e.g., PGA) look pretty high, even though the maximum earthquake is only 5.0. On p. 29 (see also comment 22), the authors justify not using a higher magnitude cutoff by saying that higher magnitudes won't contribute much. Can they do a sensitivity test showing what the effects of having higher cutoffs would be?	The focal depth is generally between 2 and 20 km in the region. We assumed a focal depth of 11 km and epicentral distance of 10 km. This results in a focal distance of 14.9 (rounded up to 15) km. A higher background earthquake will have (and should have) a significant effect on hazard calculation. But the large background earthquakes have no effect because of the way they were treated in a PSHA study. See response to comment 24 for further explanation.
36.	Leon Reiter	Figure 31	In comparing this to the blue lines in Figure 12, I am not sure why these particular New Madrid faults and lengths were chosen. Please explain.	The New Madrid faults in Figure 31 are the same as in Figure 12. See response to comment 20.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
37.	Leon Reiter	p. 43, Tables 7–9	Tables 7, 8, and 9, when compared to Figures 27–30 and 32, show that what the authors did was equivalent to a deterministic scenario (M=7.5 at 45 km). The ground motion from other magnitudes and distances are not incorporated into the estimate; uncertainty at a given ground motion is shown assuming a fixed magnitude and distance. Is this what the authors wanted? If so, provide a rationale why this is acceptable. This was also discussed in comment 15.	For a single characteristic source, SHA is equivalent to a deterministic scenario. See explanations to comments 10, 14, and 15.
38.	Leon Reiter	p. 43	It would be highly useful if a table was made comparing these results with those of other studies that estimated seismic hazard at Paducah (e.g., Risk Engineering Inc., 1999; Frankel and others, 2002) and any others that may exist. The authors of the report could then explain the differences between the results, the specific causes of these differences, and why their results are more valid. Although parts of this have been discussed in a general way in the text of the report, a specific discussion and evaluation of critical differences would be very helpful in evaluating this report and the novel way it approaches seismic hazard.	A table comparison is not easy, because hazard comparison is not only on ground-motion value, but also on frequency (return period). For a single characteristic source, SHA derives a single frequency (return period), but PSHA derives a range of frequency.
39.	Leon Reiter	p. 44–45	There are many important issues raised here. Comments 5, 9, 10, 12, 13, 14, 15, 36, and 37 address these issues and the content of p. 44–45 should be addressed in light of these comments. Similar concerns exist with respect to the executive summary.	All these really come to a single question: Is PSHA (the Cornell-McGuire method) right? It has been shown that PSHA is mathematically incorrect. This will be discussed thoroughly at the review meeting.
40.	Leon Reiter	p. 44, first paragraph	It should be made clear that although Reiter (1990) and Wang (2006) agree that seismic hazard and risk are different concepts, they do not agree on what these concepts are. The same statement is made on p. 5, first paragraph.	See explanations to comment 5.
41.	Leon Reiter	p. 46	What is the basis for the authors' recommendation of using the average of the median and the median plus one standard deviation? Why not use, for example, the mean (not shown) or the one standard deviation estimate?	There is confusion about the terms "mean" and "median" hazards. These will be addressed and discussed at the meeting.

Appendix B:
Comment on Preliminary Draft by Mai Zhou

Ground motion Y is generally modeled as a function of M and R with variability E in a regression model:

$$\ln(Y) = g(M,R) + E. \tag{1}$$

The variability E is modeled as a normal distribution with a zero mean and standard deviation $\sigma_{\ln,Y}$. In other words, the variability of ground motion Y is modeled as a log-normal distribution. Therefore, equation 1 can be rewritten as

$$\ln(Y) = g(M,R) + n\sigma_{\ln,Y} \tag{2}$$

where n is a number of standard deviations measured as the difference relative to the median ground motion $g(M,R)$.

Modern PSHA is based on the following equation:

$$\begin{aligned}\gamma(y) &= \Sigma\nu P[Y \geq y]\\ &= \Sigma\nu\iint \{1-\int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}}\exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma^2_{\ln,y}}]\, d(\ln y)\} f_M(m) f_R(r)\, dmdr,\\ &= \Sigma\iint [1-\phi(\frac{\ln(y) - g(m,r)}{2\sigma_{\ln,y}}) f_M(m) f_R(r)\, dmdr\end{aligned} \tag{3}$$

where ν is the activity rate, $f_M(m)$ and $f_R(r)$ are the probability density function of earthquake magnitude M and site-to-source distance R, respectively, $g(m,r)$ and $\sigma_{\ln,y}$ are the median and standard deviation at m and r, and $\phi(t)$ is the cumulative probability function for the standard normal random variable.

Since the modeling consequences are so crucial, I would point out a few places in the PSHA calculation that I feel need caution; a thorough review is perhaps needed.

1. Is the error distribution normal or not? Even if it is normal, does the variance of the error distribution remain a constant as M and R change? The systematic change of the variance, called variance structures, does not affect the estimation of the regression function $g(m,r)$ too badly. But for the exceedance probability, this variance structure is very important.
2. The estimation of $\sigma_{\ln,y}$, the standard deviation of E, is crucial, and is usually a harder task compared to the estimation of the regression function. If the regression function $g(m,r)$ is not specified accurately, or if other systematic influence on the regression is ignored, then often the discrepancy in the regression functions is treated as error and regulated to E, thus inflating the $\sigma_{\ln,y}$. For example, site conditions are not considered in the model. Also, if the distance R is measured with large error, the changes in ground motion due to these factors may be mixed with the intrinsic variability of E.
3. The form and accuracy of the probability density functions $f_M(m)$ and/or $f_R(r)$ affect the exceedance probability a great deal. How confident are we when we plug in a PDF for $f_R(r)$?

The assumption of normal distribution for the error E is usually granted when a regression model is assumed. This is not critical when the purpose of the model is mainly to estimate the regression function $g(M,R)$. The least squares method used in the estimation of regression function is also consistent when the error follows other types of distributions, or the variance is not constant.

But we are using the model to calculate the exceedance probability, which involves the tail behavior of the error term. The assumption of normality, and the assumption of constant variance, is critical. Even if the normal assumption is reasonable, its variance may depend on M and R. Only when M, R, and E are independent random variables can the joint probability density function of M, R, and E be written as a product:

$$f_{M,R,E}(m, r, \varepsilon) = f_M(m) f_R(r) f_E(\varepsilon), \tag{4}$$

where $f_E(\varepsilon)$ is the PDF of E. The exceedance probability $P[Y \geq y]$ is

$$\begin{aligned}P[Y \geq y] &= \iiint f_{M,R,E}(m,r,\varepsilon)\, H[g(m,r) + \varepsilon - \ln(y)]\, dmdrd\varepsilon\\ &= \iiint f_M(m) f_R(r) f_E(\varepsilon)\, H[g(m,r) + \varepsilon - \ln(y)]\, dmdrd\varepsilon,\end{aligned}$$

where $H[g(m,r) + \varepsilon - \ln(y)]$ is the Heaviside step function, which is zero if $g(m,r) + \varepsilon$ is less than $\ln(y)$, and 1 otherwise.

Because E follows a normal distribution, equation 5 can be rewritten as

$$\begin{aligned}P[Y \geq y] &= \iint \{\int f_E(\varepsilon)\, H[g(m,r) + \varepsilon - \ln(y)]\, d\varepsilon\} f_M(m) f_R(r)\, dmdr\\ &= \iint \{1 - \int_{-\infty}^{\ln(y)-g(m,r)} \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp(-\frac{\varepsilon^2}{2\sigma^2_{\ln,y}})\, d\varepsilon\} f_M(m) f_R(r)\, dmdr\end{aligned}$$

$$= \iint \{1 - \int_{-\infty}^{\ln(y)} \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[- \frac{\varepsilon - g(m,r))^2}{2\sigma_{\ln,y}^2}] d\varepsilon\} f_M(m) f_R(r) dmdr$$

$$= \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[- \frac{(\ln(\xi) - g(m,r))^2}{2\sigma_{\ln,y}^2}] d(\ln(\xi))\} f_M(m) f_R(r) dmdr$$

Therefore, we have equation 3, the heart of modern PSHA.

Appendix C:
Review Panel Comments on Final Report

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
1.	Roy Van Arsdale		[Include] an appendix illustrating your calculations for both PSHA and DSHA.	PSHA calculation is straightforward, but very time-consuming. We decided not to include it. DSHA calculation is shown in Table 8–11.
2.	Roy Van Arsdale		[Include] a brief discussion in your conclusion section pointing out the differences between your values and the USGS values.	This has been added.
1.	Gail Atkinson	general	The subject report deals with seismic hazards to the Paducah Gaseous Diffusion Plant. This review deals with the revised version, entitled: “Final Report on Seismic Hazard Assessment for the Paducah Gaseous Diffusion Plant,” dated May 11, 2007. The report is clearly written and easy to follow. Technically, it is much improved over an initial draft (March 2007) that was reviewed by a review team and discussed at a team meeting in Lexington, Ky., on April 30, 2007. The methods and conclusions of the report are now, for the most part, well reasoned, with a few significant exceptions that need to be remedied to make the report technically sound and defensible overall. I have listed my comments below by page and fraction (e.g., 2.5 indicates the middle of page 5). The most important comments, which are crucial in terms of the technical soundness of the report and its conclusions, are in bold. All suggested changes are straightforward to implement. With the bolded comments addressed as suggested, the report will then form a good assessment of the seismic hazard at Paducah.	Responses are only provided to the bolded ones. Others have been revised accordingly.
2.	Gail Atkinson	p. 20.2	The use of M_{MAX}=6.8 in Wabash is inconsistent with the estimated range of M 6.2 to 7.3 for paleoseismic events. The M_{MAX} for the Wabash Valley Seismic Zone should be at least 7.3, and possibly 7.5. See also Figure 18, which also shows higher magnitudes for paleoevents.	We used mean values (best estimate) for any set of parameters throughout this report. Figure 18 was the old estimate and used by the USGS (Frankel and others, 2002).

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9.	Gail Atkinson	Table 6	What weights were used for the ground-motion prediction equations? Do Table 7 and Figures 31–33 refer to the mean-hazard PSHA results? Sensitivity to the alternative models should be shown. The presentation of the PSHA results is incomplete.	Equal weight (0.25) was assigned to four ground-motion prediction equations. Table 7 and Figures 31–33 refer to the mean hazard. No sensitivity to alternative models was carried out in this study.
10.	Gail Atkinson	p. 44.8	Delete the entire paragraph under Table 15. You consider only probabilities to 1/2,500 in the report, then appear to state at the very end that your target probability is much lower. There is no suggestion in the report that probabilities of 1/100,000,000 are of interest, and thus none of this discussion is relevant. It just detracts from the report, which should simply end after Table 15.	Deleted.
1.	Jim Beavers		Zhenming, per our conversation today with regard to your PSHA PGA number (0.49 g) on hard rock (USGS Type A foundation) at 2,500 yr, we talked about three things that brought the number down from the 0.8 g PGA I had calculated from the USGS (1996) B-C boundary of 1.2 g and the corresponding 0.8 g Risk Engineering had calculated. These all make sense to me; as a result, the 0.49 g seems realistic to me, knowing these three items changed. To convince others that 0.49 g is the right number for this study, I would run a sensitivity analysis. For example, run your PSHA just using Frankel's attenuation and see how much it raises the 0.49 g. Then increase the magnitude to 8.0 and see how much further it raises it. Finally, change the distance to what Art used. By then you should be closer [to] 0.8 g. This will give you a feel for what is contributing to the reduction. The only other variable that may cause the 0.49 g to go up is the lower return period 500 versus 1,000, but you used that anyway. In McGuire's and Frankel's [analysis,] 0.8 g was an M 8.0 and R of 1,000. Make a few comments about your sensitivity study in section 6.1 about these contributions. This will help you down the road in case other external reviewers are brought in at the Paducah Gaseous Diffusion Plant, which is highly likely to occur for the upcoming DOE CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) Waste Disposal Facility.	The three things are: (1) the location of the New Madrid faults (farther west), (2) a smaller mean magnitude (M 7.5 versus M 7.7) for the characteristic earthquake in the New Madrid Seismic Zone, and (3) use of lower ground-motion attenuation relationships.

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3.	Gail Atkinson	p. 21.8	The treatment of the background source is not satisfactory. You cannot justify a low M_{MAX} (in the M 5 range) anywhere in the world. Most global studies suggest M_{MAX} ~7 for stable craton regions (e.g., Johnston and others, 1996). You also cannot fix an arbitrary distance. This highlights one of the weaknesses of DSHA: It cannot handle background seismicity. I suggest that for the DSHA you just state that the DSHA focuses on the perceived dominant hazard source, the New Madrid Seismic Zone, and ignores other potential contributions such as the local seismicity and the Wabash Valley Seismic Zone, which are handled in the PSHA.	As discussed in Wang (2003a), there is no contribution from those large background earthquakes because of (1) a large-area source zone and (2) a longer recurrence interval (more than 10,000 yr). Use of the large background earthquake only causes confusion.
4.	Gail Atkinson	p. 25.9	Is Figure 20 the definition of the background zone? Show the spatial definition of this zone explicitly.	The background seismicity was treated as a point source, which is similar to the smoothed-grid seismicity in the USGS maps. Figure 20 shows the earthquakes that were used to derive a and b values.
5.	Gail Atkinson	Figures 26–29	State the type of distance used in the plots; this is especially important as you made a big point of the types of distances and their impacts on these plots earlier in the report.	R_{RUP} was used throughout this report.
6.	Gail Atkinson	p. 37.3	The sentence, and corresponding approach, "We used a point source at 15 km with a maximum magnitude of M 5.0 to account for the local earthquake" is not justified. A proper areal source zone with the magnitude-recurrence relation as defined from Figure 21 should be defined and included in the PSHA, with a suitable M_{MAX} (6.5 to 7 based on global precedents). It is fine to exclude the local source from the DSHA, as long as it is properly included in the PSHA.	The USGS also used the point source (grid point) to account for the seismicity (Frankel and others, 1996, 2002).
7.	Gail Atkinson	Figure 30	Show exactly how the local and Wabash Valley Seismic Zone areal sources are defined for the PSHA.	The local zone (background) is a point source at 15 km. The Wabash Valley Seismic Zone is an areal source, shown in Figure 30.
8.	Gail Atkinson	Figure 38.1	The most important uncertainties for a logic tree in this case are the ground-motion prediction equations and the source geometry. You have ignored uncertainty in the spatial definition of the source zones. This uncertainty should ideally be considered, or as a minimum, you should state explicitly that you are ignoring uncertainty in the definition of the source zones. It is OK to use a single M_{MAX} value, as long as it is sufficiently large to be above the range of interest/sensitivity to this parameter. Properly chosen, hazard results are not very sensitive to M_{MAX}. The local seismicity is not properly treated here, as noted above, and needs to be properly included in the analysis.	It has been shown that a properly chosen M_{MAX} and distance can be used to quantify hazard at a site in the New Madrid Seismic Zone (Frankel, 2004; Petersen, 2005). The background seismicity was treated in a similar way as the USGS mapping (Frankel and others, 1996, 2002).

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2.	Jim Beavers		Also for your top-of-soil numbers, I would just go to the Bechtel-Jacobs (2002) report (BJC/PAD-356) and scale the soil-amplification numbers from Figures 7.3-1a for PGA, 7.3-1b for 0.1 s, and 7.3-1c for 1 s. We did not do an 0.2 s curve. The CERCLA will have longer-period motions, probably around 1 s. It looks like your 0.49 g will lower the long-period motions. I took a quick look at the Bechtel-Jacobs report and with a hard rock PGA of 0.49 g from Figure 7.3-1a, I get an amplification factor for PGA at top of soil of 0.8. From Figure 7.3-1b, I get an amplification factor for 0.1 s at top of soil of 1.2. And from Figure 7.3-1c, I get an amplification factor for 0.1 s at top of soil of about 2.0. You will see in Table 8-1 we ended up with a preferred method that had amplification factors, respectively, of 0.73, 0.68, and 2.55. You have a little more amplification at PGA and at 0.1 s because of the PGA being 0.49 g. But when you get out to the 1 s period, we had a 25 percent higher amplification because our hard rock PGA was 0.8 g or 0.71 g after refinement of my earlier calculations in the Bechtel-Jacobs report.	Soil amplification is not part of this project.
1.	Ken Campbell	general	It is not clear what role the independent expert review panel had in the study. It is very important that the roles of these reviewers be described, together with such information as: (1) When and where the review meeting was held and how long the meeting lasted. (2) The amount of time that each reviewer was given to perform the review. (3) The materials provided to the reviewers for review. And (4) The recommendations that were made at the review meeting by each of the reviewers. It is also important that reasons be given why some of the recommendations of the review panel, both written and verbal, were not adopted in revising the report.	Revisions have been done to address these. And other materials were also included as appendices.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
2.	Ken Campbell	general	The so-called PSHA conducted in this report is not a standard PSHA such as is done in practice. The PSHA presented in the report only takes into account the characteristic earthquake on the New Madrid Seismic Zone and the maximum magnitude earthquakes on the Wabash Valley Seismic Zone and the local source zone located at specific distances to the Paducah Gaseous Diffusion Plant site. This will not necessarily represent events that contribute the greatest to the probabilistic ground motion for a given probability of exceedance, because of trade-offs between the recurrence interval of the events and their magnitudes and distances. On the other hand, a true PSHA would also allow the noncharacteristic earthquakes to float within their area sources, thus allowing many events to occur farther from the Paducah Gaseous Diffusion Plant site than was assumed. Of course, there would be some floating earthquakes within the local source zone that would also occur closer to the Paducah Gaseous Diffusion Plant site. For a full standard PSHA, the complete recurrence curves (magnitude-frequency distributions) and distance distributions for every source should be used. Also, the epistemic uncertainty characterized by the use of multiple attenuation relationships should be included as part of the epistemic uncertainty model.	The probabilistic analysis carried out in this project is not a standard PSHA. As shown by Frankel (2004) and Petersen (2005), a simpler one, like the one carried out in this project, can provide a good estimate. This serves the purposes of this project: (1) to gain better understanding of the seismic hazard assessment at the Paducah Gaseous Diffusion Plant and its surrounding area, and (2) to communicate the hazard information more effectively to users and policy-makers.
3.	Ken Campbell	general	It was unanimous amongst the review panel members that not only should a full PSHA be done, but that the PSHA should account for epistemic uncertainty in such parameters as the characteristic and maximum magnitudes and the distances from the site to the seismic sources (in this case, the New Madrid Fault Zone and the boundaries of the Wabash Valley Seismic Zone and the local source zone). No such uncertainty was included in the revised report. In lieu of formally accounting for epistemic uncertainty, a series of sensitivity analyses could be used to show the sensitivity of the results to the modeling assumptions that were made.	The recommendation was to perform a PSHA with some discussions for improvements. This report reflects that. More analyses, including sensitivity analysis, could be done, but there is a time constraint.

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4.	Ken Campbell	general	There is a general lack of documentation regarding why certain decisions were made, such as why the specific attenuation relations used in the analysis were selected and why others were excluded and why certain investigators' characterizations of seismic sources were used and others were not. Without such documentation, the reader gets the impression that the selection was arbitrary and designed to achieve a certain result, even if that was not the case. Since the USGS National Seismic Hazard Mapping Project will generally be considered the basis for comparison, any deviation from that project's hazard model should be clearly described and explained.	In some cases, there is no such documentation to support a decision to use one parameter over the other. This is particularly true in the central United States. We tried our best in this report.
5.	Ken Campbell	general	Although the revised report has been improved considerably from the original version, there is still a perceived undercurrent of bias against PSHA that gives an impression of unprofessionalism. It is certainly appropriate to point out the weaknesses of PSHA, but they should be balanced by also discussing its strengths. DSHA also has weaknesses and strengths, but comments throughout the report tend to emphasize its strengths while emphasizing the weaknesses in PSHA.	Text has been revised to address the weaknesses of DSHA.
6.	Ken Campbell	p. 1	It appears that the USGS hazard maps, specifically with respect to their use in design, are being misrepresented. The ground-motion values from the maps are not used directly to derive design ground motion in the NEHRP and IBC design codes. Aside from the issue of deterministic caps in the design maps, the ground motion from the hazard maps are multiplied by the site factor representing the NEHRP site class for the site of interest, and this value is in turn multiplied by 2/3. For a hard-rock site in the central United States (NEHRP site class A), the site factor is 0.8 for all ground-motion parameters. Therefore, the mapped value of ground motion would be multiplied by 0.8 x 2/3 = 0.53 to derive the design value, nearly a 50 percent reduction in ground motion. Continually referencing the mapped values is confusing and gives the impression that these mapped values are used for design.	The design values (0.6 g and 0.8 g) were reduced by a factor of 1.5.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
7.	Ken Campbell	p. 1	The statement that "these high design ground motions for western Kentucky are not consistent with scientific research and observations" is not justified and, in my opinion, should be deleted. Probabilistic ground motions approaching or exceeding, say, those in San Francisco, can possibly be justified given the relatively short recurrence interval of large new Madrid earthquakes (i.e., 500 years), the factor of two increase in short-period ground motion for the same magnitude and distance in the central United States, and the lower rate of attenuation in the central United States.	This has been revised.
8.	Ken Campbell	p. 8	Deaggregation methods were developed to overcome the disadvantage in the PSHA methodology that was identified by National Research Council (1988) and have now been accepted by practitioners and regulators alike as a valid means of developing one or more design earthquakes from PSHA results.	Deaggregation is an effort in PSHA to seek the "design earthquake" (revised).
9.	Ken Campbell	p. 8	It is important to mention that the second disadvantage of PSHA of obtaining excessively large ground-motion values at very low probabilities of exceedance is not an issue when the results are constrained to reasonable probability levels (e.g., $\geq$ 2 percent probability of exceedance in 50 years). Even Figure 4 shows that the contribution of uncertainty caps out at two to three standard deviations for probabilities constrained to such levels.	Ground-motion uncertainty is an integral part of PSHA; a cap on it may not be statistically sound.
10.	Ken Campbell	p. 10	There seems to be a clear bias against PSHA, since only its disadvantages are listed, whereas only advantages are listed for DSHA. See comment 5 for additional discussion of this topic. In fact, since both methods have strengths and weaknesses, there is clear justification for using both methods.	Revised.
11.	Ken Campbell	p. 11	References for the possible causes of seismicity in the New Madrid Seismic Zone are quite old. Several new theories have been put forth since these references were written that should also be presented.	There are some new references, particularly from GPS. Those could cause confusion, however.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
12.	Ken Campbell	p. 13	The few small events that have been recorded in the Jackson Purchase Region are not sufficient to justify the strong conclusion that "there is no evidence (microseismicity) to support the northeast extensions of the New Madrid faults into the Jackson Purchase Region." Many more recordings would be required to justify such a conclusion. Even if true, the fault could be located just outside of the Jackson Purchase Region, or it could be locked and not generating earthquakes at even the microearthquake level.	Those records are surely not sufficient, but at least they are real data.
13.	Ken Campbell	p. 13	It would be useful to show a map of the New Madrid faults that were used to define the New Madrid characteristic earthquakes in relation to the Paducah Gaseous Diffusion Plant site.	It is shown in Figures 7 and 30.
14.	Ken Campbell	p. 20	It is not clear why the so-called Tri-State Seismic Source Zone rather than other alternative source zone configurations of Wheeler and Cramer (2002) were used to represent the Wabash Valley Seismic Zone. These alternative source zones would have made a valid epistemic uncertainty model.	Different names have been used for the zone in the literature. Wabash Valley Seismic Zone was used throughout this report.
15.	Ken Campbell	p. 21	The characterization of the local source zone in terms of magnitude, distance, and focal depth distributions seems arbitrary and needs to be justified. For example, as discussed in the review meeting, $M_{MAX}(M_W)=5.0$ is too low to be a reasonable estimate of the largest earthquake that can be expected to occur in the background region surrounding the Paducah Gaseous Diffusion Plant site. Based on a worldwide study, Electric Power Research Institute proposed that $M_W=6.3 \pm 0.2$ represented a reasonable estimate of maximum magnitude in nonrifted stable continental region crust. Alternatively, one could look at a much larger region of the central United States (and possibly eastern Canada) with tectonic conditions similar to the region around the Paducah Gaseous Diffusion Plant site to come up with a more reasonable estimate of M_{MAX}.	An M 8.0 or even larger earthquake can be put at the site. But it is meaningless for hazard assessment, particularly for PSHA, if the associated recurrence interval is unknown. Determination of these earthquakes should be consistent with historical and geological data.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
16.	Ken Campbell	p. 23	The only comprehensive study of recurrence intervals on the New Madrid Fault is the paleoliquefaction studies reported by Tuttle and her co-workers. She shows evidence of at least three past sequences of large liquefaction events rivaling that in 1811-1812 that suggests a mean recurrence interval of 500 yr for such large events. The 1,000-yr recurrence interval used previously by the USGS and others would appear to be no longer justified.	Here is one reference published recently: Holbrook and others (2006). There are some GPS studies available, but they were not used in this report. Mark Zoback also suggested a 1,000-yr recurrence interval at a recent EarthScope workshop.
17.	Ken Campbell	p. 28–29	The UK statistician, Mai Zhou, who was a member of the independent expert review panel, indicated to me during the review meeting that he did not see any problem with framing the PSHA integral the way that it is, even if the standard deviation of ground motion is a function of magnitude and/or distance, as long as this function of magnitude and/or distance was included in the analysis. So any statement to the contrary should be deleted.	See his review comments on the preliminary report.
18.	Ken Campbell	p. 28–29	There is no reference to studies (e.g., the recent Next Generation Attenuation of Ground Motions studies; Boore and others, 1997) that have concluded that the standard deviation of ground motion is not a significant function of magnitude. These newer studies should be reviewed and could possibly be used to justify a revision of the aleatory uncertainty model currently used to characterize ground motions in the central United States.	The way it is being modeled (finite source and global data), ground-motion uncertainty is a dependence of magnitude and distance.
19.	Ken Campbell	p. 31	The range of median PGA values from Table 5 is 0.69–1.20, not 0.46–1.20.	Revised.
20.	Ken Campbell	p. 34	The plot of the attenuation relationships in Figures 26–29 could be deceiving. For example, the plotted relationships do not all use the same distance measure and do not represent the same site conditions. If these differences were not taken into account, then the figure is incorrect and so too might be the estimates of ground motion from these relationships. If these differences were corrected for, then how were the corrections done? The relationship by Frankel and others (1996) is not that different from many of the other relationships in the distance range of 10–100 km, so I don't understand the statement to the contrary. Furthermore, the Frankel and others relationship represents NEHRP B site conditions and, using the USGS conversion factors, should be divided by 1.53 to represent the hard-rock site conditions for which estimates are sought.	All attenuations are for hard-rock sites. The distance is R_{RUP}. No distance conversion was done. Frankel's ground-motion values were corrected by the factor of 1.53.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
21.	Ken Campbell	p. 38	As mentioned in comment 2, Table 6 does not represent a true PSHA, since it does not include: (1) epistemic uncertainty in M_{CHAR} and M_{MAX}, (2) epistemic uncertainty in the location of faults and the boundaries of source zones, (3) aleatory uncertainty in the characteristic magnitude of the New Madrid faults or in the exponentially distributed magnitudes of the source zones, (4) aleatory uncertainty in the locations of earthquakes distributed within the source zones, and (5) epistemic uncertainty in recurrence parameters. It is really a pseudo-deterministic model, where the only uncertainty is the aleatory uncertainty in the estimation of ground motion.	See response to comment 2.
22.	Ken Campbell	p. 38	Why were the specific attenuation relationships selected for use in the study? For example, why was the Silva and others (2002) model chosen over the other three that he has developed and used to characterize epistemic uncertainty? Was the hard-rock or NEHRP B-C version of the Atkinson and Boore (2006) attenuation relationship used? Were differences in distance measures between the various relationships taken into account? Were differences in site classes between the various relationships taken into account?	All attenuations are for hard rock. The Silva and others (2002) model provides a reasonable value. Others represent different models (i.e., composite, double-corner, and hybrid).
23.	Ken Campbell	p. 38	I don’t see the justification for giving the 1,000-yr recurrence interval on the New Madrid Fault 25 percent weight. As mentioned before, this estimate is no longer considered to be valid and is contradicted by the latest paleoliquefaction studies.	See response to comment 16.
24.	Ken Campbell	p. 43	An estimated value of PGA from an estimated value of MMI at the Paducah Gaseous Diffusion Plant site for the February 7, 1812, earthquake using the simple relationship between PGA and MMI given by Bolt (1993) should not be used as justification for selecting a return period of 1,000 yr for determining design ground motions for the Paducah Gaseous Diffusion Plant site. New relationships between PGA and MMI, some developed specifically for the central United States, have been published and should also be reviewed and cited. Selecting an exceedance probability (or return period) should be based on other factors as well, such as whether the risk is acceptable for the particular facility and site and whether it conforms to relevant public policy guidelines.	A new reference (Atkinson and Kaka, 2007) was added.

Comment Number	Reviewer	Part of Document Referenced	Comment	Response
1.	Leon Reiter	General	At your request, I have reviewed the revised report on the Paducah facility by Zhenming Wang and Edward W. Woolery, and my comments follow. Similar to my review of the February 2007 draft report, I have employed the same general approach I found useful in reviewing many nuclear facilities and in the peer review of seismic-hazard analyses submitted to professional journals for publication. This general approach emphasizes clarity and technical justification for the methods used and the assumptions made. In general, the revised report represents an improvement over the draft report in that the controversial definitions of seismic hazard and risk and the use of a new methodology (SHA) have been omitted. Most of the comments in my review of the draft report are no longer relevant or have been addressed. However, my comments 3, 19, 22, 23, 25, 34, 35, and 38 have only been addressed partially, if at all, and they are relevant to my review of the revised report. The primary difference between the draft and revised report is the addition of a PSHA and a DSHA for the Paducah facility and the introduction of a two-level design basis. My comments on the new material in section 6 (Results) follow, along with some new specific comments on the rest of the report.	This report is not a typical site-specific seismic-hazard assessment, but a summary of scientific research on geological and seismological conditions, the methodologies, and the seismic-hazard assessment related to the Paducah Gaseous Diffusion Plant and the surrounding area. Therefore, it may be reviewed in a different way than a normal site-specific technical report. Comments 3, 19, 22, 23, 25, 34, 35, and 38 for the early version have also been addressed to some degree.

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2.	Leon Reiter	section 6 (Results)	It was not clear to me what are all the assumptions and input parameters behind the PSHA. Based on a May 25, 2007, e-mail exchange and subsequent telephone conversation with Dr. Wang, I draw the following conclusions. The New Madrid Seismic Zone, Wabash Valley Seismic Zone, and local source zones were the only ones considered in the analysis. Only one magnitude (M_{MAX}) for each source zone was used. Only one distance for each earthquake was used for each of the New Madrid and local source zones, while the earthquakes in the Wabash Valley Seismic Zone were allowed to occur anywhere within that zone. The New Madrid Seismic Zone allowed two different recurrence intervals for the controlling earthquake, while the Wabash Valley Seismic Zone and the local source zone allowed only one recurrence interval for each of the controlling earthquakes in each source zone. Four, and in one case three, different equally weighted ground-motion relationships were used, assuming the standard deviation determined by the originators of the relationships. Therefore, no uncertainty was assumed in the magnitude of controlling earthquakes, the location of these earthquakes in the New Madrid Seismic Zone and local source zone, the recurrence intervals for the controlling earthquakes in the Wabash Valley Seismic Zone and local source zone. Also, the effects of earthquakes smaller than M_{MAX} in each source zone were not taken into account. A typical PSHA would address these uncertainties. Although some of these omissions may, as Dr. Wang maintains, have little or no effect upon the results, this remains to be shown. Assumptions about the local source zone may have a larger than assumed effect, particularly for PGA. Other assumptions that need further proof include the lack of presence of the northeast extension of the New Madrid Seismic Zone and the choice of the four attenuation relationships. It would be very useful to those assessing the PSHA to have a better understanding of the bases for these assumptions and their importance. Sensitivity tests to different assumptions would be very helpful. Jim Beavers, in his May 25, 2007, e-mail to Dr. Wang, made a similar suggestion. Justification of some of the assumptions in the revised report by referral to the USGS studies is not necessarily a valid approach, because a seismic-hazard analysis for an individual nuclear facility site may require a higher level of justification than local seismic hazard extracted from a generalized nationwide study.	PSHA and DSHA in this report are not site-specific. The main purposes are to gain better understanding of the seismic-hazard assessment at the Paducah Gaseous Diffusion Plant and its surrounding area.

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3.	Leon Reiter	Results	The introduction of a two-level design basis represents a positive step. The choice of a 1,000-yr return period for ordinary structures seems to have a good basis. This is not as true for the use of the DSHA for important structures. The rationale behind the choice of the median plus one standard deviation and its correlation with the PSHA is important, and needs to be laid out. However, choice of design levels is not a seismological decision because it implies a certain level of risk acceptance, which is a social decision. Seismology is most useful when it provides the analysis that allows social decision-makers to make informed decisions.	It is true that "choice of design levels is not a seismological decision because it implies a certain level of risk acceptance, which is a social decision." But seismologists need to provide hazard information that can be understood. This is our main effort.
4.	Leon Reiter	Results	There is some confusion between the use of the terms "mean" and "median." Based upon my understanding of the revised report, the PSHA result is a mean because it represents the average of the weights applied. (Theoretically, it is still a mean, even if the uncertainties are underrepresented.) In the DSHA, the number used is the average of the medians, and, as far as I know, not what analysts intend when they use terms like "best estimate" or "mean." I suggest that the report identify this, as it does in some, but not all, tables (e.g., Tables 15 and E-3) as the average of the medians or the medians plus one standard deviation.	The median is only applied to each ground-motion attenuation relationship. The mean is used for all others.
5.	Leon Reiter	p. 2, Figure 1	Identify the location of the centers (0 km, 0 km) of the seismicity plots.	The map is schematic and cited from Stain and others (2003). No reference point was given.
6.	Leon Reiter	p. 4, third paragraph	This paragraph implies that the safe shutdown earthquake and the operating basis earthquake for nuclear power plants are only determined through DSHA. This is not true. The operating basis earthquake was always defined (10CFR Part 100, Appendix A) as "… that earthquake which could reasonably affect the plant site during the operation life of the plant…." 10CFR Part 100.23 states that "… uncertainties in defining the SSE must be addressed through an appropriate analysis such as PSHA or suitable sensitivity analyses." U.S. Nuclear Regulatory Commission Regulatory Guide 1.165 describes how PSHA can be used to determine the safe shutdown earthquake.	Although these terms originally had a clear meaning, they are confusing. All terms that could cause confusion have been deleted.
7.	Leon Reiter	p. 6, Figure 2	Why is this figure located here? As far as I can tell, it is only referred to on p. 28.	It is described on p. 5.

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8.	Leon Reiter	p. 8, first paragraph	The report's concern about the lack of a design earthquake fails to mention that McGuire (1995) not only mentions this concern, but also proposes a methodology (deaggregation) to address concern. Why isn't this discussed?	Deaggregation is an effort in PSHA to try to seek the "design earthquake." Revised.
9.	Leon Reiter	p. 8, second paragraph	Reiter (2004) does not appear in the list of references.	It is an abstract and was deleted from the references.
10.	Leon Reiter	p. 20, last paragraph	The report introduces two terms for essentially the same phenomenon (randomly occurring nearby earthquakes): "background seismicity" and "local source zone." It would be helpful if you made clearer the distinction and your use of these terms.	The manuscript has been revised to use the term "background seismicity" only.
11.	Leon Reiter	p. 28–29	What is the point of the discussion of the different source-to-site distance measures in the revised report? Is anyone suggesting the use of epicentral distance in the attenuation relationships? This discussion may be a leftover from the key arguments in the draft report about whether or not distance and magnitude are independent random variables. This is really not an important issue in the revised report.	There is a difference between epicentral and fault or other distances. This may be one of the areas in which PSHA needs to improve.
12.	Leon Reiter	p. 30, Figure 23	If the report does include this figure (see discussion above), the title should mention and explain the use of R_{EPI} and R_{RUP} in the figure.	R_{RUP} is used throughout this report (revised).
13.	Leon Reiter	p. 34, first paragraph	The final report states that ground motion at near-source has been overpredicted and references a USGS/NRC workshop in 2005 and Atkinson and Boore (2006). The USGS/NRC workshop does not appear in the list of references, and Figure 26 shows that at distances less than 10 km the Atkinson and Boore (2006) ground-motion relationship predicts higher ground motion than the other models used in the PSHA. The term "near source" needs to be clarified to justify the report's conclusion.	A CD of the workshop is available. Frankel and others (1996) only gave ground-motion values from 10 km and greater. Near-source means in this report 10–50 km.
14.	Leon Reiter	p. 34, second paragraph	The basis for picking the four attenuation relationships and excluding others (e.g., Frankel) needs to be presented.	These attenuation relationships represent different approaches (i.e., finite source/Green's function, double-corner, and hybrid methods).