Final Report: Seismic Hazard Assessment of the Paducah Gaseous Diffusion Plant Executive Summary

Technical Report · September 2015

2 authors:

Zhenming Wang
University of Kentucky

Edward Woolery
University of Kentucky

Final Report: Seismic Hazard Assessment of the Paducah Gaseous Diffusion Plant

Zhenming Wang

Kentucky Geological Survey
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, Kentucky 40506

Edward W. Woolery

Department of Earth and Environmental Sciences
309 Slone Research Building
University of Kentucky
Lexington, Kentucky 40506

June 2007

Executive Summary

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 Paducah Gaseous Diffusion Plant because of its proximity to several known seismic zones, particularly the New Madrid Seismic Zone. The issues in estimating seismic hazard are (1) the methods being used and (2) 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 what the hazard estimates at the Paducah Gaseous Diffusion Plant are. Three seismic sources (the New Madrid Seismic Zone, the Wabash Valley Seismic Zone, and the background seismicity) were identified and characterized. Four ground-motion attenuation relationships were used in this project. Probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA) were performed. A panel of six members, who are experts in geology, seismology, earthquake engineering, and statistics, provided a review of the report. The review comments and responses are included as appendices.

In PSHA, seismic hazard is defined as the annual probability of a ground motion being exceeded. The inverse of the annual probability of exceedance is defined as the return period. Therefore, seismic hazard is also defined as a 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. Figure E-1 shows the PGA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant calculated in this study. Table E-1 lists ground-motion hazards on hard rock for the Paducah Gaseous Diffusion Plant at several return periods.

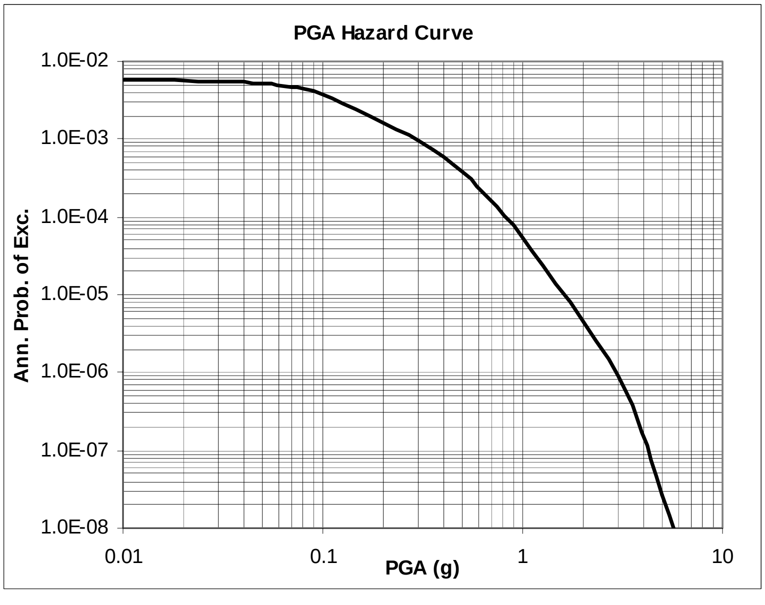


Figure E-1. PGA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant.

Table E-1. PSHA ground-motion hazards on hard rock at the Paducah Gaseous Diffusion Plant.

Ann. Prob. Exc.	Return Period (years)	Exc. Prob. in 50 years (%)	PGA (g)	0.2s PSA (g)	1.0s 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

In DSHA, seismic hazard is defined as the ground motion(s) from a single or several earthquakes that are expected to produce maximum values (impacts) at a site. DSHA emphasizes ground-motion hazard from an individual earthquake (scenario), such as the maximum credible earthquake (MCE) or maximum considered earthquake, and explicitly determines ground-motion hazard with a level of uncertainty. DSHA results show that the large earthquakes in the New Madrid Seismic Zone dominate the hazard at the Paducah Gaseous Diffusion Plant. Table E-2 lists ground-motion hazards estimated for the Paducah Gaseous Diffusion Plant from the large earthquakes in the New Madrid Seismic Zone. The return period for these ground motions is about 500 to 1,000 years.

Table E-2. DSHA ground-motion hazards on hard rock at the Paducah Gaseous Diffusion Plant.

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

Return period: 500 to 1,000 years

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 (Table E-2) from the large earthquake in the New Madrid Seismic Zone, whereas PSHA provides a range of ground-motion hazards (Fig. E-1) from all earthquakes being considered. Table E-3 lists recommended ground motions for engineering design consideration for facilities at the Paducah Gaseous Diffusion Plant. All the hazard estimates are on hard rock, and no amplification by the near-surface soils is considered in this report.

Table E-3. Recommended ground motions on hard rock at the Paducah Gaseous Diffusion Plant

Facility	DSHA	PSHA		PGA (g)	0.2s PSA (g)	1.0s PSA (g)
		Return Period (years)	Exc. Prob. in 50 years (%)			
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 of Contents

Executive Summary ……………………………………………………………….i
Table of Contents …………………………………………………………....iii
List of Figures ………..……………………………………….……………..iv
List of Tables ………………………………………………….……………..vi
1.0 **Introduction**…………………………………………………………...……1
2.0 **Methodology** ……………………………………………………………………4
  2.1 Probabilistic Seismic Hazard Analysis ……….……………………………4
  2.2 Deterministic Seismic Hazard Analysis ……………..………………….....10
3.0 **Seismic Sources** ……………………………………………………………..12
  3.1 New Madrid Seismic Zone ……………………………………………..12
  3.2 Wabash Valley Seismic Zone …………………………………………...17
  3.3 Background Seismicity ……...……………………………………….…21
4.0 **Magnitude – Recurrence Relationship** ………………………………………24
  4.1 New Madrid Seismic Zone ……………………………………………..24
  4.2 Wabash Valley Seismic Zone …………………………………………..26
  4.3 Local Source Zone ………..………………………………………….…26
5.0 **Ground-Motion Attenuation Relationship** ……………………………….……29
6.0 **Results** ……………………………………………………………………….38
  6.1 **PSHA Results**……………………………………………………..39
  6.2 **DSHA Results**……………………………………………………..41
7.0 **Conclusion and Recommendation**……………………….........................43
8.0 **References** ……………………………………………………………….46
9.0 **Appendix A** …………………………………………………………...A-1
10.0 **Appendix B** ………………………………………………………....B-1
11.0 **Appendix C** ………………………………………………………....C-1
12.0 **Appendix D** …………………………………………………….......D-1

List of Figures

Figure 1. Earthquakes with magnitude 5 or greater since 1900 in California and the New Madrid Seismic Zone 2
Figure 2. Ground-motion attenuation relationship 6
Figure 3. Hazard curve at a site 40 km from the source for a characteristic earthquake of M7.7 with a recurrence time of 500 years in the New Madrid Seismic Zone. The median ground motion (μ) is 0.36g, and the standard deviation ($\sigma_{\ln}$) is 0.60. $\varepsilon=(\ln y - \ln \mu)/\sigma_{\ln}$ 7
Figure 4. PGA hazard curves showing the effect of ground-motion uncertainty 9
Figure 5. PGA hazard curves from the Yucca Mountain project (Abrahamson and Bommer, 2005) 10
Figure 6. Seismicity between 1974 and 2005 in the central United States 13
Figure 7. New Madrid faults. Pseudo-faults (red) were used in the 1996 and 2002 USGS seismic hazard maps 15
Figure 8. Bouguer gravity anomaly and 1974–94 earthquake epicenters and the New Madrid Rift Complex 16
Figure 9. Dense seismic network and earthquakes recorded between January 2003 and June 2005 in the Jackson Purchase Region 17
Figure 10. Epicentral locations of the damaging earthquakes in the Wabash Valley Seismic Zone 19
Figure 11. Earthquakes and faults in the lower Wabash Valley 20
Figure 12. New Madrid and Wabash Valley Seismic Zone 21
Figure 13. Seismic sources that were considered in the national seismic hazard maps ... 22
Figure 14. Background earthquakes (M_{max}) used in the national seismic hazard maps ... 22
Figure 15. Maximum background earthquakes in Kentucky 23
Figure 16. Magnitude-frequency relationship in the New Madrid Seismic Zone 25
Figure 17. Magnitude-frequency (Gutenburg-Richter) curve for the New Madrid Seismic Zone. Diamond–historical rate, triangle–geological rate 25
Figure 18. Magnitude-frequency relationship in the Wabash Valley Seismic Zone 27
Figure 19. Magnitude-frequency (Gutenburg-Richter) curve for the Wabash Valley Seismic Zone. Diamond–historical rate, triangle–geological (paleoliquefaction) rate 27
Figure 20. Recorded earthquakes with magnitude greater than 2.5 surrounding PGDP between 1978 and 2006 28
Figure 21. Magnitude-frequency (Gutenburg-Richter) curve for the local source 28
Figure 22. Horizontal uncorrected PGA vs. distance to the fault for the Parkfield earthquake of September 28, 2004 30
Figure 23. Strong-motion stations and accelerograms recorded in the 2004 M6.0 Parkfield earthquake, for the east-west component 31
Figure 24. Magnitude-distance-region distribution of selected recordings 33
Figure 25. Log values of horizontal component 5% pseudo-acceleration at frequencies 0.5, 1, and 5 Hz, and PGA, for ENA rock sites. 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 34

Figure 26. PGA attenuation relationships at hard rock for an M7.5 earthquake in the central United States 36
Figure 27. PGA attenuation relationships at hard rock for an M5.0 earthquake in the central United States 36
Figure 28. The 0.2s PSA attenuation relationships used in this study at hard rock for an M7.5 earthquake in the central United States 37
Figure 29. The 1.0s PSA attenuation relationships used in this study at hard rock for an M7.5 earthquake in the central United States 37
Figure 30. Seismic sources for the Paducah Gaseous Diffusion Plant 38
Figure 31. PGA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant 40
Figure 32. The 0.2s PSA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant 40
Figure 33. The 1.0s PSA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant 41
Figure 34. Isoseismal map of the February 7, 1812, New Madrid earthquake 45

List of Tables

Table 1. Comparisons between California and western Kentucky 2
Table 2. Parameters of earthquakes 16
Table 3. Damaging earthquakes in the Wabash Valley Seismic Zone 18
Table 4. Earthquakes with magnitude equal to or greater than M4.0 in the New Madrid Seismic Zone 26
Table 5. Median ground motions for an M7.7 New Madrid earthquake at 15 km for a hard-rock site from several attenuation relationships 32
Table 6. Input parameters and weights being used in PSHA for PGDP 39
Table 7. Ground-motion values on hard rock at PGDP 39
Table 8. Median PGA on hard rock at the Paducah Gaseous Diffusion Plant from the three seismic sources 42
Table 9. PGA at the Paducah Gaseous Diffusion Plant from the characteristic earthquake in the New Madrid Seismic Zone..42
Table 10. The 0.2s PSA at the Paducah Gaseous Diffusion Plant from the characteristic earthquake in the New Madrid Seismic Zone..42
Table 11. The 1.0s PSA at the Paducah Gaseous Diffusion Plant from the characteristic earthquake in the New Madrid Seismic Zone..42
Table 12. Ground-motion hazards on hard rock at the Paducah Gaseous Diffusion Plant determined by PSHA 43
Table 13. Ground-motion hazards on hard rock at the Paducah Gaseous Diffusion Plant determined by DSHA 43
Table 14. Recommended ground motions on hard rock at the Paducah Gaseous Diffusion Plant 44
Table 15. Comparison of mean PGA estimates on hard rock at the Paducah Gaseous Diffusion Plant determined from PSHA. 45

1.0. 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 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 motions with 2 percent probability of exceedance (PE) in 50 years. These maps predict very high ground motion in many counties in western Kentucky: peak ground acceleration (PGA) of 1.0g or higher. These high ground-motion estimates affect everything in western Kentucky from building a single-family home to environmental clean-up at the Superfund site of 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 PE in 50 years are considered. The Structural Engineers Association of Kentucky (SEAOK, 2002) also 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.

Figure 1 shows schematic comparison of seismic hazard for the New Madrid Seismic Zone and southern California on two time scales in California and the central United States (Stein and others, 2003). The 2000 International Building Code (IBC-2000) (ICC, 2000), based on the 1996 USGS maps with 2 percent PE in 50 years, requires a design PGA of about 0.6g in Paducah and about 0.8g at the Paducah Gaseous Diffusion Plant. Currently, the highest building-design PGA used in California (UBC-97) is capped at about 0.4g. These high design ground motions for western Kentucky are not consistent with the level of seismic activity. Although earthquakes are occurring in Kentucky and surrounding states, especially in the well-known New Madrid Seismic Zone where at least three large earthquakes (M7.0–8.0) occurred in 1811–1812, earthquake recurrence rates are much lower in the region than in California, the Pacific Northwest, and Alaska. Table 1 compares the basic geological and seismological observations and design PGA in California and western Kentucky. These comparisons clearly show that the higher design ground motion in 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 at the Paducah Gaseous Diffusion Plant and its surrounding area, and to communicate the hazard information more effectively to the users and policy makers. In order to achieve these objectives, the following tasks were established: 1) micro-seismicity observation in Paducah area, 2) thorough literature review, 3) seismic source characterization, 4) probabilistic seismic hazard analysis

(PSHA), 5) deterministic seismic hazard analysis (DSHA), 6) preliminary report, 7) panel review, and 8) final report (see **Appendix A**). The focus of this project is on reviewing the methodology and data used by the U.S. Geological Survey because of the broad implication of the U.S. Geological Survey's seismic hazard assessments. As a result, a series of activities was carried out, including workshops, professional conferences and publications, and personal meetings and communications (Wang, 2003a and b, 2005a, b, c, and d, 2006a and b, in press; Wang and others, 2003a and b, 2004a and b, 2005; Cobb, 2004, 2006; Wang and Ormsbee, 2005).

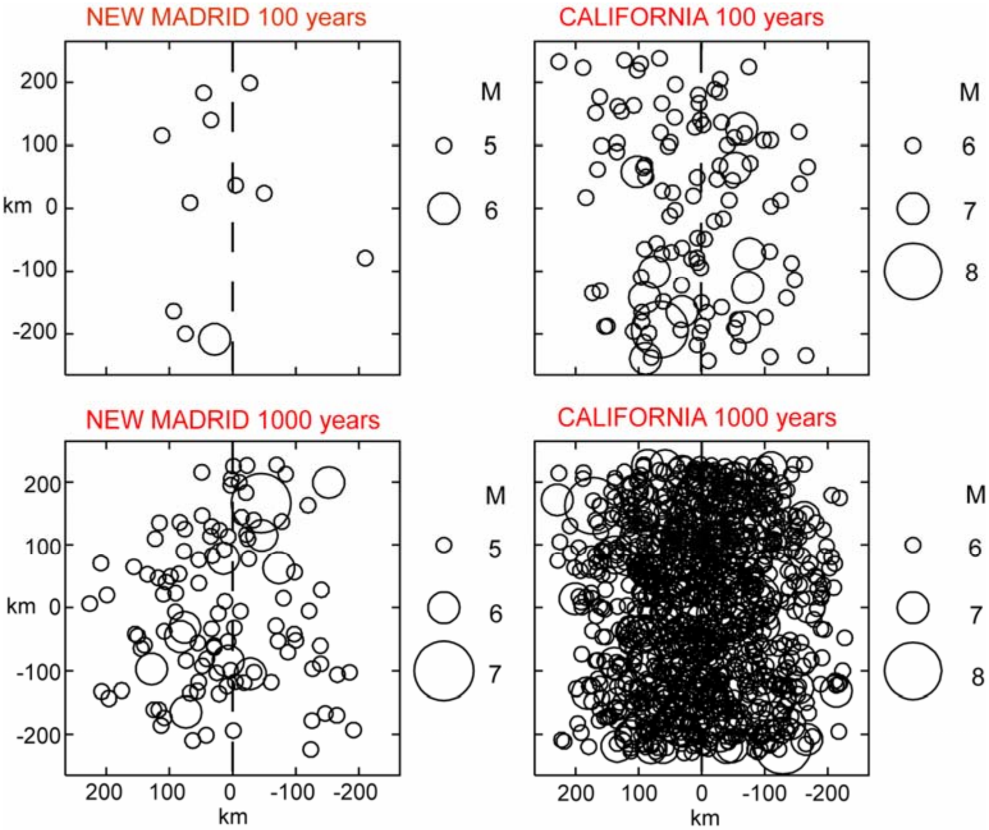


Figure 1. Schematic comparison of seismic hazard for the New Madrid Seismic Zone and southern California on two time scales. Circles marks area of shaking with acceleration > 0.2g (Stein and others, 2003).

Table 1. Design ground motion, geology, and seismicity comparisons between California and western Kentucky.

	California		Western Kentucky	
Design PGA	≤0.4g (UBC97)	≤0.7g (CALTRAN)	≥0.4g (IBC-2000)	≥0.6g (bridge)
Geology	San Andreas Fault Displacement≥20 mm/y		New Madrid Fault Displacement≤2 mm/y	
Seismicity	High M7–8: ~100y M6–7: ~20-50y		Low M7–8: ~500y or longer M6–7: ?	

A review panel consisting of national and international experts on geology, seismology, engineering seismology, and engineering was formed to review a preliminary report that summarized the results from tasks 2) through 5). A statistician was added to the review panel under the suggestion of members of the panel. **Appendix B** lists members of the review panel. The review was divided into two parts, individual review (three days) and panel review (one day) in Lexington. The preliminary report was submitted to the members in late February 2007 for the individual review. The written comments provided by the members on the preliminary report and responses are included in this report as **Appendix C**. Consequently, a panel review meeting was held on April 30, 2007 in Lexington, Kentucky, to discuss the preliminary report with focus on 1) ground-motion attenuation relationship – uncertainty, dependency, and hazard calculation in PSHA, 2) seismic hazard analysis (SHA) – temporal and spatial measurements, uncertainties, and quantification, and 3) seismic hazard assessment for PGDP – 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. These include:

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

The recommendations from the review panel at the meeting on April 30, 2007 were:

1. to perform a PSHA with some discussions for improvements,
2. to perform a DSHA,
3. to revise the local source zone.

A draft final report was completed according to the recommendations and sent to the members of the review panel for final review on May 11, 2007. Comments on the draft final report from members of the review panel are included in **Appendix D**. **Appendix D** also includes the responses to the members' comments.

2.0. Methodology

Two methods, probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA), are commonly used for seismic-hazard assessment. PSHA and DSHA follow similar steps in estimation of seismic hazard (Reiter, 1990; Kramer, 1996):

1. Determination of earthquake sources
2. Determination of earthquake occurrence frequencies by selecting controlling earthquake(s): the maximum magnitude, maximum credible, or maximum considered earthquake
3. Determination of ground-motion attenuation relationships
4. Determination of seismic hazard.

The differences between PSHA and DSHA are in step (4), on how to define and calculate seismic hazard.

In PSHA, seismic hazard is defined as the annual probability of a ground motion being exceeded at a site (National Research Council, 1988; SSHAC, 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. PSHA 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 parameter, path, and site condition) (Cornell, 1968, 1971). The end results from PSHA are seismic hazard curves: a relationship between a ground-motion parameter (i.e., peak ground acceleration [PGA], peak ground velocity [PGV], and response acceleration at certain periods) and its annual probability of exceedance or return period.

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

2.1. PSHA

PSHA was originally developed to derive theoretical ground-motion hazard curves at a site where there are not 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). The objective of PSHA is to derive theoretical ground-motion hazard curves for a site (Cornell, 1968, 1971). According to Cornell (1968, 1971) and McGuire (1995, 2004), the heart of PSHA is

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

where v is the activity rate, $f_M(m)$ and $f_R(r)$ are the probability density function (**PDF**) 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. $f_M(m)$ and $f_R(r)$ were introduced to account for the uncertainty of earthquake magnitude and distance, respectively (Cornell, 1968, 1971; McGuire, 2004). 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; EPRI, 2003; Atkinson and Boore, 2006). Ground motion Y is generally modeled as a function of M and R with uncertainty E (capital epsilon):

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

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; EPRI, 2003; Atkinson and Boore, 2006). In other words, 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 **PDF** of E. The exceedance probability $P[Y \geq y]$ is

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

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

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

where $\ln y_{mr}=f(m,r)$. Therefore, we have equation (1), the heart of PSHA (Cornell, 1968, 1971; McGuire, 1995, 2004).

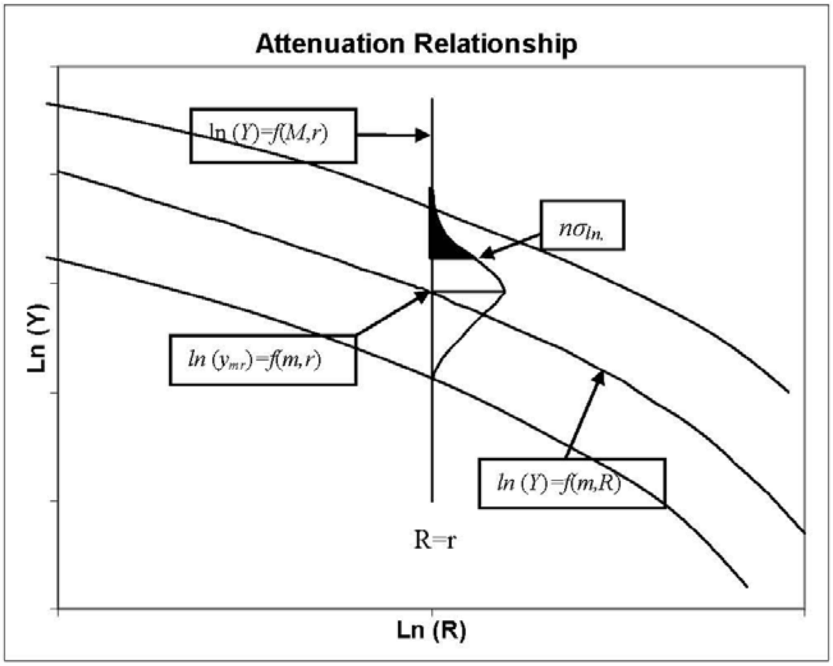


Figure 2. Ground-motion attenuation relationship.

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

$$T_{rp}(y) = \frac{1}{\gamma(y)} = \frac{1}{\sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dmdr}. \qquad (7)$$

If all seismic sources are characteristic, the return period is

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

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

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

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

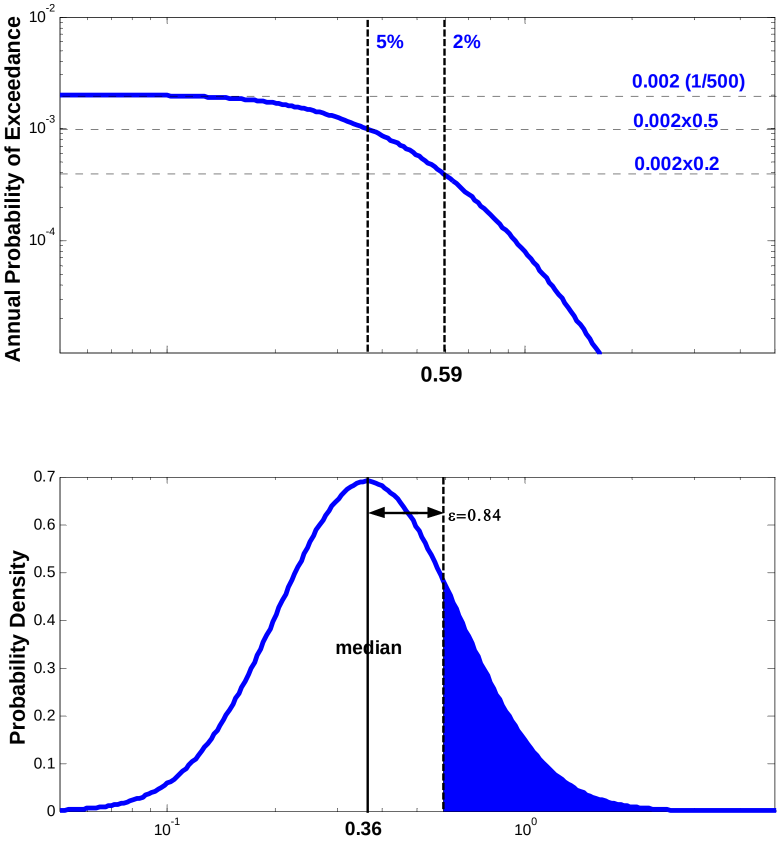


Figure 3. Hazard curve at a site 40 km from the source for a characteristic earthquake of **M**7.7 with a recurrence time of 500 years in the New Madrid Seismic Zone. The median ground motion (μ) is 0.36g, and the standard deviation ($\sigma_{\ln}$) is 0.60. $\varepsilon = (\ln y - \ln \mu)/\sigma_{\ln}$ (Wang and others, 2005).

The main purpose of PSHA is to directly incorporate uncertainty in earthquake size, frequency, location, and ground-motion. As demonstrated above, ground-motion uncertainty is implicitly incorporated and becomes an integral part of PSHA. 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 (SSHAC, 1997). These implicit and explicit incorporations of the uncertainty also have disadvantages, however. One such disadvantage, recognized by the first thorough review of PSHA by the committee chaired by Aki (National Research Council, 1988), is that the individual earthquake (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 term, by a magnitude 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 (de-aggregation) to seek the "design earthquake."

Another disadvantage 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, 2003b, 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 (10g PGA or higher) if a long return period (100,000,000 years) 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 11g would be the result at the nuclear waste repository site in Yucca Mountain, Nev., if a return period of 100,000,000 years is considered (Abrahamson and Bommer, 2005). A significantly higher ground motion would have to be considered in re-evaluation of the nuclear power plants in Switzerland if a return period of 10,000,000 to 100,000,000 years is considered (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).

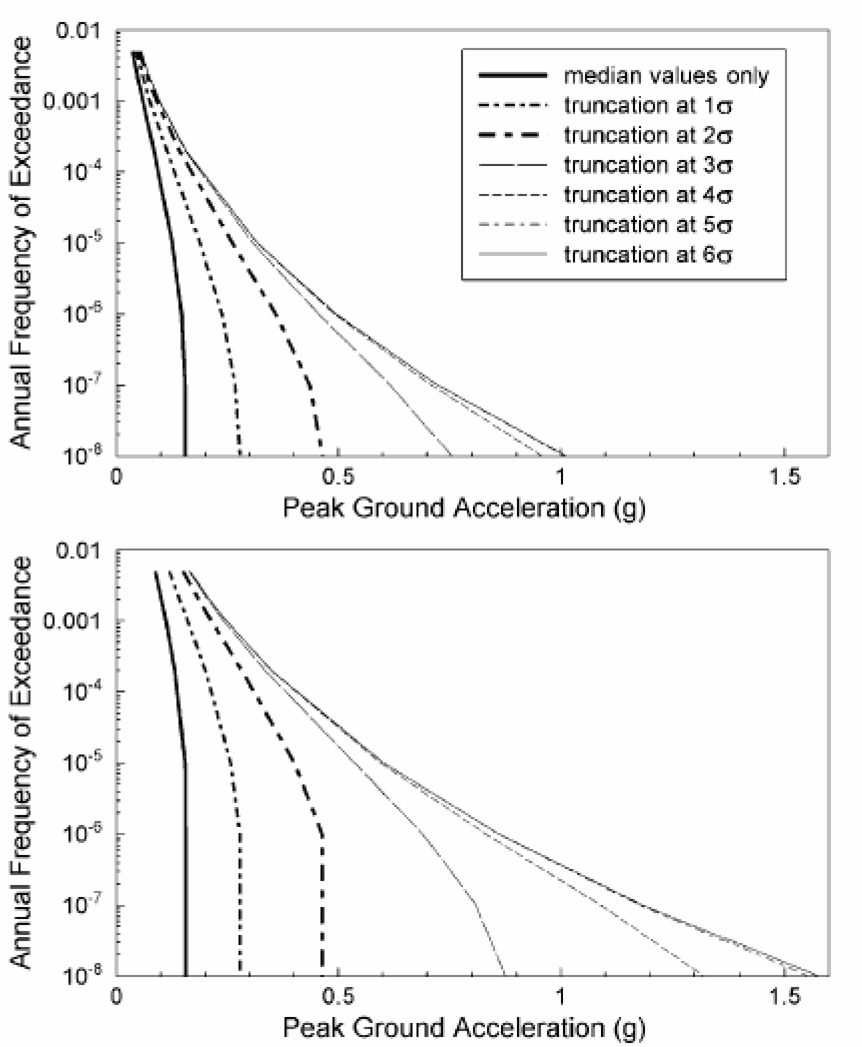


Figure 4. PGA hazard curves showing the effect of ground-motion uncertainty (Bommer and Abrahamson, 2006).

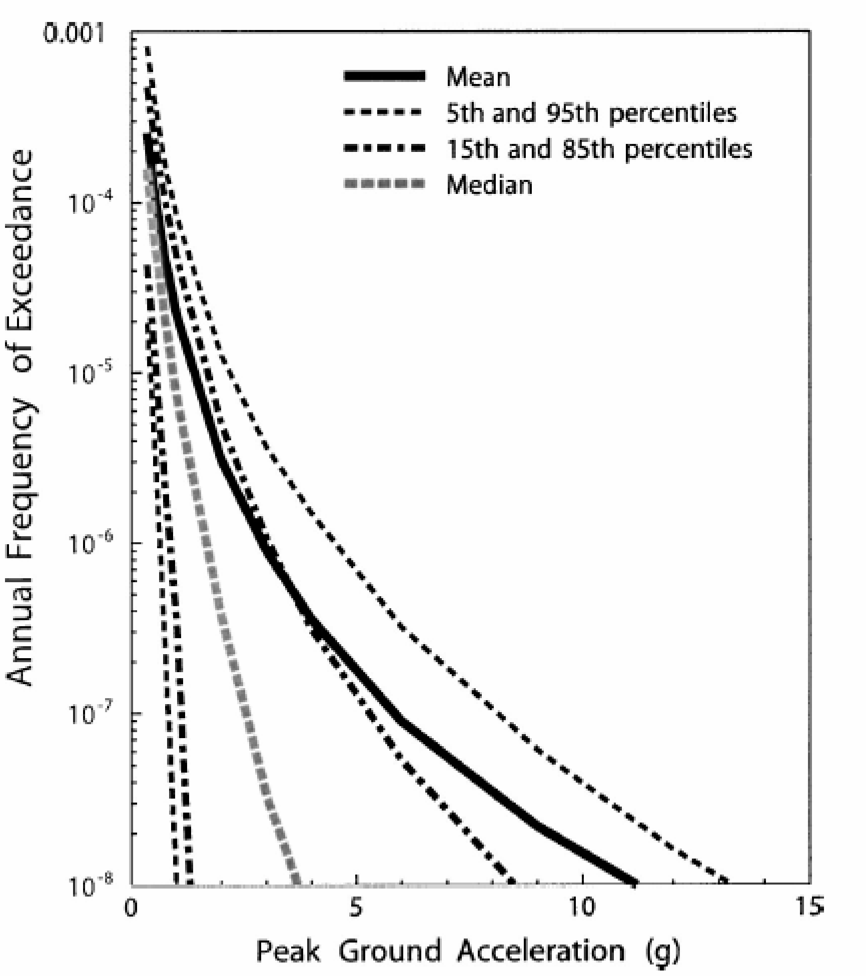


Figure 5. PGA hazard curves from the Yucca Mountain project (Abrahamson and Bommer, 2005).

2.2. DSHA

As discussed earlier, there is a fundamental difference between PSHA and DSHA in how to define and calculate seismic hazard. DSHA emphasizes the ground motion from an individual earthquake, such as the maximum credible earthquake and maximum probable earthquake. The steps outlined in Reiter (1990) and Krinitzsky (1995, 2002) are herein used 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 the results from DSHA. The advantages of DSHA are 1) "an easily understood and transmitted method of estimating seismic hazard" and 2) "clear to the analyst (earth scientist), the user (engineer) and those elements of the general public who are interested 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). The other disadvantage is that “frequency of occurrence is not explicitly taken into account” (Reiter, 1990). In other words, DSHA does not carry 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.” The plausible deterministic earthquakes are always associated with a recurrence interval, so in this sense DSHA actually does carry a unit of time (Wang and others, 2004).

3.0. 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 (EPRI, 1988; Bernreuter and others, 1989; REI, 1999; Geomatrix Consultants Inc., 2004). Seismic source zones considered in this study are discussed below.

3.1. New Madrid Seismic Zone

3.1.1. *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 those events in southeastern Missouri between New Madrid and Charleston, Mo., 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 can be seen 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 (Mchar) 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)."

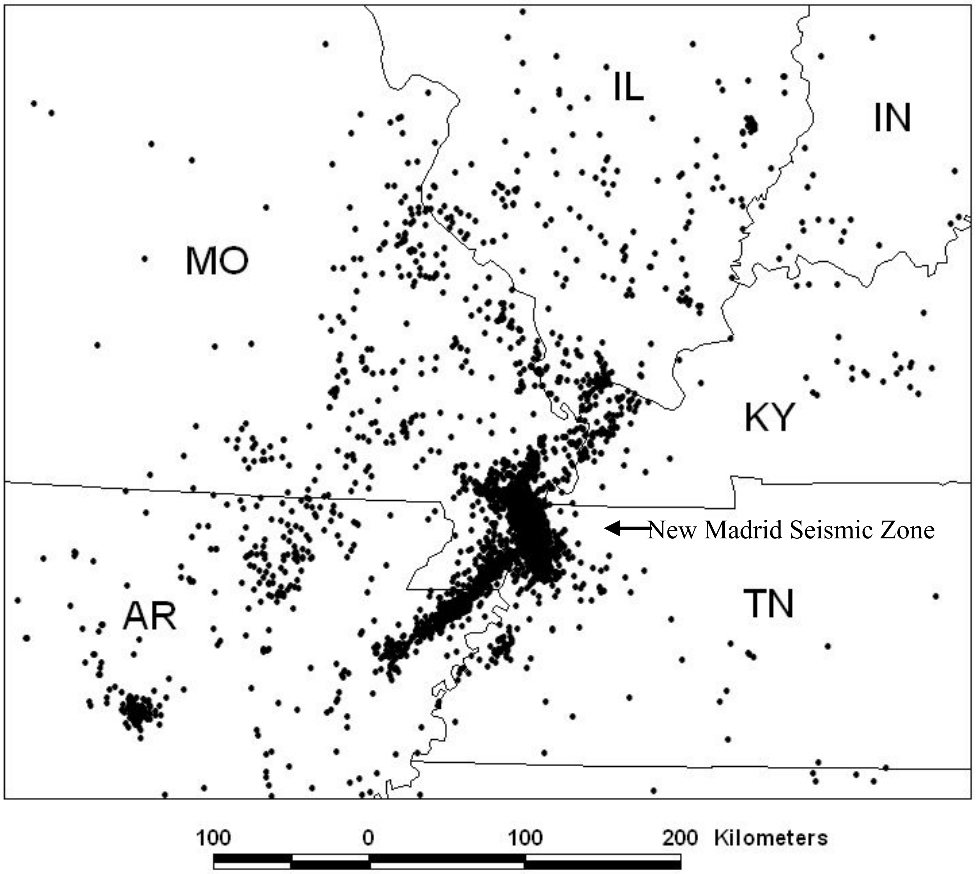


Figure 6. Seismicity between 1974 and 2005 in the central United States.

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; REI, 1999), consistent geologic and seismologic evidence indicate 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 epicenters 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 northeast 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 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 (<11,000 years) displacement along previously interpreted faults underlying the site (William Lettis & Associates Inc., 2006). Thus, no geologic evidence suggests 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).

3.1.2. *Maximum Magnitude*

The other large uncertainty for the New Madrid Seismic Zone is the estimate of the maximum magnitude. A single moment magnitude of **M**8.0 was used in the 1996 national maps (Frankel and others, 1996), whereas an Mchar 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 **M**7.2 to 7.5. GPS observations also suggest a similar magnitude (~**M**7) (Newman and others, 1999, Calais and others, 2006).

Although the uncertainties in the locations of the New Madrid faults and the associated maximum magnitude are large, there is a general agreement among scientists that the location of the New Madrid faults outlined by Johnston and Schweig (1996) is more appropriate for seismic hazard assessment (Cramer, 2004; Geomatrix Consultants Inc., 2004; Windeler, 2006). Recent studies also suggest that the maximum magnitude for the New Madrid Seismic Zone is 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 site (PGDP) and the New Madrid faults (blue lines) are much shorter than the one between the site and the faults (red lines) used in the national hazard maps (Frankel and others, 1996, 2002).

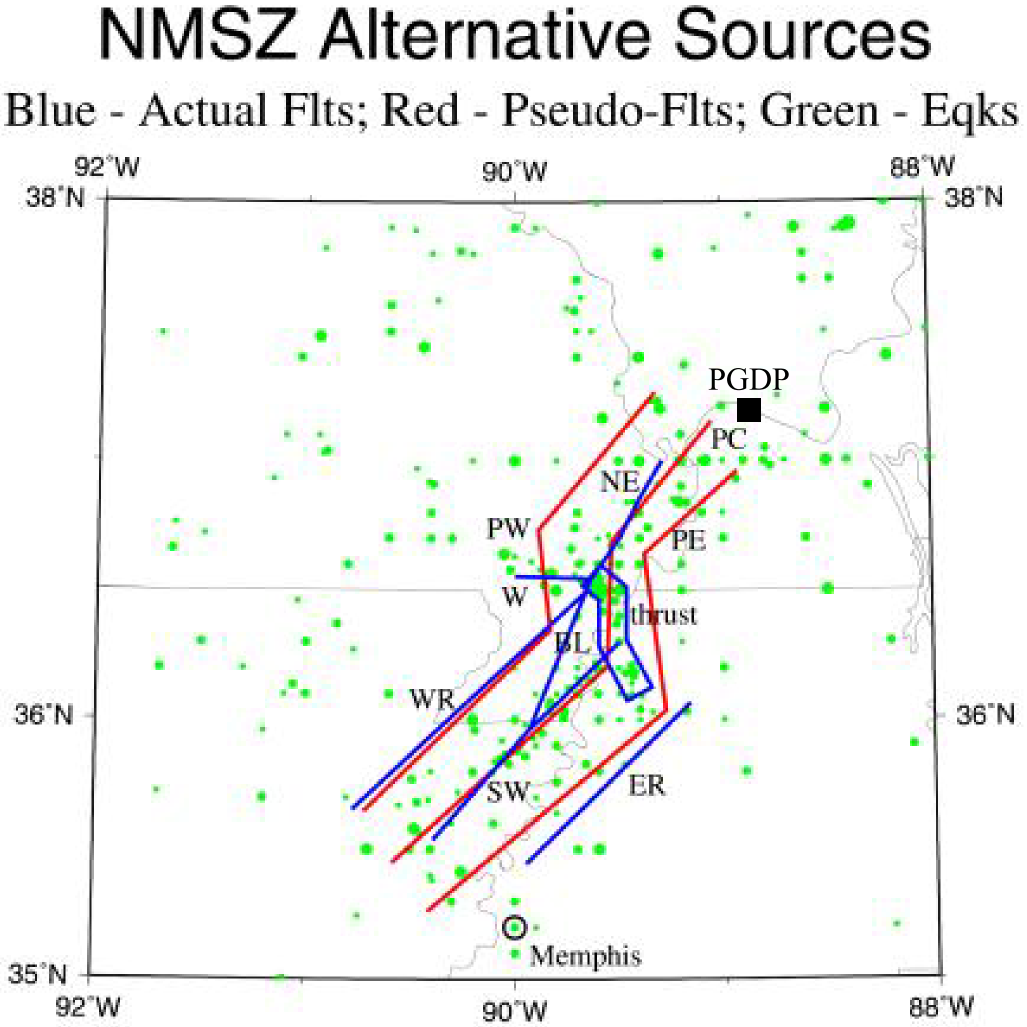


Figure 7. New Madrid faults (Cramer, 2004). Pseudo-faults (lines in red) were used in the 1996 and 2002 USGS seismic hazard maps (Frankel and others, 1996, 2002).

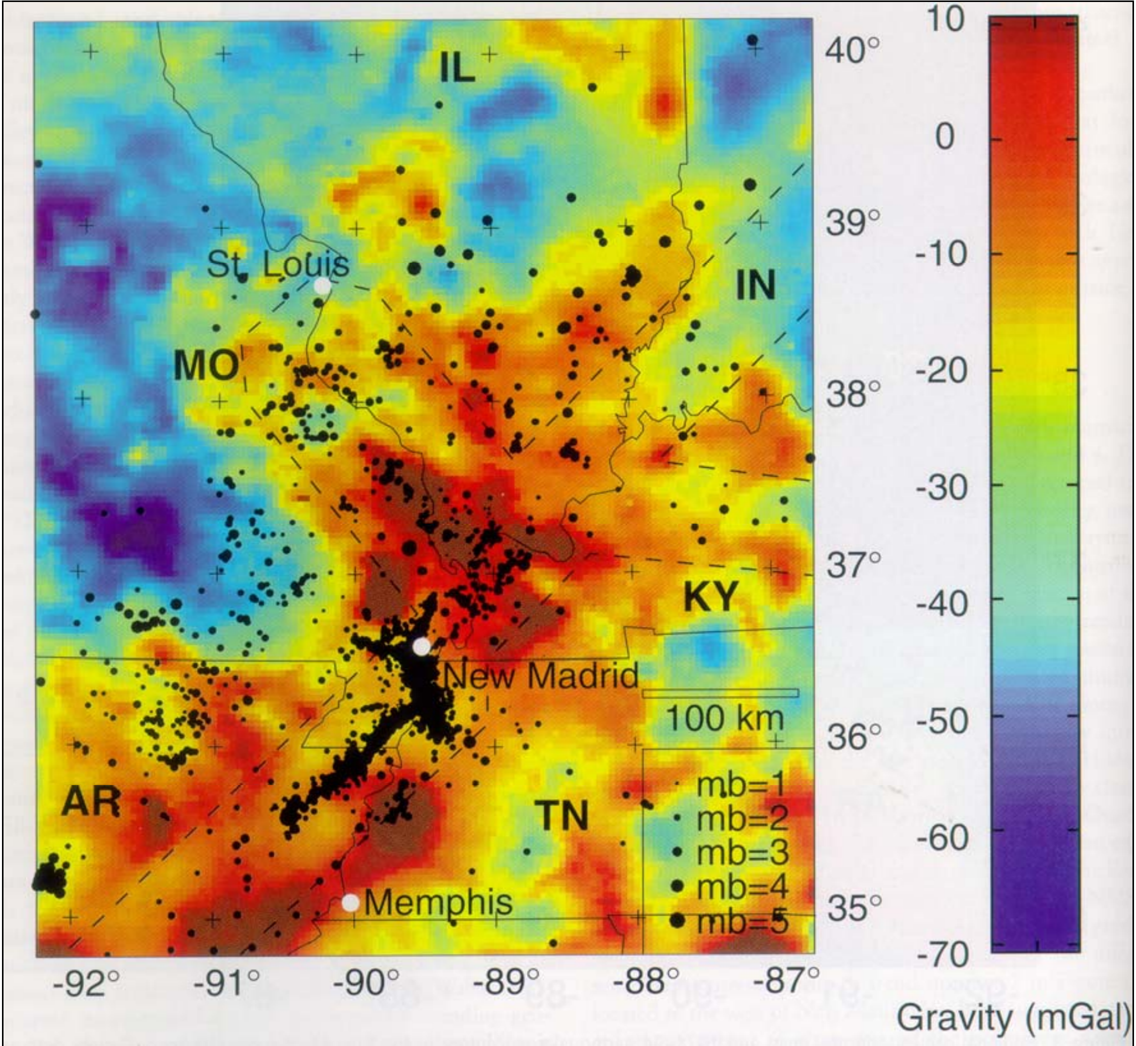


Figure 8. Bouguer gravity anomaly and 1974–94 earthquake epicenters and the New Madrid Rift Complex (Braile and others, 1997).

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

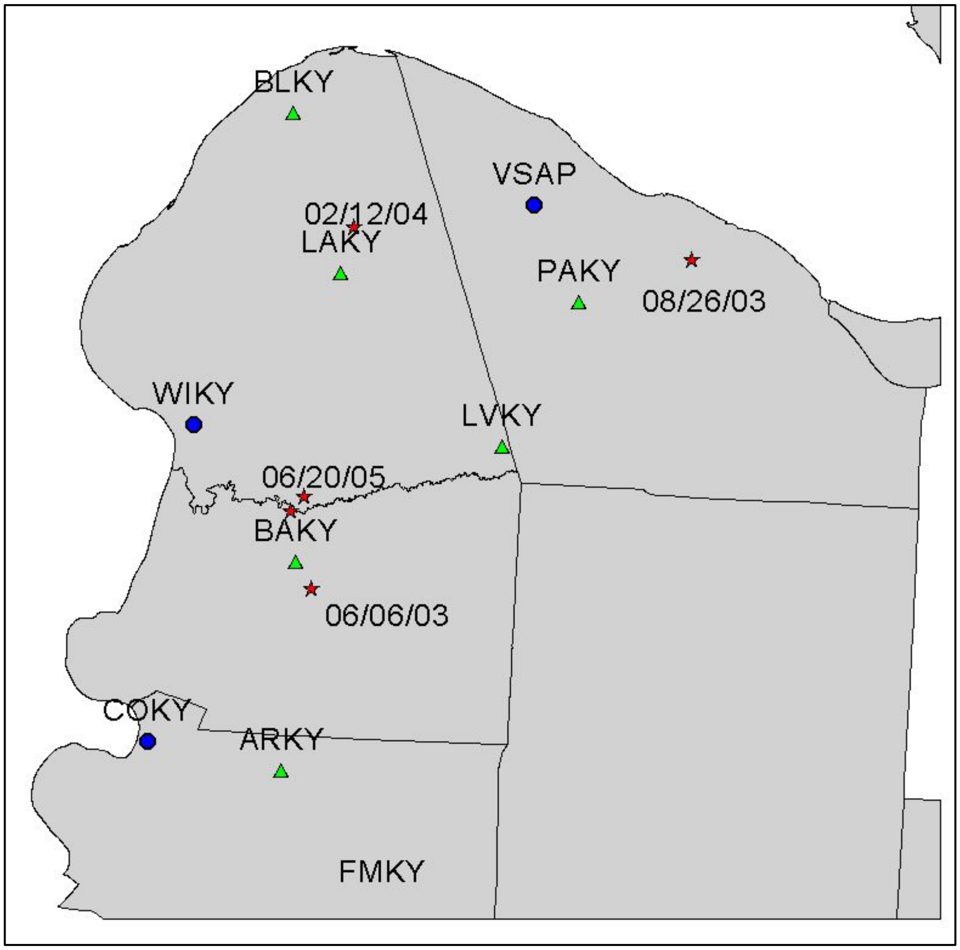


Figure 9. Seismic network and earthquakes (stars) recorded between January 2003 and June 2005 in the Jackson Purchase Region (Anderson and others, 2005). Triangle – short-period seismic station; Circle – strong motion station.

3.2. 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 ≥5 $m_{b,Lg}$ earthquakes in the area between 1875 and 1975, and (3) the presence of the 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 (MMI≥VI) earthquakes in the seismic zone (Stover and Coffman, 1993) and the location of the 5.1 $m_{b,Lg}$ September 27, 1909, earthquake (10) that occurred just north of the seismic zone. Dates, times, and epicentral locations of the damaging earthquakes 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, there has never been an adequate number of permanent seismic stations in the seismic zone 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 that their focal depths and focal mechanisms could be estimated using the radiation pattern of their Rayleigh and Love waves (Herrmann and Ammon, 1997).

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

Event No.	Date (Mo-Day-Yr)	Time (GMT)	Lat./Long. (°N/°W)	Magnitude $m_{b,Lg}$[1]	M_w[2]	Depth[3] (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.

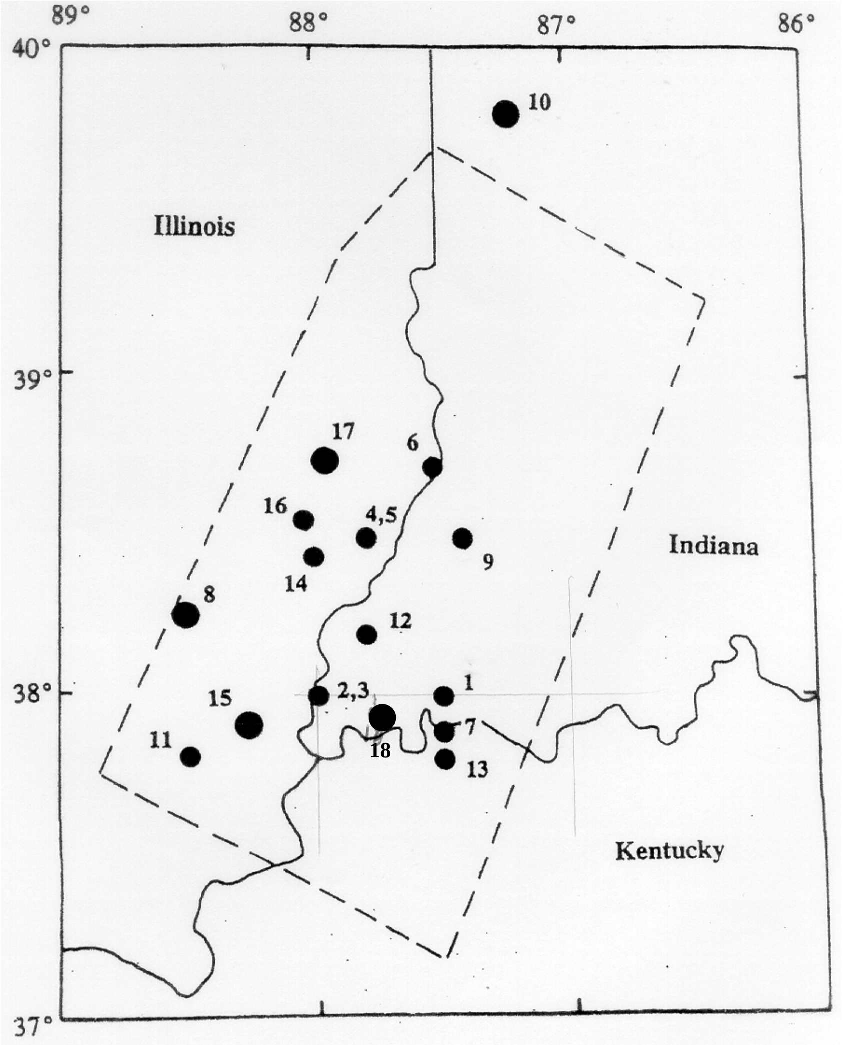


Figure 10. Epicentral locations of the felt earthquakes in the Wabash Valley Seismic Zone.

The largest instrumentally recorded historical earthquake in the Wabash Valley Seismic Zone is the November 9, 1968, earthquake (event 15 in Table 3). McBride and others (2002) believed that the November 9, 1968, earthquake occurred as a result of the 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 (M4.6) was well located (Table 3). Kim (2003) also believed that the June 18, 2002, earthquake occurred as a result of the 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-Pillipstown and the 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) as exhibiting 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 non seismogenic. Woolery (2005) found that the Hovey Lake Fault (one of the Wabash Valley faults) moved as late as approximately 37,000 years before the present.

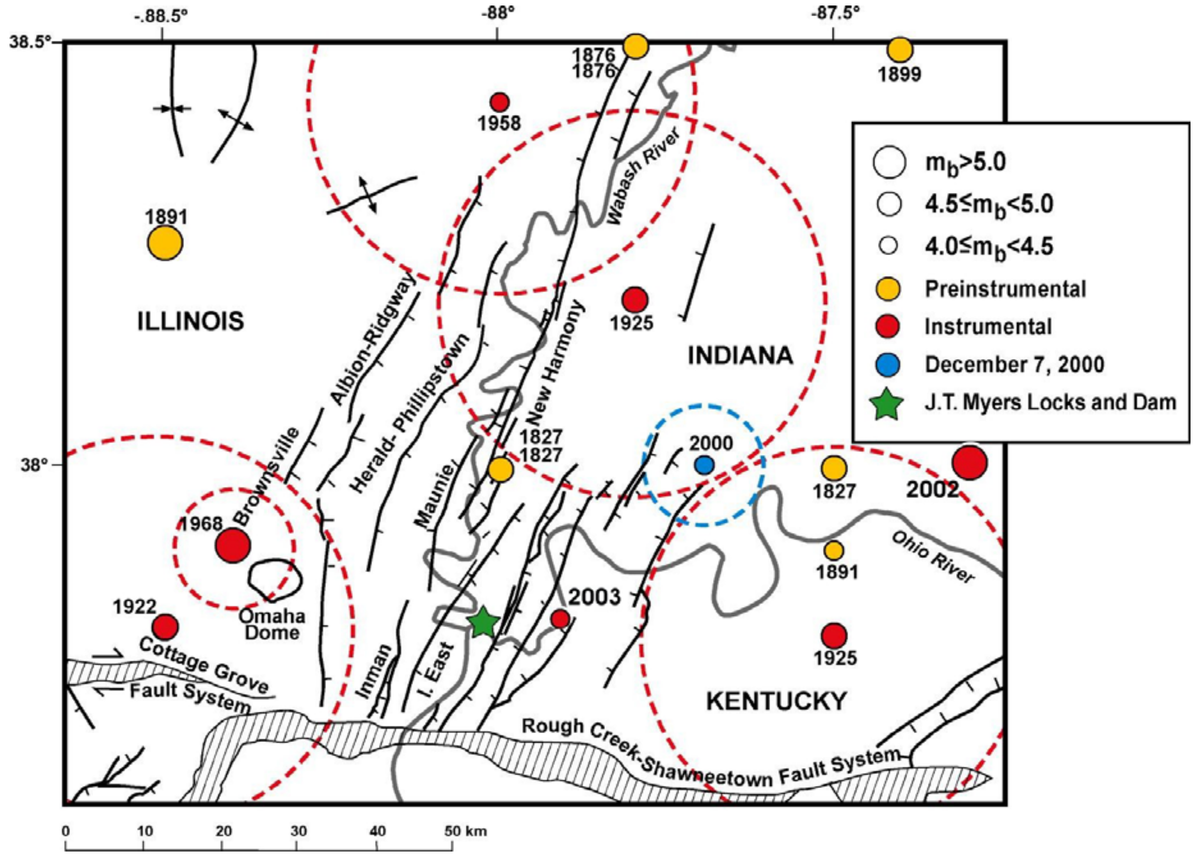


Figure 11. Earthquakes and faults in the lower Wabash Valley.

As discussed above, there is no clear evidence to directly link any of the earthquakes in the Wabash Valley Seismic Zone to a specific fault. Thus, the Wabash Valley Seismic Zone was treated as an areal source in the seismic hazard analyses (Frankel and others, 1996, 2002; Wheeler and Frankel, 2000). The maximum magnitude of M7.5 was assigned to the zone in the national seismic hazard maps (Frankel and others, 1996, 2002; Wheeler and Frankel, 2000), and was 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 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 M6.8 to the Wabash Valley Seismic Zone (Fig. 12) based on these studies (Street and others, 2004; Olson and others, 2005).

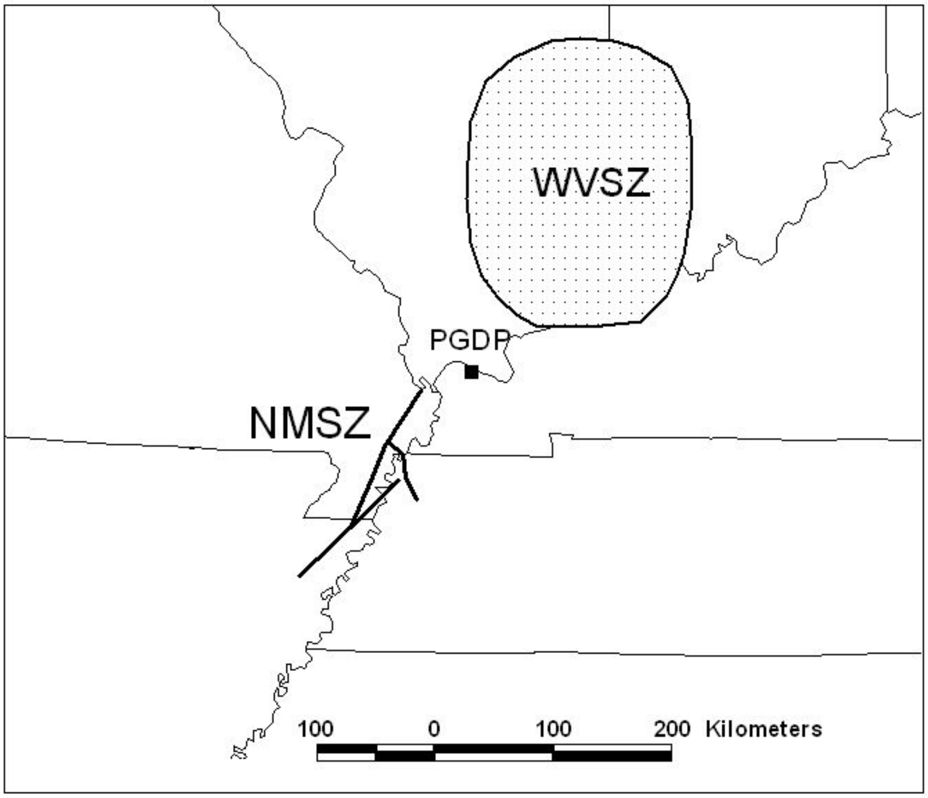


Figure 12. New Madrid faults and Wabash Valley Seismic Zone.

3.3. 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 ($m_{b,Lg}$4.0) in central Kentucky is not associated with any known seismic zone. Many earthquakes were recorded by the University of Kentucky Seismic and Strong-Motion Network since 1984 (Street and Wang, 2003). These earthquakes were called background seismicity (Street and others, 1996). Contribution to seismic hazard from the background seismicity was considered with 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 the large earthquakes in the central and eastern United

States (Frankel and others, 1996, 2002). Although magnitude is large (M7.0 and 7.5), the large background earthquakes have no contribution to the seismic hazard because of (1) a large-area source zone and (2) a longer recurrence interval (more than 10,000 years) in the national seismic hazard maps (Wang, 2003). Therefore, the use of these large background earthquakes is not necessary (Wang, 2003).

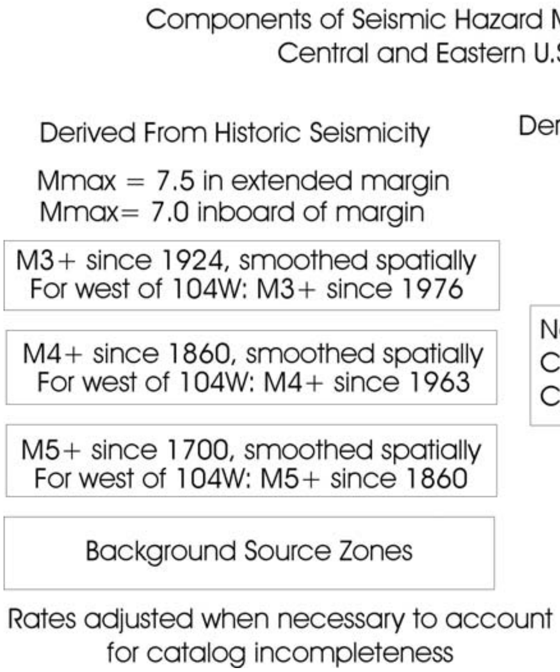


Figure 13. Seismic sources that were considered in the national seismic hazard maps (Frankel and others, 2002).

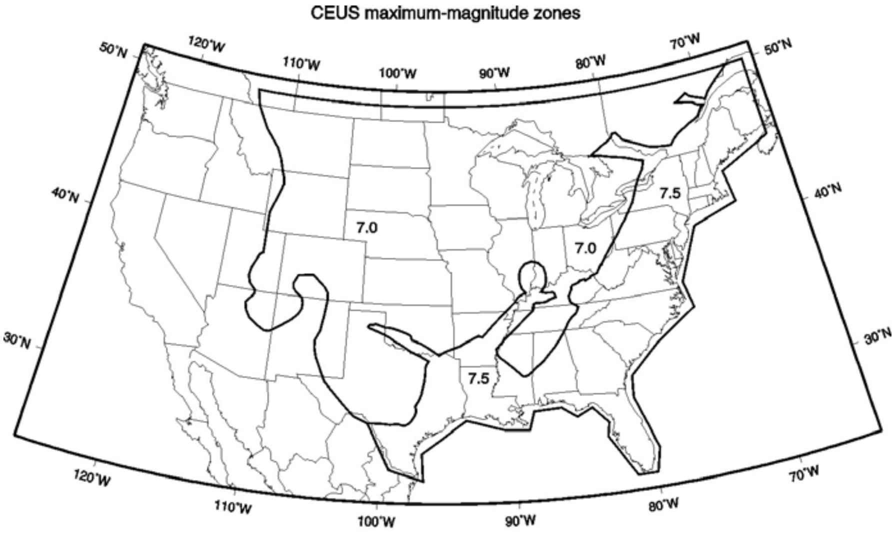


Figure 14. Background earthquakes (M_{max}) used in the national seismic hazard maps (Frankel and others, 2002).

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 for the background seismicity (Fig. 15) in the eight counties in western Kentucky (Ballard, Carlisle, Fulton, Graves, Hickman, Livingston, Marshall, and McCracken) of 5.3 $m_{b,Lg}$ (M5.0). This magnitude is based on moderate-size historical events, and occasional events in the counties that have been recorded by the University of Kentucky Seismic and Strong-Motion Network, such as the June 6, 2003, Bardwell, Ky., earthquake (Wang and others, 2003a). Within the eight counties, many earthquakes measuring 3.0 $m_{b,Lg}$ or larger have been recorded, such as the June 6, 2003, Bardwell, Ky., earthquake (M4.0), 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 this local source is 14 km. For this project, the shortest distance of 15 km was used. A point source of M5.0 earthquake with a distance of 15 km was considered to account for hazard contribution from the background seismicity.

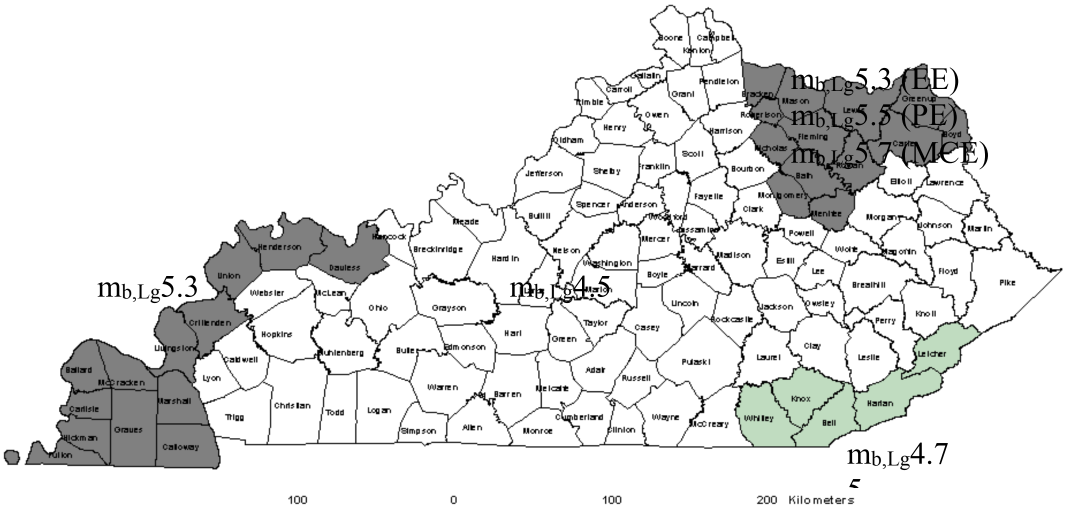


Figure 15. Maximum background earthquakes in Kentucky (Street and others, 1996).

4.0. Magnitude-Recurrence Relationship

In the central United States, seismicity rate is relatively low in comparison with that in California and there are no instrumental recordings on strong and large earthquakes (M>6.0). There are only two post 1811-1812 strong events (6.0<M<6.5): the 1843 Marked Tree, Ark., and the 1895 Charleston, Mo., earthquake (M6.0). Bakun and others (2003) recently suggested that the 1895 Charleston, Mo., earthquake was 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 (7.0<M<8.0) and are of safety concern in the area. The instrumental and historical records are insufficient to construct the magnitude-occurrence relationships in the central United States, so prehistoric records (paleoliquefaction) (Tuttle and others, 2002) had to be used (Frankel and others, 1996, 2002). Figures 16 and 18 show the magnitude-occurrence relationships for the New Madrid Seismic Zone (Frankel and others, 1996) and the Wabash Valley Seismic Zone (Wheeler and Cramer, 2002) based on instrumental, historical, and paleoliquefaction records.

4.1. *New Madrid Seismic Zone*

As shown in Figure 16, the annual rate derived from instrumental and historical earthquakes is not consistent with that derived from paleoliquefaction records. Figure 16 also shows that there is a lack of strong earthquakes of M6.0 to 7.0, or an earthquake deficit, 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 M7.5 earthquake is less than 0.0001 (recurrence interval is longer than 10,000 years) in the New Madrid Seismic Zone (Fig. 16). Paleoliquefaction records, however, reveal an annual occurrence rate of about 0.002 (recurrence interval of about 500 years) for a M7.5 earthquake in the New Madrid Seismic Zone. A recent study by Holbrook and others (2006) suggests that earthquakes may be temporally clustered on millennial scales and that these large earthquakes have been treated as characteristic events (Frankel and others, 1996, 2002; Geomatrix Consultants Inc., 2004).

Table 4 lists instrumental and historical earthquakes with magnitude equal to or greater than M4.0 known to have occurred in the New Madrid Seismic Zone (Bakun and Hopper, 2004). Figure 17 shows the Gutenberg-Richter curve for earthquakes with magnitudes between M4.0 and M5.0 in the New Madrid Seismic Zone (Table 4). The *a* and *b* values were estimated to be about 3.15 and 1.0, respectively, from earthquakes with magnitudes between M4.0 and M5.0 (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 large earthquakes (M≥6.0) in the New Madrid Seismic Zone, the recurrence interval for large earthquake would be quite long, about 700 years for M6.0, 7,000 years for M7.0, and 70,000 years for M8.0 earthquakes. This is why the large earthquakes (M≥7.0) in the New Madrid Seismic Zone are treated as characteristic. In this study, we assigned a magnitude of M7.5 with a mean recurrence interval of 500 to 1,000 years for the characteristic event along the New

Madrid faults. The mean recurrence interval of 500 to 1,000 years is based on the geological studies (Tuttle and others, 2002; Holbrook and others, 2006).

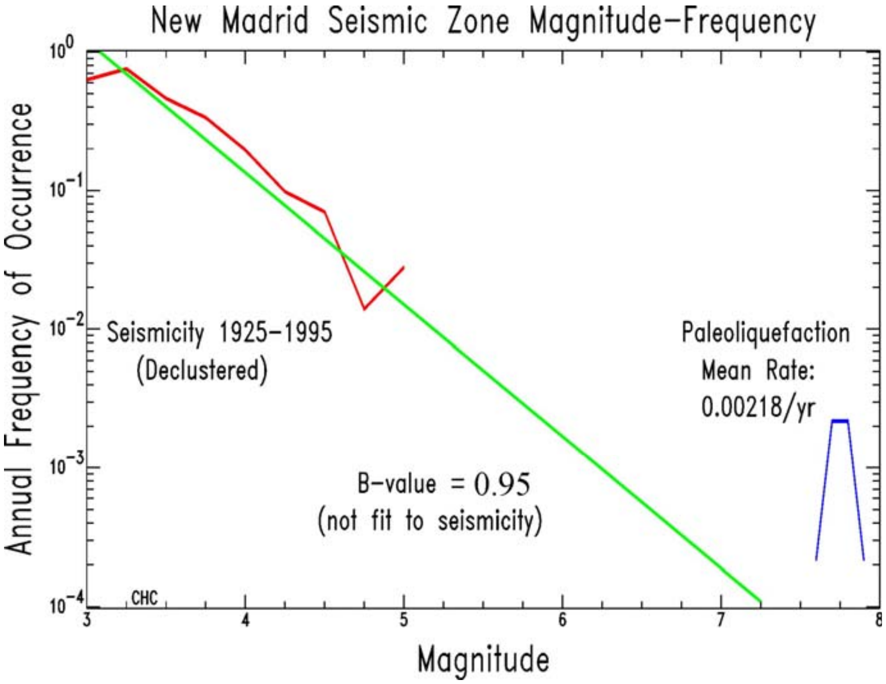


Figure 16. Magnitude-frequency relationship in the New Madrid Seismic Zone (Frankel and others, 1996).

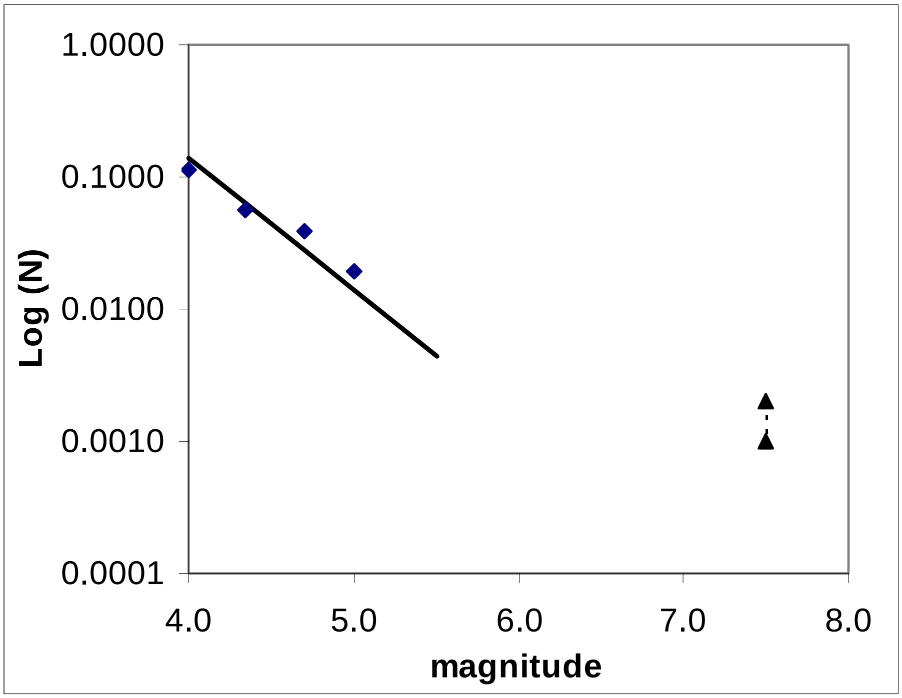


Figure 17. Magnitude-frequency (Gutenberg-Richter) curve for the New Madrid Seismic Zone. Diamond–historical rate, triangle–geological rate.

Table 4. Earthquakes with magnitude equal to or greater than M4.0 in the New Madrid Seismic Zone (Bakun and Hopper, 2004).

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

4.2. *Wabash Valley Seismic Zone*

The 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 (≤M5.0) (Wheeler and Cramer, 2002). Figure 19 shows the Gutenburg-Richter curve for the Wabash Valley Seismic Zone based on Bakun and Hopper (2004) data (a=3.0, b=1.0). We derived a mean recurrence interval of about 4,000 years for an earthquake with magnitude of M6.8 or greater from Figure 19. This recurrence interval is consistent with the 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.

4.3. *Background Seismicity*

The occurrence frequency of the maximum earthquake for the background earthquake was determined from the earthquakes with magnitude greater than M2.5 surrounding the Paducah Gaseous Diffusion Plant (Fig. 20). This is similar to the smoothed seismicity that 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 M5.0 earthquake.

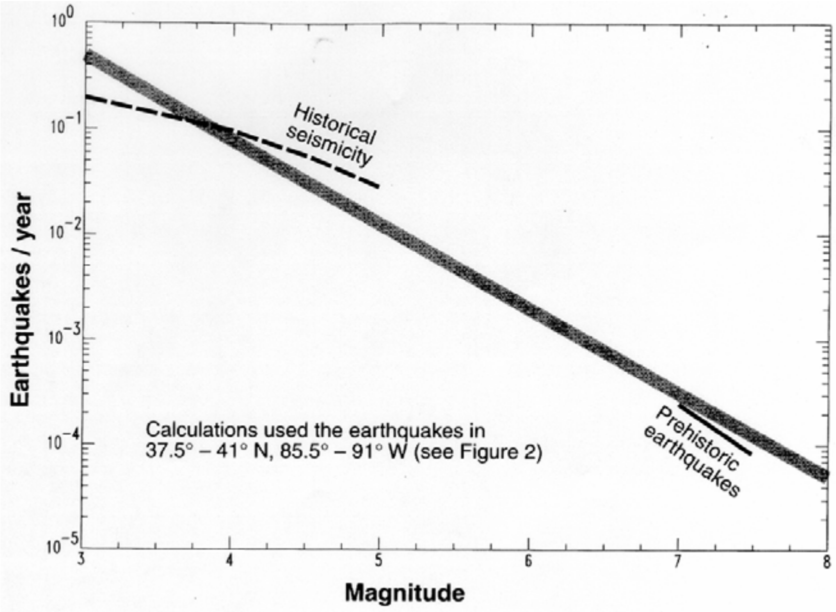


Figure 18. Magnitude-frequency relationship in the Wabash Valley Seismic Zone (Wheeler and Cramer, 2002).

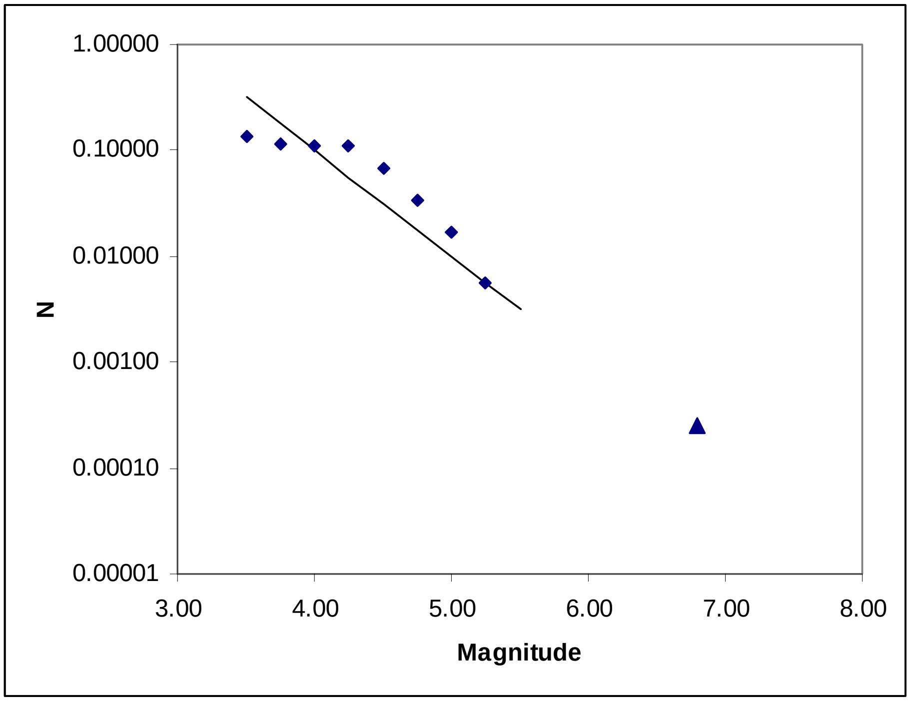


Figure 19. Magnitude-frequency (Gutenberg-Richter) curve for the Wabash Valley Seismic Zone. Diamond–historical rate, triangle–geological (paleoliquefaction) rate.

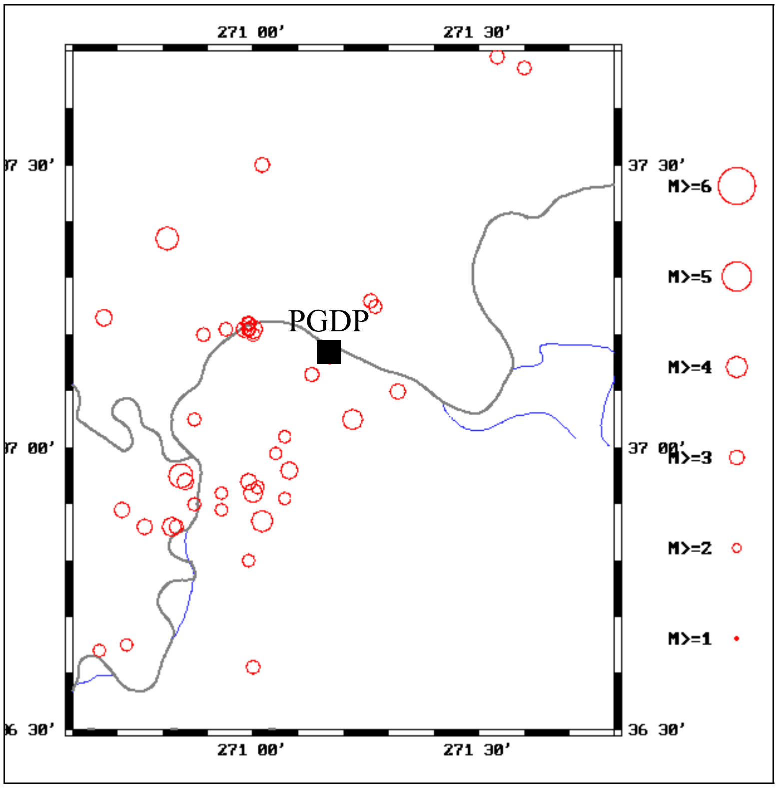


Figure 20. Recorded earthquakes with magnitude greater than 2.5 surrounding the Paducah Gaseous Diffusion Plant between 1978 and 2006.

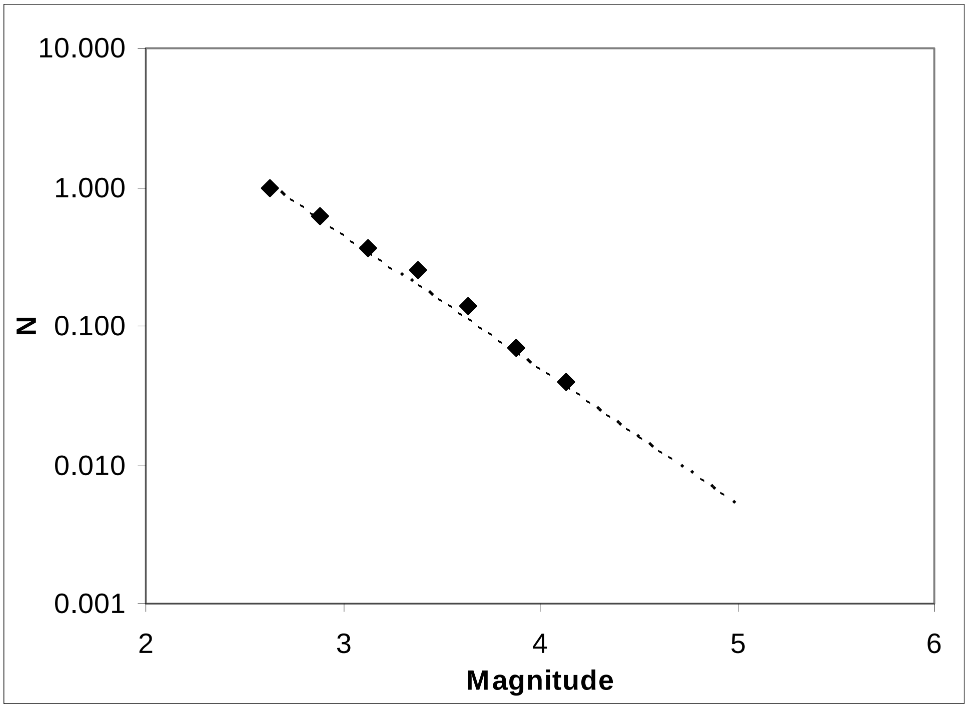


Figure 21. Magnitude-frequency (Gutenberg-Richter) curve for the background seismicity.

5.0. 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., PGA, PGV, MMI, or PSA 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 vs. 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 strong-motion stations and accelerograms recorded in the 2004 **M**6.0 Parkfield earthquake for the east-west component (Shakal and others, 2006). As shown in Figure 23, 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 of parameters (i.e., $f(M,R)$ and $\sigma_{ln,Y}$) would result if the epicentral distance was used (blue diamond). This shows that the ground-motion attenuation relationship, equation [2] or [3], depends on how earthquake source (i.e., point vs. finite), source-to-site distance (i.e., R_{RUP}, R_{JB}, R_{EPI}, or R_{HYP}), and site conditions (i.e., rock vs. 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 for the central and eastern United States:

$$\begin{aligned}\log(PSA) = {} & c_1 + c_2 M + c_3 M^2 + (c_4 + c_5 M) f_1 + (c_6 + c_7 M) f_2 + (c_8 + c_9 M) f_0 \\ & + c_{10} R_{cd} + n\sigma_{\log,PSA}\end{aligned} \tag{10}$$

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 closet distance to the fault (R_{RUP});
R_0 = 10 km;
R_1 = 70 km;
R_2 = 140 km.

And Silva and others (2002) used the functional form of

$$\ln(Y) = c_1 + c_2 M + (c_6 + c_7 M)\ln(R + e^{c_4}) + c_{10}(M-6)^2 + n\sigma_{\ln,Y} \tag{11}$$

where R is the closest distance to the surface projection of the rupture surface (R_{JB}). Therefore, the ground-motion attenuation relationship depends not only on the functional form and associated constants being used, but also on how earthquake source (i.e., point vs. finite), source-to-site distance (i.e., R_{RUP}, R_{JB}, R_{EPI}, or R_{HYP}), and site conditions (i.e., rock vs. 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 may have a significant impact on hazard estimates (Carroll, 2003; Wang and Zhou, in press).

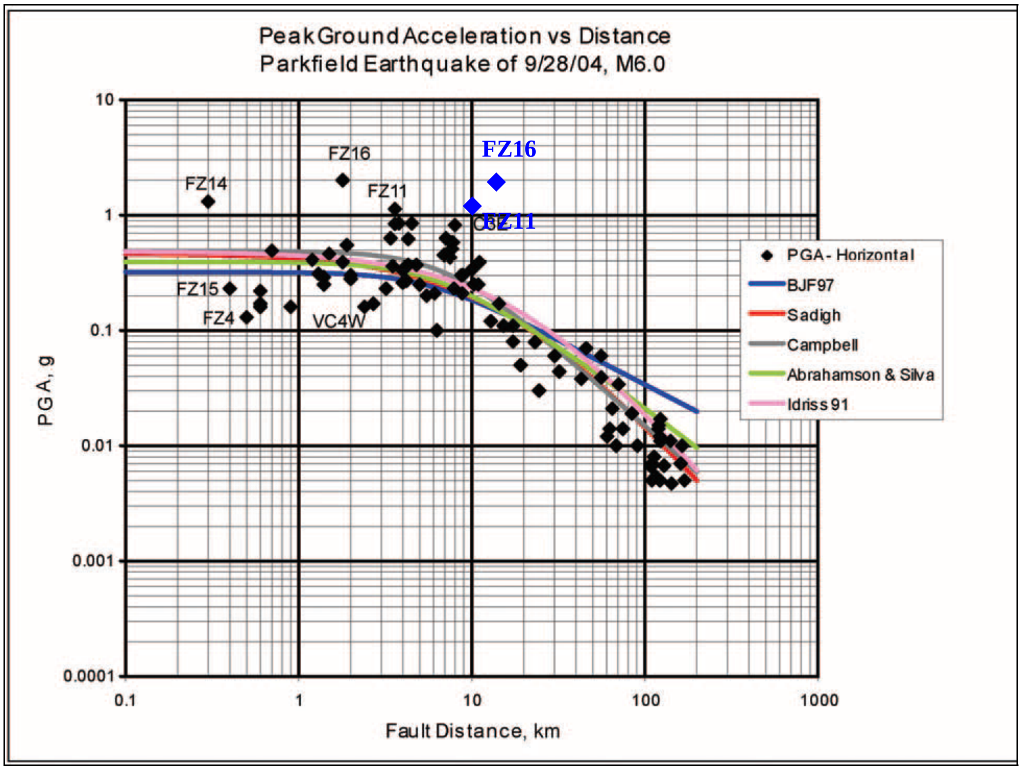


Figure 22. Horizontal uncorrected PGA vs. distance to the fault for the Parkfield earthquake of September 28, 2004 (Shakal and others, 2006). Blue diamonds are plots for stations FZ11 and FZ16 if the epicentral distance is measured.

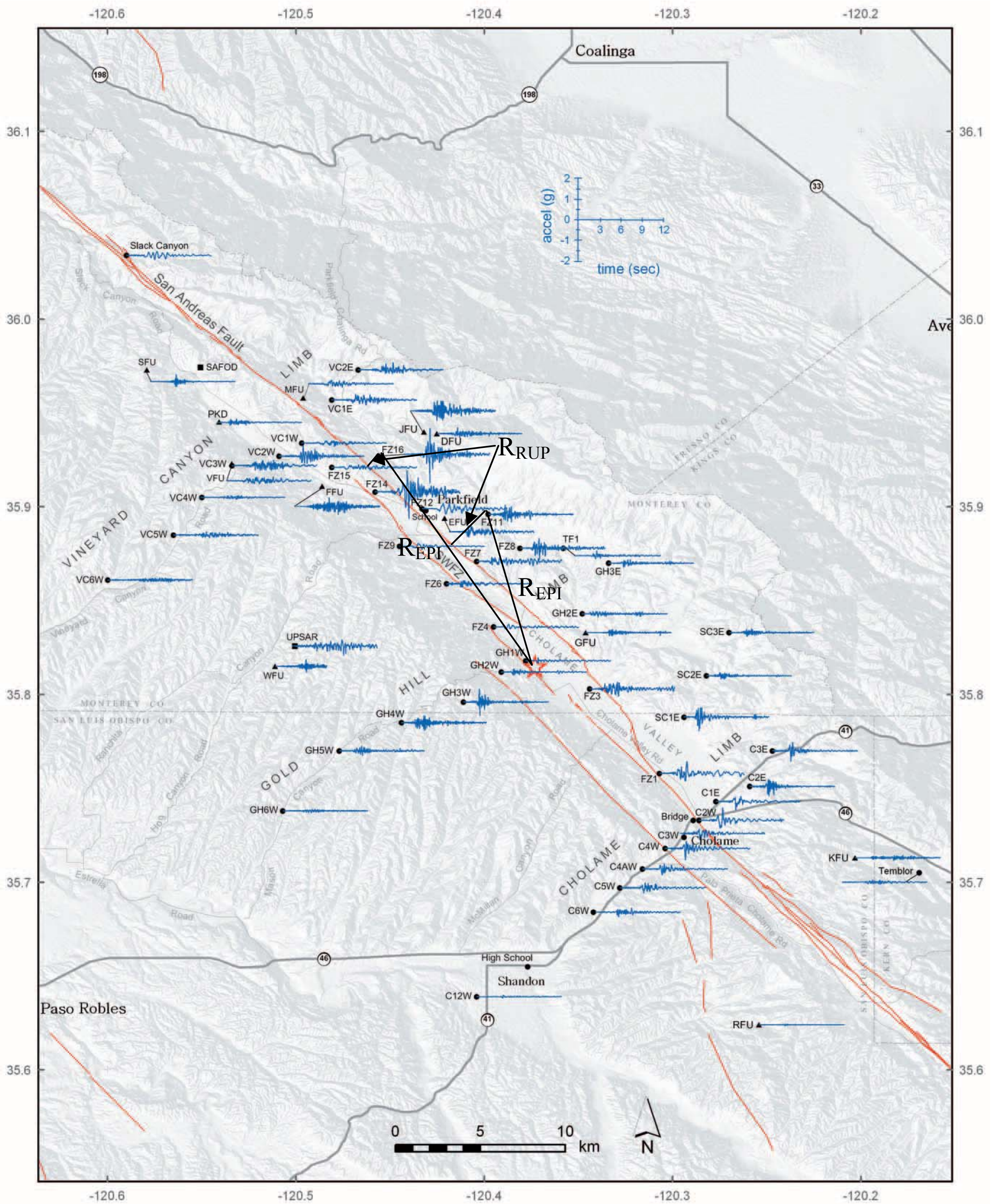


Figure 23. Strong-motion stations and accelerograms recorded in the 2004 **M**6.0 Parkfield earthquake for the east-west component (Shakal and others, 2006). R_{RUP} - the closet distance to fault rupture; R_{EPI} – epicentral distance.

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 world-wide data being used for development of ground-motion attenuation relationship for the PEER-Lifelines Next Generation Attenuation of Ground Motion (NGA) Project by Chiou and Youngs (2006). In contrast, all the attenuation relationships currently available for the central United States are based on theoretical models with very limited observations (Frankel and others, 1996; Toro and others, 1997; Somerville and others, 2001; Silva and others, 2002; Campbell, 2003; EPRI, 2003; Atkinson and Boore, 2006). Figure 25 shows the simulated data being used for the ground-motion attenuation analysis by Atkinson and Boore (2006) for the central and eastern United States.

This significant difference results in differences in ground-motion uncertainties in both median and standard deviation for the central United States. 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 0.38g between four attenuation relationships for a M7.8 earthquake at 15 km in San Francisco (Frankel, 2004). For comparison, Table 5 lists the median ground motions (PGA) for a M7.7 earthquake at 15 km from the New Madrid Seismic Zone with five attenuation relationships. The range of the median PGA in the central United States is between 0.69 and 1.20g. Similarly, Frankel (2004) showed a large range of median ground motions, especially in near-source (<30 km). The theoretical models predict higher median ground motions (PGA and 5 Hz S.A.) in the central United States than the ones in the west for a similar earthquake. Thus, the theoretical models predict not only higher median ground motion in comparison with a similar magnitude in the West, but also a larger range (uncertainty). Some theoretical models also predict higher standard deviations in the central and eastern United States than in the west. Recent studies suggest that the standard deviation should be similar in the two regions (Atkinson and Boore, 2006).

Table 5. Median ground motions for a M7.7 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

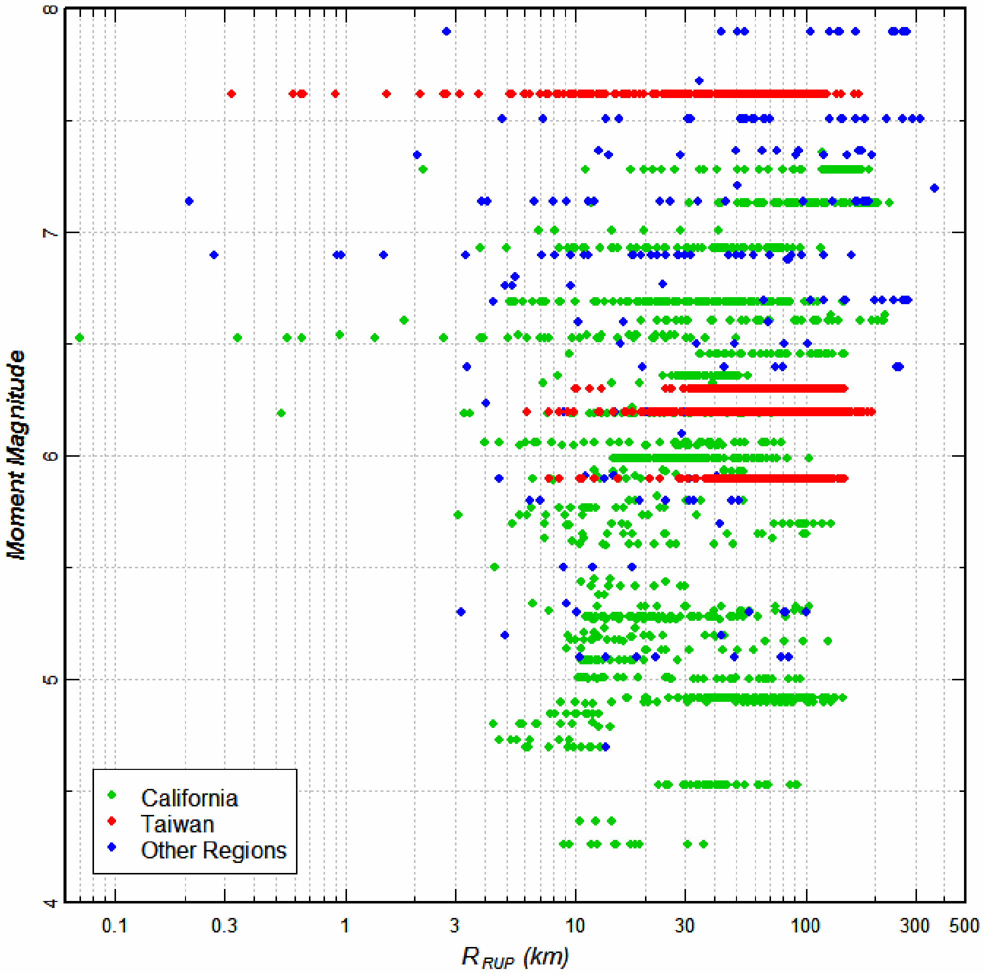


Figure 24. Magnitude-distance-region distribution of selected recordings (Chiou and Youngs, 2006).

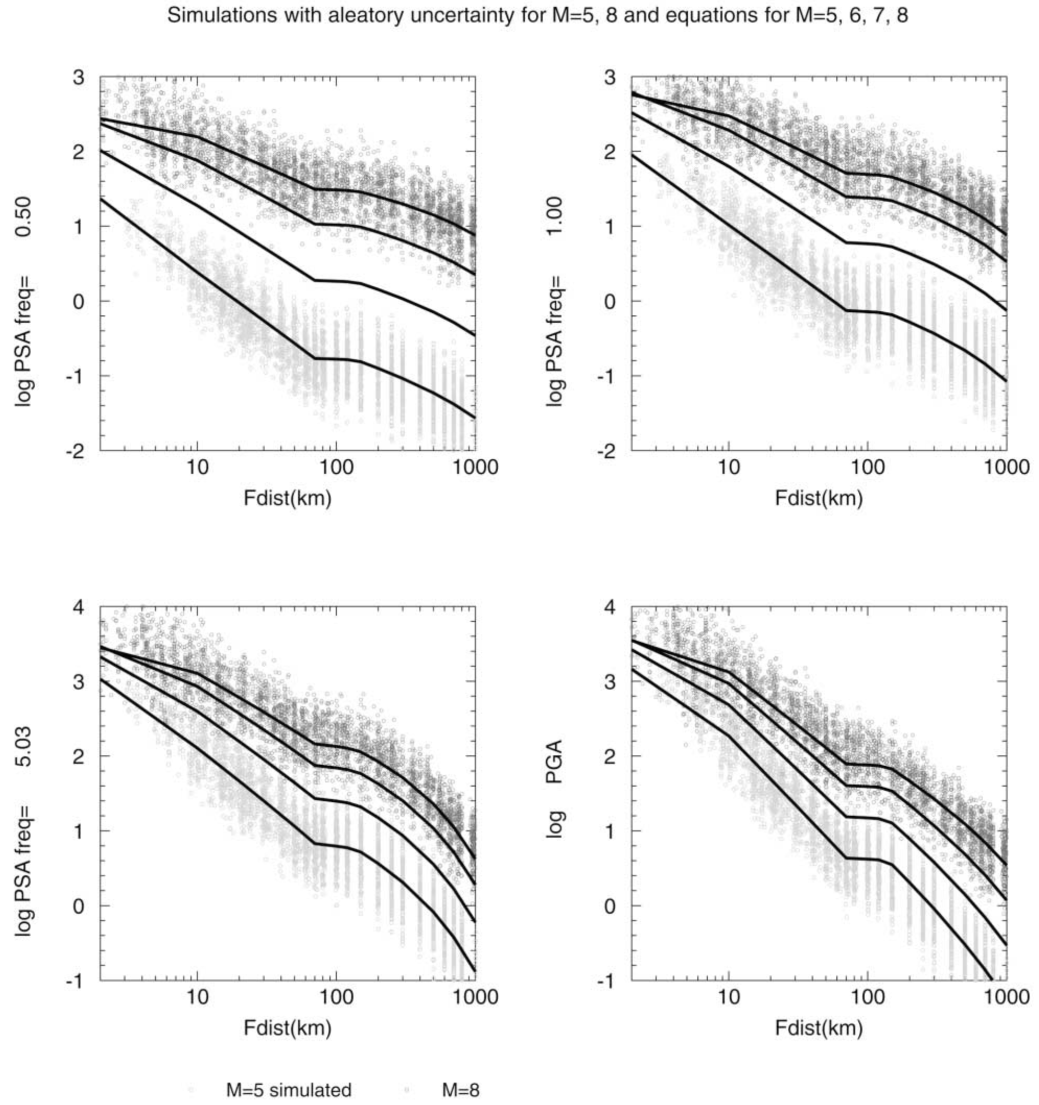


Figure 25. Log values of horizontal component 5% pseudo-acceleration at frequencies 0.5, 1, and 5 Hz, and PGA, for rock sites in eastern North America. Dots show PSA from simulations, including aleatory uncertainty, for **M** 5 (light) and **M** 8 (dark). Solid lines show predicted amplitudes from regression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

Use of different attenuation relationships will result in different ground-motion estimates, for near-source (10 to 30 km) in particular. As stated by Frankel and others (2002), “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 concluded by SSHAC (1997), “one key source of difficulty is failure to recognize that 1) there is not likely to be ‘consensus’ (as the work 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 chose ground-motion attenuation relationships for seismic hazard analysis. Recent studies have shown that ground motion at near-source has been over-predicted, however (USGS/NRC Workshop, 2005; Atkinson and Boore, 2006), even on the West Coast, where ground motion was overly predicted at near-source (Abrahamson, 2006; Boore and Atkinson, 2006; Campbell and Bozorgnia, 2006; Chiou and Youngs, 2006). There is a consensus that many current attenuation relationships predict too high ground motion at near-source, particularly Frankel and others’(1996) attenuation relationship, in the central and eastern United States (USGS/NRC Workshop, 2005). Figure 26 shows some of the ground-motion attenuation relationships for a M7.5 earthquake in the central United States. As shown in the figure, the Frankel and others (1996) attenuation relationship predicts higher PGA at near-source between 10 and 50 km. Figure 27 shows some of the ground-motion attenuation relationships for a M5.0 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 attenuation relationships represent different approaches (i.e., finite source/green function, double-corner, and hybrid methods). Figures 28 and 29 show 0.2s and 1.0s response accelerations of the four attenuation relationships for a M7.5 earthquake in the central United States. The rupture distance is used throughout this report.

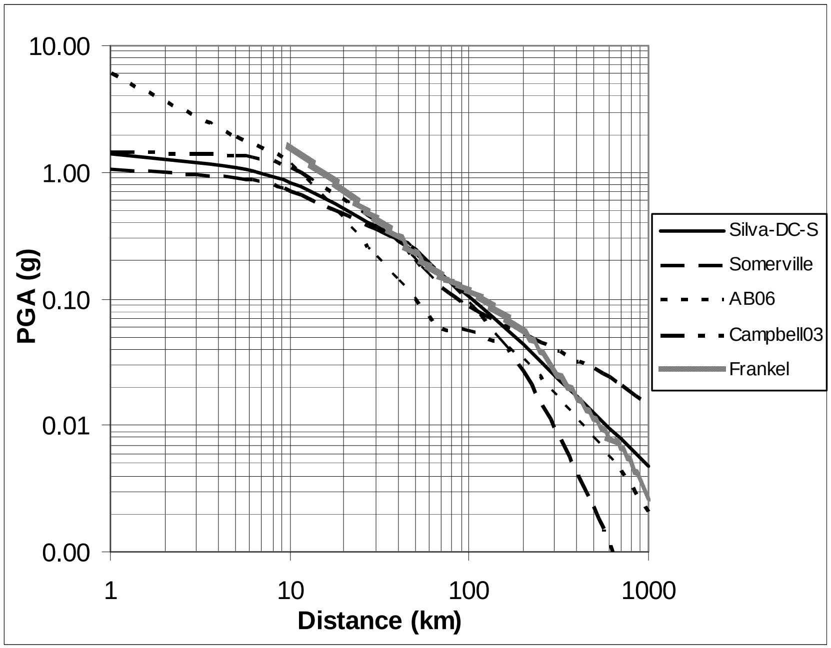


Figure 26. PGA attenuation relationships at hard rock for an M7.5 earthquake in the central United States.

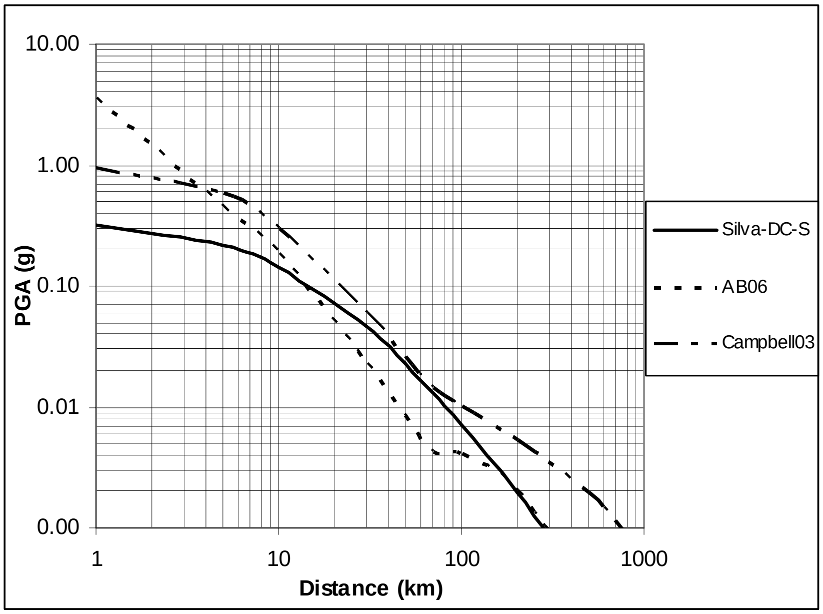


Figure 27. PGA attenuation relationships at hard rock for a M5.0 earthquake in the central United States.

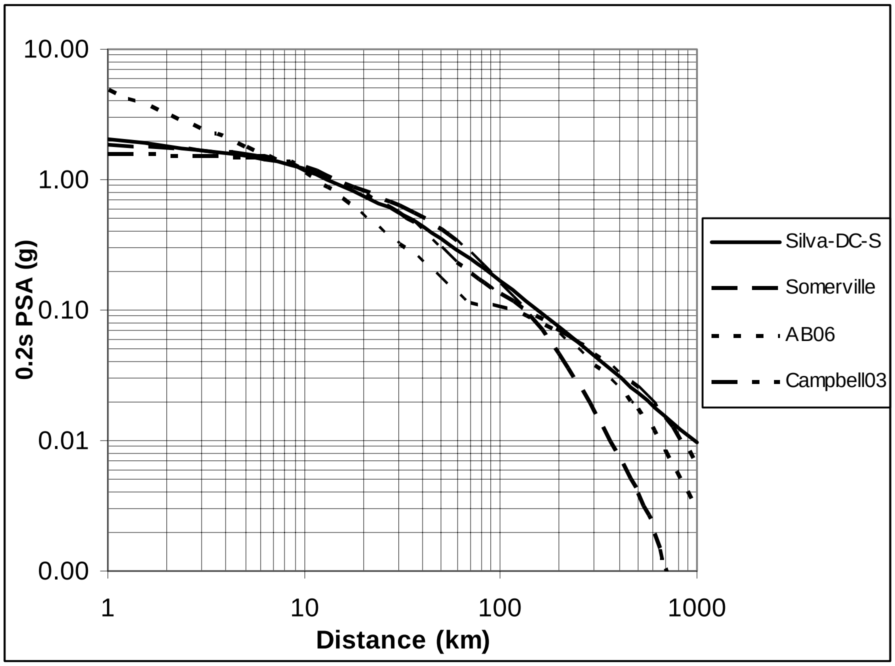


Figure 28. The 0.2s PSA attenuation relationships used in this study at hard rock for a M7.5 earthquake in the central United States.

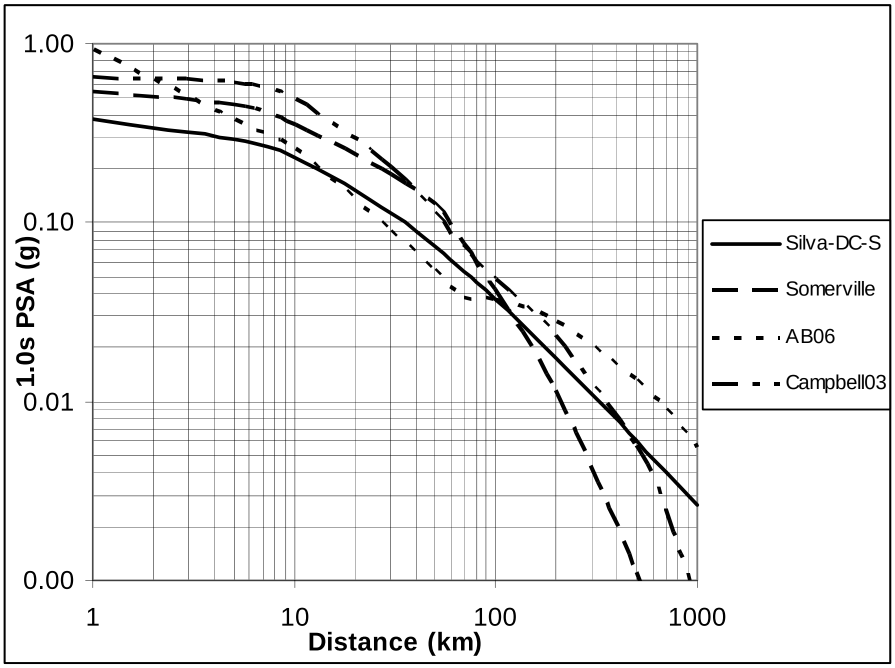


Figure 29. The 1.0s PSA attenuation relationships used in this study at hard rock for a M7.5 earthquake in the central United States.

6.0. 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; Geometrics 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 15 km with a maximum magnitude of M5.0 (Fig. 30) to account for the local earthquake for the Paducah Gaseous Diffusion Plant.

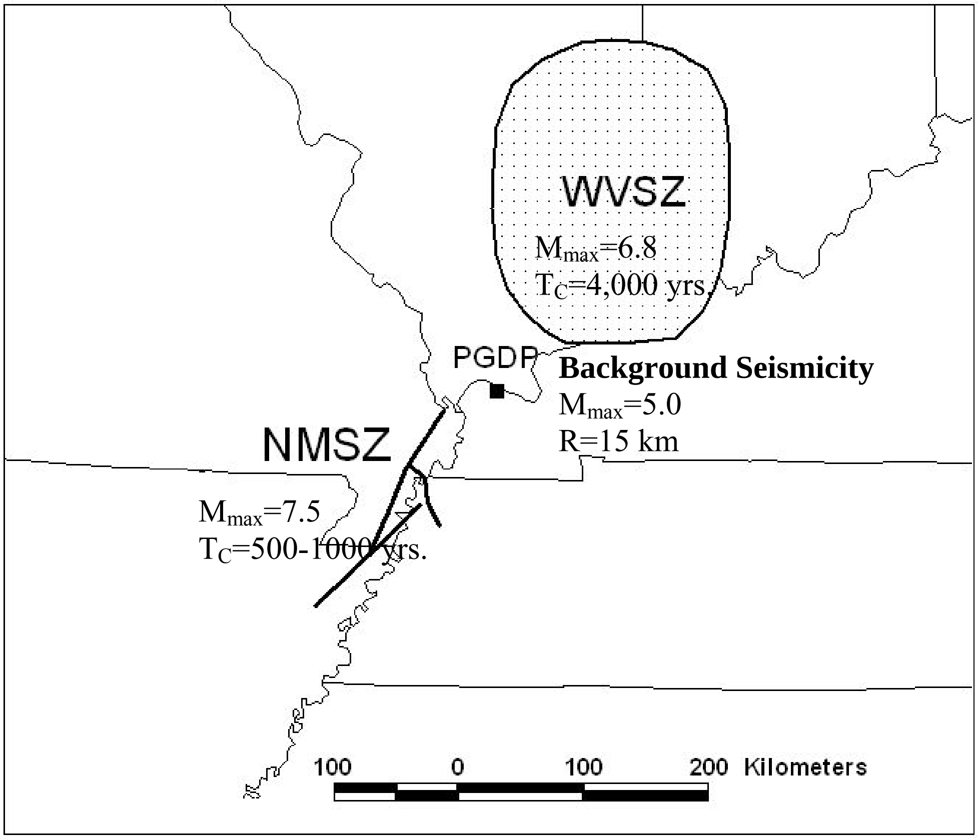


Figure 30. Seismic sources for the Paducah Gaseous Diffusion Plant.

6.1. PSHA Results

As discussed earlier, the ground-motion uncertainty is inherently a part of PSHA, and other uncertainties, such as fault location, are treated with logic trees, by which different weights are assigned manually to a set of expert estimates for each input parameter (SSHAC, 1997). In this project, the following weights (Table 6) were used to account for the uncertainties in location, magnitude, recurrence-interval, and attenuation relationship. It has been shown that the ground-motion hazard at site in the New Madrid Seismic Zone can be estimated with a single equivalent magnitude and distance (Frankel, 2004). The de-aggregation analysis also shows that ground motion hazard in Paducah can be approximated by a single equivalent magnitude and distance (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, 0.2s PSA, and 1.0s PSA are shown in Figures 31 through 33. Table 7 lists ground-motion values on hard rock at several annual probabilities of exceedance at the Paducah Gaseous Diffusion Plant.

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

Source	M_{max} (mean)	Recurrence interval (yrs.) (mean)	Distance (km) (mean)	Attenuation
NMSZ (characteristic)	7.5	500 (0.75) 1,000 (0.25)	40	AB-06 (0.25) Campbell-03 (0.25) Silva-DC-S (0.25) Somerville (0.25)
WVSZ (areal)	6.8	4000 (1.0)	60	AB-06 (0.25) Campbell-03 (0.25) Silva-DC-S (0.25) Somerville (0.25)
Background Seismicity (point)	5.0	200 (1.0)	15	AB-06 (0.33) Campbell-03 (0.33) Silva-DC-S (0.33)

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

Ann. Prob. Exc.	Return Period (years)	PGA (g)	0.2s PSA (g)	1.0s 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

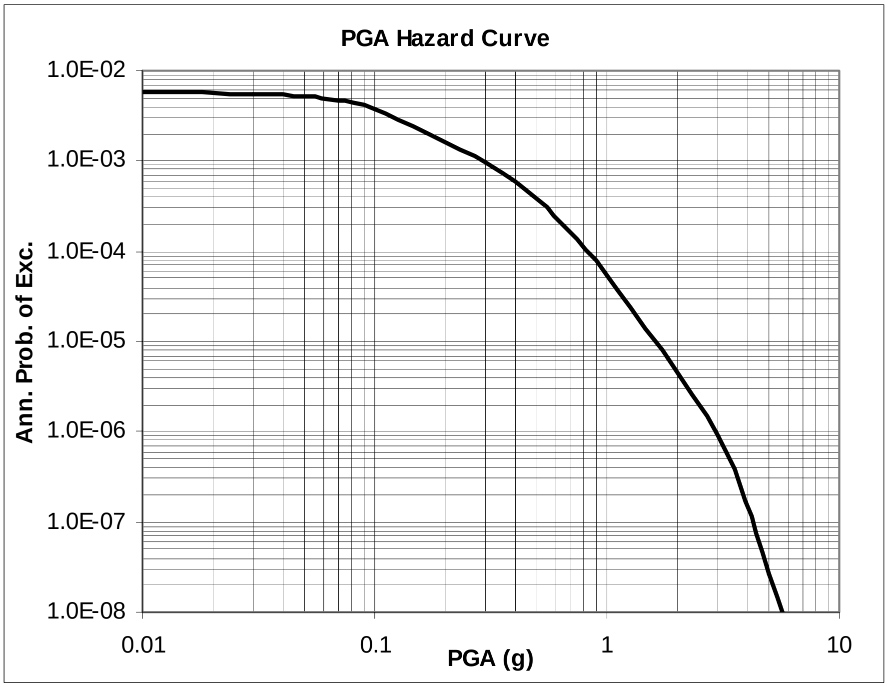


Figure 31. Mean PGA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant.

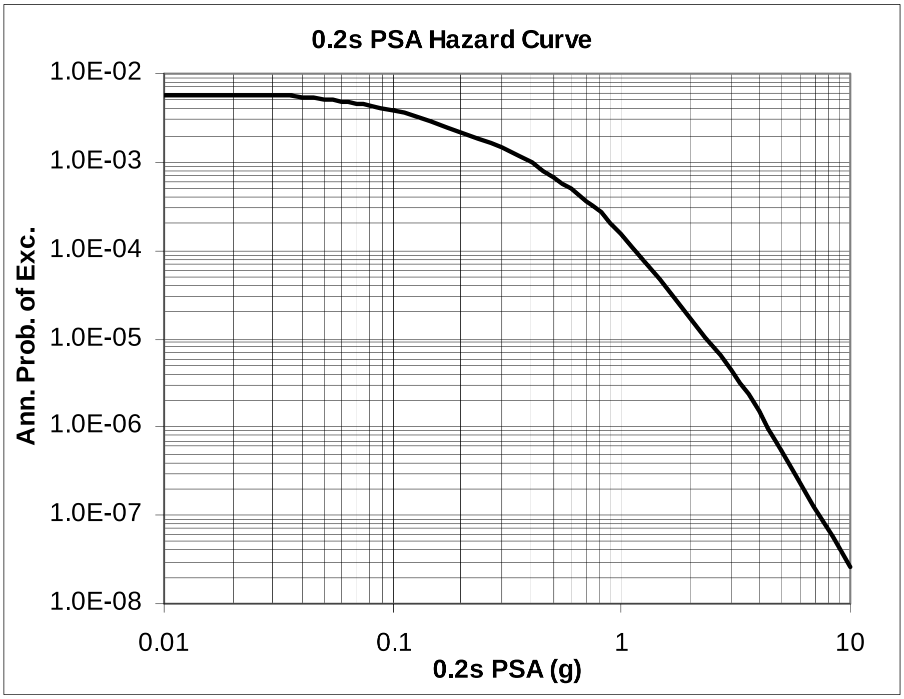


Figure 32. Mean 0.2s PSA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant.

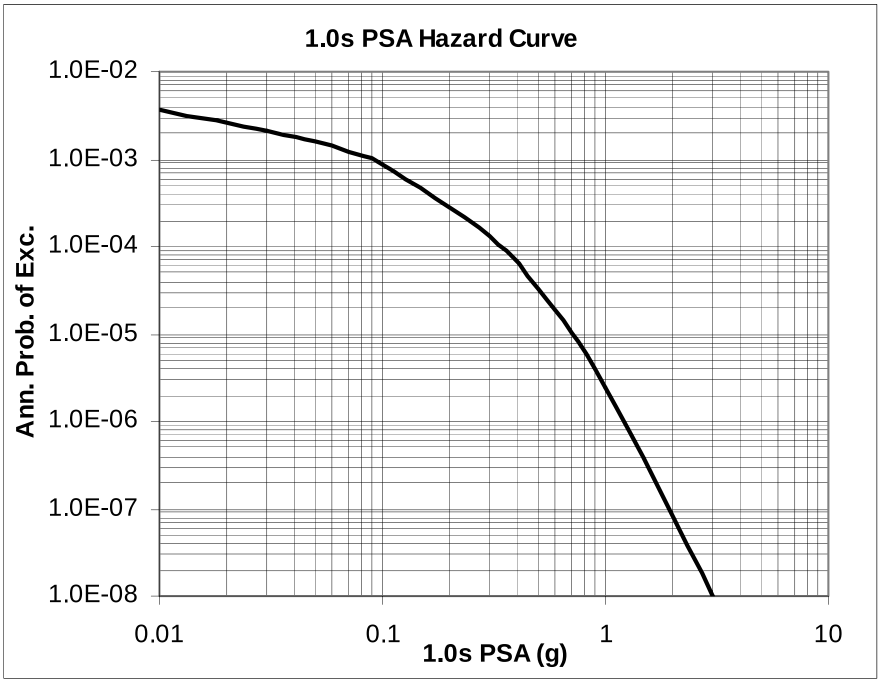


Figure 33. Mean 1.0s PSA hazard curve on hard rock at the Paducah Gaseous Diffusion Plant.

6.2. DSHA Results

Table 8 lists the median PGA values for the three sources affecting the Paducah Gaseous Diffusion Plant (Fig. 30), using the four attenuation relationships. As shown in Table 8, the characteristic earthquake in the New Madrid Seismic Zone dominates the hazard at the plant. Tables 9, 10, and 11 list PGA and 0.2s and 1.0s PSA hazards at the Paducah Gaseous Diffusion Plant from the characteristic earthquake in the New Madrid Seismic Zone for the four ground-motion attenuation relations (Somerville and others, 2001; Silva and others, 2002; Campbell, 2003; 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 in the New Madrid Seismic Zone.

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

Source	AB-06 (g)	Campbell-03 (g)	Silva-DC-S (g)	Somerville (g)
NMSZ	0.14	0.28	0.29	0.29
WVSZ	0.04	0.09	0.11	0.10
Background Seismicity	0.11	0.17	0.10	n/a

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

	Median (g)	Median +1$\sigma_{\ln,y}$ (g)	Median+2$\sigma_{\ln,y}$ (g)	1.5 Median (g)
AB-06	0.14	0.28	0.56	0.21
Campbell-03	0.28	0.55	1.08	0.42
Silva-DC-S	0.29	0.67	1.55	0.44
Somerville	0.29	0.52	0.94	0.44
Average	0.25	0.51	1.03	0.38

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

	Median (g)	Median+1$\sigma_{\ln,y}$ (g)	Median +2$\sigma_{\ln,y}$ (g)	1.5 Median (g)
AB-06	0.23	0.46	0.92	0.35
Campbell-03	0.40	0.82	1.68	0.60
Silva-DC-S	0.43	0.99	2.29	0.65
Somerville	0.51	0.93	1.71	0.77
Average	0.39	0.80	1.65	0.59

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

	Median (g)	Median+1$\sigma_{\ln,y}$ (g)	Median +2$\sigma_{\ln,y}$ (g)	1.5 Median (g)
AB-06	0.07	0.14	0.28	0.11
Campbell-03	0.15	0.31	0.65	0.23
Silva-DC-S	0.09	0.21	0.51	0.14
Somerville	0.15	0.30	0.60	0.23
Average	0.12	0.24	0.51	0.18

7.0. Conclusion and Recommendation

Estimating seismic hazard at the Paducah Gaseous Diffusion Plant is difficult because of the lack of instrumental ground-motion observations from large earthquakes in the region. Three seismic sources (i.e., the New Madrid Seismic Zone, the 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 at several commonly considered return periods. Table 13 lists ground-motion hazards with associated uncertainty derived from DSHA.

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

Ann. Prob. Exc.	Return Period (years)	Exc. Prob. in 50 years (%)	PGA (g)	0.2s PSA (g)	1.0s 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 on hard rock at the Paducah Gaseous Diffusion Plant determined by DSHA.

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

These results show that PSHA and DSHA utilize the same geological and seismological parameters, but produce quite different estimates of ground motion at the Paducah Gaseous Diffusion Plant because of the differences in defining the seismic hazard. In PSHA, seismic hazard is defined as the return period (or annual probability of exceedance) having a ground motion larger than a specific value. PSHA calculates seismic hazard from all earthquake sources in consideration, and incorporates uncertainty in earthquake size and location and ground motion implicitly. In DSHA, seismic hazard is defined as the ground motion(s) from a single or several earthquakes that have maximum values (impacts) at a site. DSHA emphasizes the ground motion from an individual earthquake, such as the maximum credible earthquake and maximum probable earthquake, and explicitly determines ground-motion hazard with a 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, similar to the 1811-1812 New Madrid events, in the New Madrid Seismic Zone 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 0.25g at the Paducah Gaseous Diffusion Plant from the New Madrid earthquakes (Table 13). This estimate is consistent with the limited MMI data (Fig. 34). Figure 34 shows that the Paducah Gaseous Diffusion Plant site experienced a MMI VIII intensity, which is equivalent to a PGA of 0.20 to 0.30 g (Bolt, 1993; Atkinson and Kala, 2006). This suggests that the PGA level of 0.25 to 0.3g 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 the ground motion with 1,000-year return period, produced by the US Geological Survey (Frankel and others, 1996), was proposed and selected as the basis for seismic design of residential buildings in western Kentucky (SEAOK, 2002). The ground motion with 1,000-year return period has also been considered as the upper level ground motion for seismic retrofit of highway structures in the central and eastern United States (FHWA, 2006). For other important facilities, the DSHA ground motion with one standard deviation (0.51g PGA) might be considered (Table 13). This ground motion (0.51g PGA) is similar to the ground motion (0.49g PGA) with a 2,500-year return period derived from PSHA (Table 12). Table 14 lists the 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 REI (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), a smaller mean magnitude (M7.5) for the characteristic earthquake in the New Madrid Seismic Zone, and use of lower ground motion attenuation relationships.

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

Facility	DSHA	PSHA		PGA (g)	0.2s PSA (g)	1.0s PSA (g)
		Return Period (years)	Exc. Prob. in 50 years (%)			
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

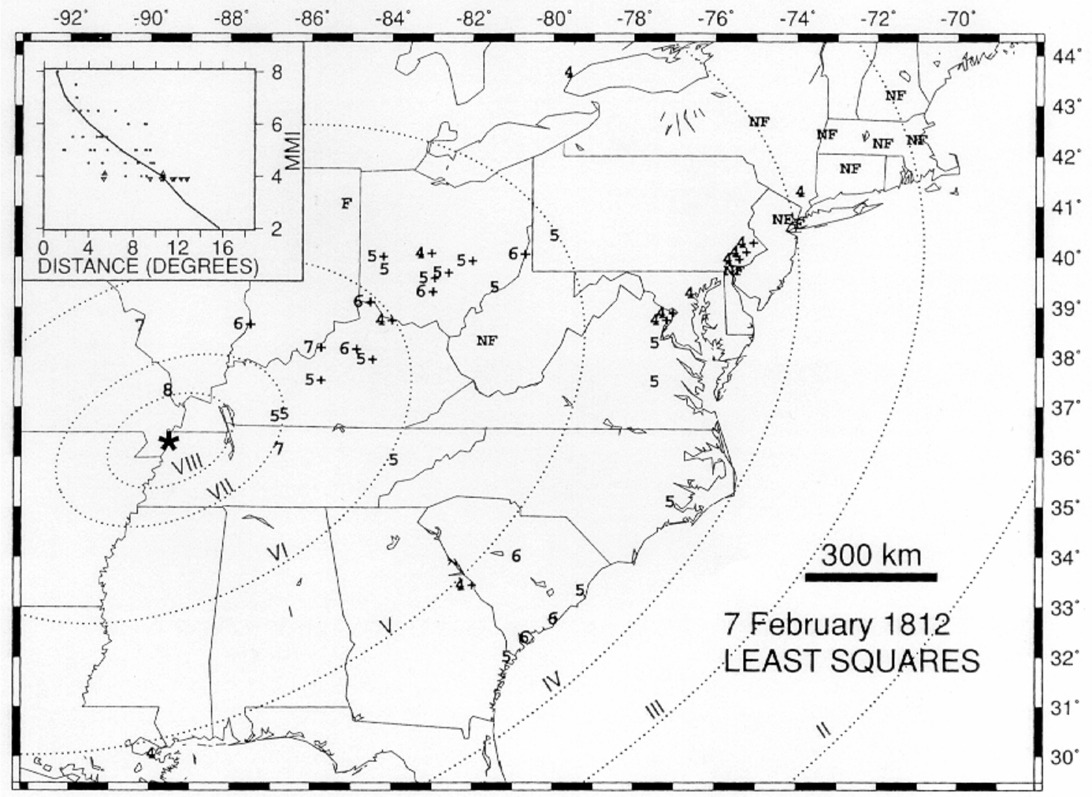


Figure 34. Isoseismal map of the February 7, 1812, New Madrid earthquake (Hough and others, 2000).

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

Return Period (years)	This study (g)	USGS -2002[1)] (g)	REI –1999 (g)
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.

8.0. References

Abrahamson, N., 2006, Lesson learned from ground rupture and strong motion [abstract]: Seismological Research Letters, v. 77, p. 225.

Abrahamson, N.A., and Bommer, J.J., 2005, Probability and uncertainty in seismic hazard analysis: Earthquake Spectra, v. 21, p. 603–607.

Abrahamson, N.A., and Silva, W.J., 1997, Empirical response spectral attenuation relations for shallow crustal earthquakes: Seismological Research Letters, v. 68, p. 94-127.

Akkar, S., and Bommer, J.J., 2007, Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East: Bulletin of the Seismological Society of America, v. 97, 511–532.

Anderson, C., Wang, Z., and Woolery, E.W., 2005, Observed Seismicity in the Jackson Purchase Region of Western Kentucky between January 2003 and June 2005: the 77th Annual Meeting of the Eastern Section of the Seismological Society of America, Memphis, Tennessee, October 3-4, 2005.

Atkinson, G., and Boore, D., 1995, New ground-motion relations for eastern North America: Bulletin of the Seismological Society of America, v. 85, p. 17–30.

Atkinson, G.M., and Boore, D.M., 2006, Earthquake ground-motion predictions for eastern North America: Bulletin of the Seismological Society of America, v. 96, p. 2181–2205.

Atkinson, G.M., and Kaka, S.I., 2007, Relationship between felt intensity and instrumental ground motion in the central United States and California: Bulletin of the Seismological Society of America, v. 97, p. 497–510.

Bakun, W.H., and Hopper, M.G., 2004, Historical seismic activity in the central United States: Seismological Research Letters, v. 75, p. 564–574.

Bakun, W.H., Johnston, A.C., and Hopper, M.G., 2003, Estimating locations and magnitudes of earthquakes in eastern North America from modified Mercalli intensities: Bulletin of the Seismological Society of America, v. 93, p. 190–202.

Baldwin, J.N., Harris, J.B., Van Arsdale, R.B., Givler, R., Kelson, K.I., Sexton, J.L., Lake, M., 2005, Constraints on the location of the late Quaternary Reelfoot and New Madrid North Faults in the northern New Madrid Seismic Zone, central United States: Seismological Research Letters, v. 76, p. 772–789.

Bear, G.W., Rupp, J.A., and Rudman, A.J., 1997, Seismic interpretations of the deep structure of the Wabash Valley Fault System: Seismological Research Letters, v. 68, p. 624–640.

Benjamin, J.R., and Cornell, C.A., 1970, Probability, statistics, and decision for civil engineers: New York, McGraw-Hill, 684 p.

Bernreuter, D.L., Savy, J.B., Mensing, R.W., and Chen, J.C., 1989, Seismic hazard characterization of 69 nuclear plant sites east of the Rocky Mountains, Report NUREG/CR-5250, v. 1–8.

Bolt, B., 1993, Earthquakes, W.H. Freeman and Company, San Francisco, CA, 241 p.

Bommer, J.J., and Abrahamson, N.A., 2006, Why do modern probabilistic seismic-hazard analyses often lead to increased hazard estimates?: Bulletin of the Seismological Society of America, v. 96, p. 1976–1977.

Boore, D.M., and Atkinson, G.M., 2006, Boore-Atkinson provisional NGA empirical ground-motion model for the average horizontal component of PGA, PGV and SA at spectral periods of 0.05, 0.1, 0.2, 0.3, 0.5, 1, 2, 3, 4, and 5 seconds: v. 1.7, 63 p.

Boore, D.M., Joyner, W.B., and Fumal, T.E., 1997, Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work: Seismological Research Letters, v. 68, p.128–153.

Braile, L.W., Hinze, W.J., and Keller, G.R., 1997, New Madrid seismicity, gravity anomalies, and interpreted ancient rift structure: Seismological Research Letters, v. 63, p. 599–610.

Braile, L.W., Hinze, W.J., Keller, G.R., Lidiak, E.G., and Sexton, J.L., 1986, Tectonic development of the New Madrid Rift Complex, Mississippi Embayment, North America: Tectonophysics, v. 131, p. 1–21.

Building Seismic Safety Council (BSSC), 1998, NEHRP recommended provisions for seismic regulations for new buildings [1997 ed.]: Federal Emergency Management Agency, FEMA 302, 337 p.

Building Seismic Safety Council (BSSC), 2004, NEHRP recommended provisions for seismic regulations for new buildings [2003 ed.]: Federal Emergency Management Agency, FEMA 450, 340 p.

Calais, E., Han, J.Y., DeMets, C., and Nocquet, J.M., 2006, Deformation of the North American plate interior from a decade of continuous GPS measurements: Journal of Geophysical Research, v. 111, p.

Campbell, K.W., 2003, Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America: Bulletin of the Seismological Society of America, v. 93, p. 1012–1033.

Campbell, K.W., 1981, Near-source attenuation of peak horizontal acceleration: Bulletin of the Seismological Society of America, v. 71, p. 2039- 2070.

Campbell, K.W. and Bozorgnia, Y., 2006, Campbell-Bozorgnia NGA empirical ground motion model for the average horizontal component of PGA, PGV, PGD and SA at selected spectral periods ranging from 0.01–10.0 seconds: v. 1.0, 193 p.

Carroll, R., 2003, Variances are not always nuisance parameters. Biometrics, v. 59, p. 211-220.

Chiou, B.S.-J., and Youngs, R.R., 2006, Chiou and Youngs PEER-NGA empirical ground motion model for the average horizontal component of peak acceleration and pseudo-spectral acceleration for spectral periods of 0.01 to 10 seconds, 71 p.

Chiu, J.-M., Johnston, A.C., and. Yang, Y.T, 1992, Imaging the active faults of the Central New Madrid Seismic Zone using PANDA array data: Seismological Research Letters, v. 63, p. 375–393.

Cobb, J.C., 2004, USGS National Seismic Hazards Mapping Program and States: De facto Setting Public Policy for States: A presentation to the USGS Science Earthquake Studies Advisory Committee, June 3, 2004, Memphis, Tenn.

Cobb, J.C., 2006, USGS National Seismic Hazard Maps: Kentucky Issues: earthquake.usgs.gov/research/hazmaps/whats_new/workshops/CEUS_workshop.php [accessed 5/31/2007].

Cornell, C.A., 1968, Engineeing seismic risk analysis: Bulletin of the Seismological

Society of America, v. 58, p. 1583–1606.

Cornell, C.A., 1971, Probabilistic analysis of damage to structures under seismic loads, *in* Howells, D.A., Haigh, I.P., and Taylor, C., eds., Dynamic waves in civil engineering: Proceedings of a conference organized by the Society for Earthquake and Civil Engineering Dynamics: New York, John Wiley, p. 473–493.

Cramer, C.H., 2001, The New Madrid Seismic Zone: Capturing uncertainty in seismic hazard analyses: Seismological Research Letters, v. 72, p. 664–672.

Cramer, C.H., 2004, Earthscope and PSHA 2004: www.ceri.memphis.edu/usgs/products/ppt_db2.html [accessed 9/20/2005].

Electric Power Research Institute (EPRI), 1988, Seismic hazard methodology for central and eastern United States: EPRI NR-4726, 10 v.

Electric Power Research Institute (EPRI), 2003, CEUS ground motion project, model development and results: Report 1008910, 67 p.

Federal Highway Administration (FHWA), 2006, Seismic Retrofitting Manual for Highway Structures: Part 1 - Bridges, U.S. Department of Transportation, Federal Highway Administration, Publication No. FHWA-HRT-06-032, 656 p.

Frankel, A., 2004, How can seismic hazard around the New Madrid Seismic Zone be similar to that in California?: Seismological Research Letters, v. 75, p. 575–586.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic hazard maps: Documentation June 1996: U.S. Geological Survey Open-File Report 96-532, 110 p.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M**.**, and Rukstales, K.S., 2002, Documentation for the 2002 update of the national seismic hazard maps: U.S. Geological Survey Open-File Report 02-420, 33 p.

Geomatrix Consultants Inc., 2004, Dam safety seismic hazard assessment: Tennessee Valley Authority, Project 9223, 137 p.

Hanks,T.C., and Cornell, C.A., 1994, Probabilistic seismic hazard analysis: A beginner’s guide, in *Proceedings of the Fifth Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping*, pp. I/1-1–I/1-17, N. C. State Univ., Raleigh, North Carolina.

Herrmann, R.B., and Ammon, C.J., 1997, Faulting parameters of earthquakes in the New Madrid, Missouri, region: Engineering Geology, v. 46, p. 299–311.

Holbrook, J., Autin, W.J., Rittenour, T.M., Marshak, S., and Goble, R.J., 2006, Stratigraphic evidence for millennial-scale temporal clustering of earthquakes on a continental-interior fault: Holocene Mississippi River floodplain deposits, New Madrid Seismic Zone, USA: Tectonophysics, v. 420, p. 431–454.

Horton, S.P., Kim, W., and Withers, M., 2005, The 6 June 2003 Bardwell, Kentucky, earthquake sequence: Evidence for a locally perturbed stress field in the Mississippi Embayment: Bulletin of the Seismological Society of America, v. 95**,** p. 431–445.

Hough, S.E., Armbruster, J.G., Seeber, L., and Hough, J.F., 2000, On the modified Mercalli intensities and magnitudes of the 1811–12 New Madrid earthquakes: Journal of Geophysical Research, v. 105, p. 23,839–23,864.

International Code Council (ICC), 2000, International Building Code: 678 p.

Johnston, A.C., 1996b, Seismic moment assessment of earthquakes in stable continental regions—I. Instrumental seismicity: *Geophys. J. Int.*, v. 124, p. 381–414.

Johnston, A.C., 1996a, Seismic moment assessment of stable continental earthquake, III., 1811–182 New Madrid, 1886 Charleston, and 1755 Lisbon: *Geophys. J. Int.*, v. 126, p. 314–344.

Johnston, A.C., and Schweig, E.S., 1996, The enigma of the New Madrid earthquakes of 1811–1812: Annual Review of Earth and Planetary Sciences, v. 24, p. 339–384.

Joyner, W.B., and Boore, D.M., 1981, Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake: Bulletin of the Seismological Society of America, v. 71, p. 2,011–2,038.

Kenner, S.J., and Segall, P., 2000, A mechanical model for intraplate earthquakes: Application to the New Madrid Seismic Zone: Science, v. 289, p. 2,329–2,332.

Kim, W., 2003, June 18, 2002, Evansville, Indiana Earthquake: Reactivation of ancient rift in the Wabash Valley Fault Zone?: Bulletin of the Seismological Society of America, v. 93, p. 2201–2211.

Klügel, J.-U., 2005, Problems in the application of the SSHAC probability method or assessing earthquake hazards at Swiss nuclear power plants: Engineering Geology, v. 78, p. 285–307.

Kramer, S.L., 1996, Geotechnical earthquake engineering: Upper Saddle River, N.J., Prentice Hall, 653 p.

Krinitzsky, E.L., 1995, Deterministic versus probabilistic seismic hazard analysis for critical structures: Engineering Geology, v. 40, p. 1–7.

Krinitzsky, E.L., 2002, How to obtain earthquake ground motions for engineering design: Engineering Geology, v. 65, p. 1–16.

McBride, J.H., Hildenbrand, T.G., Stephenson, W.J., and Potter, C.J., 2002, Interpreting the earthquake source of the Wabash Valley Seismic Zone (Illinois, Indiana, and Kentucky) from seismic reflection, gravity, and magnetic intensity data: Seismological Research Letters, v. 73, p. 660–686.

McGuire, R.K., 1976, FORTRAN computer program for seismic risk analysis: U.S. Geological Survey Open-File Report 76-67.

McGuire, R.K., 1995, Probabilistic seismic hazard analysis and design earthquakes: Closing the loop: Bulletin of the Seismological Society of America, v. 85, p. 1275–1284.

McGuire, R.K., 2004, Seismic hazard and risk analysis: Earthquake Engineering Research Institute, MNO-10, 221 p.

McGuire, R.K., Cornell, C.A., and Toro, G.R., 2005, The case for using mean seismic hazard: Earthquake Spectra, v. 21, p. 879–886.

Mendenhall, W., Scheaffer, R.L., and Wackerly, D.D., 1986, Mathematical statistics with applications: Boston, Duxbury Press, 750 p.

Mueller, K., and Pujol, J., 2001, Three-dimensional geometry of the Reelfoot blind thrust: Implications for moment release and earthquake magnitude in the New Madrid Seismic Zone: Bulletin of the Seismological Society of America, v. 91, p. 1563–1573.

Munson, P.J., Munson, C.A., and Pond, E.C., 1995, Paleoliquefaction evidence for a strong Holocene earthquake in south-central Indiana: Geology, v. 23, p. 325–328.

Munson, P.J., Obermeier, S.F., Munson, C.A., and Hajic, E.R., 1997, Liquefaction evidence for Holocene and latest Pleistocene earthquakes in southern halves of Indiana and Illinois: A preliminary overview: Seismological Research Letters*,* v. 68, p. 521–536.

Musson, R.M.W., 2005, Against fractiles: Earthquake Spectra, v. 21, p. 887–891.

National Research Council, 1988, Probabilistic seismic hazard analysis, report of the Panel on Seismic Hazard Analysis: Washington, D.C., National Academy Press, 97 p.

Newman, A., Stein, S., Weber, J., Engeln, J., Mao, A., and Dixon, T., 1999, Slow deformation and low seismic hazard at the New Madrid Seismic Zone: Science, v. 284, p. 619–621.

Nuclear Regulatory Commission, 1997, Regulatory Guide 1.165, Identification and characterization of seismic sources and determination of safe shutdown earthquake ground motion.

Nuttli, O.W., and Herrmann, R.B., 1978, Credible earthquakes in the central United States, *in* State-of-the art for assessing earthquake hazards in the United States: U.S. Army Corps of Engineers Geotechnical Lab Report 12, 99 p.

Obermeier, S.F., Bleuer, N.R., Munson, C.A., Munson, P.J., Martin, W.S., McWilliams, K.M., Tabacznski, D.A., Odum, J.K., Rubin, M., and Eggert, D.L., 1991, Evidence of strong earthquake shaking in the lower Wabash Valley from prehistoric liquefaction features: Science, v. 251, p. 1061–1063.

Obermeier, S.F., Martin, J.R., Frankel, A.D., Youd, T.L., Munson, P.J., Munson, C.A., and Pond, E.C., 1993, Liquefaction evidence for one or more strong Holocene earthquakes in the Wabash Valley of southern Indiana and Illinois: US Geological Survey Professional Paper 1536, 27 p.

Olson, S.M., Green, R.A., and Obermeier, S.F., 2005, Revised magnitude-bound relation for the Wabash Valley Seismic Zone of the central United States: Seismological Research Letters*,* v. 76, p. 756–771.

Petersen, M., 2005, National seismic hazard maps:Issues for Kentucky, *in* Wang, Z., comp., Better Understanding and Communication of the National Seismic Hazard Maps: Summary of USGS-KGS Meeting on Seismic Hazard Assessment in Western Kentucky, Kentucky Geological Survey, ser. 12, Special Publication 7, 47 p.

Pond, E.C. and Martin, J.R., 1997, Estimated magnitudes and accelerations associated with prehistoric earthquakes in the Wabash Valley of the central United States: Seismological Research Letters, v. 68, p. 611–623.

Reiter, L., 1990, Earthquake hazard analysis: New York, Columbia University Press, 254p.

Risk Engineering Inc. (REI), 1999, Updated probabilistic seismic hazard analysis for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky: Final report, 124 p.

Sadigh, K., Chang, C.Y., Egan, J.A., Makdisi, F., and Youngs, R.R., 1997, Attenuation relationships for shallow crustal earthquakes based on California strong motion data: Seismological Research Letters*,* v. 68, p.180–189.

Scherbaum, F., Bommer, J., Bungum, H., Cotton, F., and Abrahamson, N., 2005, Composite ground-motion models and logic trees: Methodology, sensitivities, and uncertainties: Bulletin of the Seismological Society of America, v. 95, p. 1575–1593.

Senior Seismic Hazard Analysis Committee (SSHAC), 1997, Recommendations for probabilistic seismic hazard analysis: Guidance on uncertainty and use of experts: Lawrence Livermore National Laboratory, NUREG/CR-6372, 81 p.

Sexton, J.L., Braile, L.W., Hinze, W.J., and Campbell, M.J., 1996, Seismic reflection profiling studies of a buried Precambrian rift beneath the Wabash Valley Fault Zone: Geophysics, v. 51, p. 640–660.

Shakal, A., Haddadi, H., Graizer, V., Lin, K., and Huang, M., 2006, Some key features of the strong-motion data from the **M** 6.0 Parkfield, California, earthquake of 28 September 2004: Bulletin of the Seismological Society of America, v. 96, p. S90–118.

Silva, W., Gregor, N., and Darragh, R., 2002, Development of regional hard rock attenuation relationships for central and eastern North America: Pacific Engineering and Analysis, 311 Pomona Ave., El Cerrito, CA 94530, 57 p.

Somerville, P., Collins, N., Abrahamson, N., Graves, R., and Saikia, C., 2001, Ground motion attenuation relations for the central and eastern United States: Final report to U.S. Geological Survey, 16 p.

Stein, S., Tomasello, J., and Newman, A., 2003, Should Memphis build for California's earthquakes?: EOS, Transactions of the American Geophysical Union, v. 84, p. 177, 184–185.

Stepp, J.C., Wong, I., Whitney, J., Quittmeyer, R., Abrahamson, N., Toro, G., Youngs, R., Coppersmith, K., Savy, J., Sullivan, T., and Yucca Mountain PSHA project members, 2001. Probabilistic seismic hazard analysis for ground motions and fault displacements at Yucca Mountain, Nevada: Earthquake Spectra, v. 17, p. 113–151.

Stover, C.W., and Coffman, J.L., 1993, Seismicity of the United States, 1568–1989 (rev.): U.S. Geological Survey Professional Paper 1527, 418 p.

Street, R., and Wang, Z., 2003, Analysis of strong motion records from the University of Kentucky accelerometers in the New Madrid Seismic Zones: 1990 through 2001: Report to the U.S. Geological Survey, Award Number 02HQGR0016, 10 p.

Street, R.L., Bauer, R.A., and Woolery, E.W., 2004, Short note: Magnitude scaling of prehistorical earthquakes in the Wabash Valley Seismic Zone of the central United States: Seismological Research Letters*,* v. 75, p. 637–641.

Street, R., Wang, Z., Harik, I., and Allen, D.,1996, Source zones, recurrence rates, and time histories for earthquakes affecting Kentucky: Kentucky Transportation Center, University of Kentucky, Research Report KCT-96-4, 187 p.

Structural Engineers Association of Kentucky (SEAOK), 2002, White Paper on Review of the 2002 Kentucky Residential Code (2nd ed.), SEAOK Document WP-01-2.1, 66 p.

Toro, G.R., Abrahamson, N.A., and Schneider, J.F., 1997, Model of strong ground motions from earthquakes in central and eastern North America: Best estimates and uncertainties: Seismological Research Letters, v. 68, p. 41–57.

Toro, G.R., Silva, W.J., McGuire, R.K., and Herrmann, R.B., 1992, Probabilsitic seismic hazard mapping of the Mississippi Embayment: Seismological Research Letters, v. 63, p. 449–475.

Tuttle, M.P. and Schweig, E.S., 2000, Earthquake potential of the New Madrid Seismic Zone [abs.]: EOS, Transactions of the American Geophysical Union, v. 81, p. S308–309.

Tuttle, M.P., Schweig, E.S., Sims, J.D., Lafferty, R.H., Wolf, L.W., and Haynes, M.L., 2002, The earthquake potential of the New Madrid Seismic Zone: Bulletin of the Seismological Society of America, v. 92, p. 2080–2089.

U.S. Geological Survey (USGS)/Nuclear Regulatory Commission (NRC), 2005, Workshop on attenuation of ground motion in the central and eastern United States: CD–ROM.

Wang, Z., 2003a, Summary for the USGS NEHRP Hazard Maps, *in* Wang, Z., comp., the Kentucky NEHRP Seismic Hazard and Design Maps Workshop proceedings: Kentucky Geological Survey, ser. 12, Special Publication 5, p. 16–18.

Wang, Z. (compiler), 2003b, Proceedings of The Kentucky NEHRP Seismic Hazards and Design Maps Workshop, November 18, 2002, Lexington, Kentucky, Kentucky Geological Survey, ser. 12, Special Publication 5, 38p.

Wang, Z., 2005a, Comment on J.U. Klügel's: Problems in the Application of the SSHAC Probability Method for Assessing Earthquake Hazards at Swiss Nuclear Power Plants, in Engineering Geology, vol. 78, pp. 285-307, Engineering Geology, v. 82, p. 86-88.

Wang, Z., 2005b, Reply to "Comment on 'Comparison between probabilistic seismic hazard analysis and flood frequency analysis' by Zhenming Wang and Lindell Ormsbee" by R. M. W. Musson: EOS, Transactions of the American Geophysical Union, v. 86, p. 354.

Wang, Z., 2005c, Reply to "Comment on 'Comparison between probabilistic seismic hazard analysis and flood frequency analysis' by Zhenming Wang and Lindell Ormsbee" by Thomas L Holzer: EOS, Transactions of the American Geophysical Union, v. 86, p. 303.

Wang, Z. (compiler), 2005d, Better Understanding and Communication of the National Seismic Hazard Maps: Summary of USGS-KGS Meeting on Seismic Hazard Assessment in Western Kentucky, Kentucky Geological Survey, ser. 12, Special Publication 7, 47 p.

Wang, Z., 2006a, Understanding Seismic Hazard and Risk Assessments: An Example in the New Madrid Seismic Zone of the Central United States, Proceedings of the 8th National Conference on Earthquake Engineering, April 18-22, 2006, San Francisco, CA, Paper no. 416.

Wang, Z., 2006b, Addendum to the PEGASOS Follow-Up Workshop, Swissnuclear workshop on the refinement of the PEGASOS Project, November 28-29, 2006, Zurich, Swizzerland.

Wang, Z., in press, Seismic Hazard and Risk Assessment in the Intraplate Environment: The New Madrid Seismic Zone of the Central United States: GSA Book SPE425: Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues, ed. Seth Stein and Stéphane Mazzotti.

Wang, Z., and Ormsbee, L., 2005, Comparison between probabilistic seismic hazard analysis and flood frequency analysis: EOS, Transactions of the American Geophysical Union, v. 86, p. 45, 51-52.

Wang, Z., and Zhou, M., in press, Comment on “Why Do Modern Probabilistic Seismic Hazard Analyses Often Lead to Increased Hazard Estimates?” by Julian J. Bommer and Norman A. Abrahamson: Bulletin of the Seismological Society of America.

Wang, Z., Woolery, E.W., and Shi, B., 2003a, Observed seismicity (earthquake activity) in the Jackson Purchase Region of western Kentucky: January through June 2003: Kentucky Geological Survey, ser. 12, Special Publication 6, 16 p.

Wang, Z., Woolery, E.W., Shi, B., and Kiefer, J.D., 2003b, Communicating with uncertainty: A critical issue with probabilistic seismic hazard analysis: EOS, Transactions of the American Geophysical Union, v. 84, p. 501, 506, 508.

Wang, Z., E.W. Woolery, B. Shi, and J.D. Kiefer, 2004a, Reply to Comment on “Communicating with Uncertainty: A Critical Issue with Probabilistic Seismic Hazard Analysis” by R.M.W. Musson: EOS, Transactions of the American Geophysical Union, v. 85, p. 236.

Wang, Z., Woolery, E.W., Shi, B., and Kiefer, J.D., 2004b, Reply to “Comment on ‘Communicating with Uncertainty: A Critical Issue with Probabilistic Seismic Hazard Analysis’”by C.H. Cramer: EOS, Transactions of the American Geophysical Union, v. 85, p. 283, 286.

Wang, Z., Woolery, E.W., Shi, B., and Kiefer, J.D., 2005, Comment on “How Can Seismic Hazard around the New Madrid Seismic Zone Be Similar to that in California?” by Arthur Frankel: Seismological Research Letters, v. 76, p. 466–471.

Wheeler, R.L., 1997, Boundary separating the seismically active Reelfoot Rift from the sparsely seismic Rough Creek Graben, Kentucky and Illinois: Seismological Research Letters, v. 63, p. 586–598.

Wheeler, R.L., and Cramer, C.H., 2002, Updated seismic hazard in the southern Illinois Basin – Geological and geophysical foundations for use in the 2002 USGS national seismic-hazard maps: Seismological Research Letters, v. 73, p. 776-791.

Wheeler, R.L., and Frankel, A., 2000, Geology in the 1996 USGS seismic-hazard maps, central and eastern United States: Seismological Research Letters, v.71, p. 273–282.

William Lettis & Associates Inc., 2006, Investigation of Holocene faulting at proposed C-746-U landfill expansion, Paducah Gaseous Diffusion Plant, Paducah, Kentucky: 66 p.

Windeler, D., 2006, USGS workshop on the 2007 CEUS hazard map update: Some “user perspectives” from insurance loss modeling: earthquake.usgs.gov/research/hazmaps/whats_new/workshops/CEUS_workshop.php [accessed 5/31/2007].

Woolery, E.W., 2005, Geophysical and geological evidence of Neotectonic deformation along the Hovey Lake fault, lower Wabash Valley Fault System: Bulletin of the Seismological Society of America, v. 95, p. 1193–1201.

Youngs, R.R., Chiou, S.J., Silva, W.J., and Humphrey, J.R., 1997, Strong ground motion attenuation relationship for subduction zone earthquake: Seismological Research Letters, v. 68, p. 58–73.

Youngs, R.R., Abrahamson, N., Makdisi, F.I., and Sadigh, K., 1995, Magnitude-dependent variance of peak ground acceleration: Bulletin of the Seismological Society of America, v. 85, p. 1161–1176.

Zoback, M.L., 1992, Stress field constraints on intraplate seismicity in eastern North America: Journal of Geophysical Research, v. 97, p. 11,761–11,782.

Zoback, M.D., Prescott, W.H., and Kroeger, S.W., 1985, Evidence for lower crustal ductile strain localization in southern New York: Nature, v. 317, p. 705-707.

Zoback, M.D., Zoback, M.L., Mount, V.S., Suppe, J., Eaton, J.P., Eaton, J.P., Healy, J.H., Oppenheimer, D., Reasenberg, P., Jones, L., Raleigh, C.B., Wong, I.G., Scotti, A., and Wentworth, O.C., 1987, New evidence on the state of stress of the San Andreas fault system: Science, v. 238, p. 1105-1111.

Appendix A – Project Proposal

TITLE: Enhancing Earthquake Monitoring and Assessing Seismic Hazard for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky

GOALS

The goals for this proposal are:

1) to better monitor and locate earthquakes in the area and;
2) to provide an independent and peer reviewed ground motion hazard assessment for the Paducah Gaseous Diffusion Plant (PGDP).

OBJECTIVES

In the central United States, the best information for determining seismogenic faults (faults that are capable of generating earthquakes) is seismicity (earthquake activity). Until recently, the lack of seismic stations in the area has precluded any definitive determination of the active faults in the area. Earthquakes occur periodically in area surrounding PGDP, for example, the August 26, 2003 west Paducah earthquake (m_b 3.2). In order to better monitor and locate earthquakes, a temporary seismic network has been deployed in the area, with support from the Commonwealth of Kentucky. The seismic stations are still not dense enough to accurately locate earthquakes in area surround PGDP, however. Additional seismic stations are needed.

Federal government agencies, including the U.S. Nuclear Regulatory Commission, use the seismic hazard maps developed by the U.S. Geological Survey for seismic safety regulations. These maps are based on a 2 percent probability that a ground motion will be exceeded in 50 years (2,500-year return period). The maps predict very high ground motion for the area surrounding the PGDP. These high seismic hazard estimates for the area have a significant impact on seismic regulations and engineering designs for facilities at the PGDP. The seismic hazard at the PGDP has also been estimated by many other public and private organizations. The results are significantly different among these estimates.

The tasks for this study include:

Task 1. *Micro-seismicity observation in Paducah area*. We propose to complete two seismic stations, one at the PGDP and the other in Paducah, and to install three new seismic stations in the area. These stations, combined with the eight existing seismic stations, will enhance our capability to monitor micro-seismicity in the area.

Task 2. *Thorough literature review*. There are many new developments and data on seismic hazard assessment methodology, geology, and seismology locally, regionally, and nationally. The focus will be on the new geological and geophysical investigations in the area. The literature review will ensure the use of the best data and methodology.

Task 3. *Seismic source Characterization.* Based on the information derived from Task 1 and 2, the seismic sources in and around the PGDP and their characteristics will be defined.

Task 4. *Probabilistic seismic hazard analysis (PSHA)*. PSHA will be performed based on the seismic source data from Task 3.

Task 5. *Deterministic seismic hazard analysis (DSHA).* DSHA will be performed based on the seismic source data from Task 3.

Task 6. Preliminary report.

Task 7. *Panel review*. A 5-member review panel consisting of national and international experts will be formed to review the preliminary report.

Task 8. Final report.

Appendix B – Agenda of the Independent Technical Review Meeting

Independent Technical Review

For

Final Research Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant

By

Zhenming Wang and Edward W. Woolery

Date: April 30, 2007

Place: Room 102, Mining and Mineral Resources Building, UK campus

Agenda

8:00-8:10	Introduction	**Ed Woolery**
8:10-8:20	Nature of the Project	**Lindell Ormsbee** (Director, Kentucky Water Resource Institute)
8:20-8:30	Issues Related to Seismic Hazard Assessment in Western Kentucky	**Jim Cobb** (Director, Kentucky Geological Survey)
8:30-10:00	Ground Motion Attenuation Relationship – uncertainty, dependency, and hazard calculation in PSHA (focus)	**Woolery/Wang**
	8:30-9:00 Presentation	**Zhenming Wang**
	9:00-9:50 Q/A and Discussion	**Panel members**
	9:50-10:00 Q/A	**from attendees**
10:00-10:30	Coffee Break	
10:30-12:00	Seismic Hazard Analysis (SHA) – temporal and spatial measurements, uncertainties, and quantification (focus)	**Woolery/Wang**
	10:30-11:00 Presentation	**Zhenming Wang**
	11:00-11:50 Q/A and Discussion	**Panel members**
	11:50-12:00 Q/A	**from attendees**
12:00-13:00	Lunch Break	
13:00-14:30	Seismic Hazard Assessment for PGDP – input parameters: sources, occurrence frequency, and ground motion attenuation (focus)	**Woolery/Wang**
	13:00-13:30 Presentation	**Zhenming Wang**
	13:30-14:20 Q/A and Discussion	**Panel members**
	14:20-14:30 Q/A	**from attendees**
14:30-14:45	Break	
14:45-16:00	Discussion and Summary	**Wang/Woolery**

Members of Independent Technical Review Panel

1. Roy B. Van Arsdale
8872 Farmoor Road
Germantown, TN 38139
E-mail: rvanrsdl@memphis.edu
Phone: 901-678-4356

2. Gail Atkinson
280 McLean Ave.
Arnprior, ON K7S 3T2
Canada
E-mail: gmatkinson@aol.com
Phone: 613-623-3240

3. James E. Beavers
James E Beavers Consultants
6318 Beaver Ridge Road
Knoxville, TN 37931
E-mail: jbeavers@jebconsultants.com
Phone: 865-690-8936

4. Kenneth W. Campbell
1030 NW 161st Place
Beaverton, OR 97006
E-mail: ken.w.campbell@comcast.net
Phone: 503-533-4359

5. Leon Reiter
1960 Dundee Road
Rockville, MD 20850
E-mail: harrietleon@verizon.net
Phone: 301- 279-0509

6. Mai Zhou
Department of Statistics
849 POT
University of Kentucky
Lexington, KY 40506-0027
E-mail: mai@ms.uky.edu
Phone: 859-257-6912

Appendix C – Review Comments and Responses for the Preliminary Report (February 2007)

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
1	Roy Van-Arsdale	General	Although the work of Tuttle et al. is the most recent to address earthquake recurrence in the New Madrid seismic zone, an earlier article came to the same conclusion. Kelson et al. (1996) concluded that the recurrence interval on Reelfoot fault earthquakes in between 400 and 500 years. This is significant because the earthquake recurrence interval is tied to a specific fault.	A recent study by Holbrook et al. (2006) indicates the earthquake recurrence interval of about 1,000 years for the same fault. This is the reason that a range of recurrence interval, 500 to 1,000 years, 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 et al. (2002) address this and there is also evidence for this clustering in Van Arsdale et al. (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 vs. 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 effect on your 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 southern end of 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 id the strike of fault in this transition zone. Do the faults continue N45E 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 N60W regional maximum stress	These are very good comment. The questions need to be addressed through future studies.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
4	Roy Van-Arsdale	General	You do not address the large number of earthquakes that trend into western Kentucky inllustrated 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 more dense network (Wang and others, 2003a; Horton and others, 2005; Anderson and others, 2005) shows consistent difference between the earthquakes in the New Madrid 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 in the Jackson Purchase Region. On the other hand, there are geologic evidences showing the northeast extensions of the New Madrid faults on Missouri side, such as Baldwin and others (2005).	
5	Roy Van-Arsdale	Executive Summery	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 following examples: 1) Mojave desert has high seismic hazard (frequent large earthquakes, such as Hechtor Mine earthquake), but has low seismic risk because few exposures (people and property). 2) San Simeon area has relative low seismic hazard (compare to Mojave desert), but has higher seismic risk because high expotures.	
6	Roy Van-Arsdale	Chapter 3, Section 1 (page 21)	The Reel rift –Rough Creek graben-Rome trough is commonly considered to be one large perhaps discontinuous Cambrian rift	This is good comment. There relationship between them in Quaternary, particularly in Holocene, is not clear which has impact on seismic hazard assessment	
7	Roy Van-Arsdale	Chapter 3, Section 1 (page 21)	What about dense seismicity in W Ky in Fig. 11?	See response to comment #4	
8	Roy Van-Arsdale	Chapter 3, Section 1 (page 21)	True, also a black hole of no data	See response to comment #3	
9	Roy Van-Arsdale	Chapter 3, Section 1 (page 24)	Why not through 2006?	All earthquakes up to March 2007 will be included.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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 (PSHA) 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 Assessment (SHA). 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 the question 1 is clear: PSHA may not be appropriate for seismic hazard assessment because it contains a mathematical error in its formulation: incorrectly treating the ground-motion uncertainty as an independent random variable. The 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 measurement (occurrence of an earthquake and its consequence [ground motion] at a site) with spatial measurement (ground-motion variability due to the source, path, and site effects). The results from a PSHA study are artifact. The answer to the question 2 is also clear: SHA is appropriate because 1) it was peer reviewed (paper no. 416, Proceedings of the 8th U.S. National Conference on Earthquake Engineering, April 18-22, 2006; Chapter 24, GSA Special Publication 425, in press), 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 Stein and others (2005, 2006).	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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 CUS 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%/50 year 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 (ATC-USGS hazard workshop, 2006), return period derived from PSHA is interpreted and used as mean recurrence interval (MRI) and compared with those of wind, snow, and other hazards. However, the return period is not equal or equivalent to MRI. The proposed approach is not new, but a re-introduction of an old one (Milne and Davenport, 1969) with addition of uncertainty. Return period derived from the proposed approach is identical to MRI derived from wind, flood, and other hazard analysis.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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 (Mx=5) and Wabash (Mx=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 exceedence of any given ground motion level, as is shown in the appended illustration. 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 earthquake. 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 one (this is the result of incorrect formulation of PSHA), i.e. using the ground motion uncertainty to extrapolate the frequency (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 subjective one. The maximum magnitude for Wabash (Mx=6.8) source is based on the most recent studies (Street and others, 2004; Olson and others, 2005). The maximum magnitudes for the background (Mx=5) source 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 the 2% in 50 year 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.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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.	With universally referred in government regulations, codes, and other relevant documents, the USGS maps have to be discussed. Revision will be done to reflect these and add more explanations	
6	Gail Atkinson	Specific (P 2)	Fig. 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 Stein and others (2003)	
7	Gail Atkinson	Specific (P 3.3)	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 in government regulations, codes, and other relevant documents, and general implication 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 (P 5)	(and 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 (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), 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." 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."	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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," a magnitude recurrence curve is a hazard curve because an M6.0 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 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 through this report. The discussion of seismic risk will help to understand why and how we do seismic hazard analysis.	
12	Gail Atkinson	Specific (P 11)	The arguments presented regarding Eqn 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 (PEER/NGA). 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 Eq. 4 is focal distance (Cornell, 1968). 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 Eq. 4 is to account for the uncertainty of focal point (distribution). The uncertainty of focal point is accounted in part by the uncertainty of ground motion because R is measured as a single distance (rupture, JB, or seismogenic) regardless focal distance. Eq.4 counts the distance uncertainty, at least some portion, twice. Similarly, $f_M(m)$ in Eq. 4 is to account for the uncertainty of magnitude (distribution). Also similarly, the ground motion standard deviation is dependent of M. Again, Eq.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 years. 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 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). The same interpretation was also given by (Frankel, 2004, 2005; Holzer, 2005)	

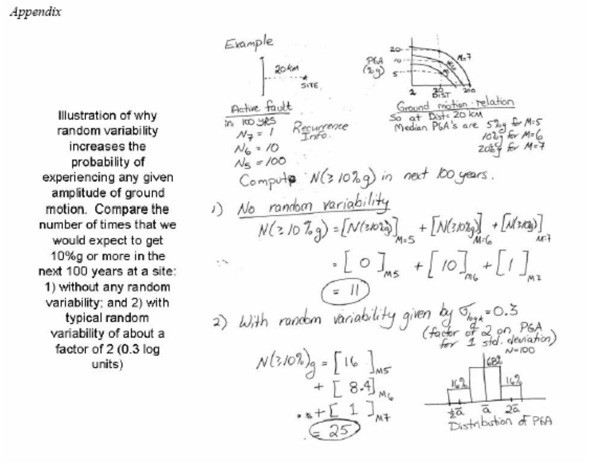
Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
14	Gail Atkinson	Specific (P 15.8)	This reasoning is not correct. PSHA is simply a compound probability, like any other compound probability. Space and time are both relevant in determining the likelihood of receiving 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 events 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 a dependent of magnitude and distance. The uncertainty in the location of a future event is considered by confident 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 Fig. 10 is incorrect (Fig. 15?)		
19	Gail Atkinson	Specific (P 26)	Include Paducah location on Fig. 15		
20	Gail Atkinson	Specific (P 28)	A maximum magnitude of M6.8 cannot be arbitrarily assigned to the Wabash source in this way. This is a subjective “MCE” with an unknown exceedence probability. It has no physical basis as a limit on magnitude.	See response to the general comment #3	
21	Gail Atkinson	Specific (P 28.5)	Add lat, lon to figure 17.		

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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 Mx=5 to background seismicity is not justified.	See response to the general comment #3	
23	Gail Atkinson	Specific (P 30)	Figure 20 demonstrates that the possibility of a large local earthquake (M6 to 6.5) is not a negligible contributor to hazard. Why is there no contribution from M5 to 5.5 shown on this figure?	This figure is from Peterson (2005) showing that there are earthquakes closer to the site	
24	Gail Atkinson	Specific (P 33)	It is possible on Fig. 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 GR 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 catalogue 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 ENA ground motions are higher than CA motions, and point out that this only applies at high frequencies.	Will revise.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
27	Gail Atkinson	Specific (P 37.5)	The differences in standard deviation are exaggerated. Most recent studies suggest that sigma should be similar in ENA and CA (eg. EPRI, 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).	
28	Gail Atkinson	Specific (P 37.6)	The AB95 and F96 relations (and arguably also the T97 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) ENA model uses a finite-fault source. It predicts a PGA of approximately 0.7g for the cited distance of 15 km from an M7.7 event on hard rock. Thus the relevant estimates of median PGA for hard rock, in my view, range from 0.7g (AB06 and S01) to 0.9g (C03).	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 AB06 is for distance to fault, so in the case of moderate events this is likely to always be greater than a few km (eg. an M5.0 earthquake would likely correspond to about Dfault=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 M5.0 at 15 km is particularly arbitrary. The nearest location for both NMSZ and WVSZ 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 confident level because uncertainty in ground motion is dependent of both of them. Otherwise, uncertainties will be counted twice or three times (in PSHA). Also see the response to the general comment #3 on M5.0 and the distance.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
31	Gail Atkinson	Specific (P 42)	Fig. 32 is not actually the probability of exceedence 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 are not included. 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 Mx=5, is apparent.	The annual probability of exceedance (i.e., frequency by McGuire [2004]) is temporal measure. The sigma (ground motion) is spatial measure. The 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	
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 comment #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.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
36	Gail Atkinson	Appendix	 *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 $\sigma_{\log A} = 0.3$ (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 	The example shows the problem associated with mixing the temporal measure with spatial one. The examples you shown are all "deterministic" interpretation. The probability that PGA exceeds 0.1g is 84 percent if M7 event occurs. An event with 84 percent probability of occurrence is not necessary to occur (statistics), but is interpreted as sure to occur (one event). Similarly, the probability that PGA exceeds 0.1g is 50 percent if M6 event occurs. If earthquake occurrences follow Poisson distribution, the probability that at least one PGA exceeds 0.1g is about 99.3 percent if 10 M6 events occur. This can not be interpreted as 10 events (PGA exceeds 0.1g). The probability that PGA exceeds 0.1g is 16 percent if M5 event occurs. The probability that at least one PGA exceeds 0.1g is about 99.99999 percent if 100 M5 events occur. This can not be interpreted as no event (PGA exceeds 0.1g) to occur.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
1	Jim Beavers	comment #1 (P i, 1st paragraph)	Line 7, it is stated: Seismic risk, on the other handed, 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, Illinois to collapse. Thus, I passsed 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 time period, such as 1% of 10,000 cfs being exceeded in one year (Gupta, 1989). Similarly, 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, the larger magnitude, the higher potential to cause harm, a magnitude *M* or greater with a MRI is seismic hazard. Similarly, MMI or ground motion at a site is a property of an earthquake, MMI VIII (or PGA 0.25–0.30g) or greater with a return period is seismic hazard. MMI VIII is described to have a considerable damage to ordinary buildings. Consequently, a 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 described 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 (*M* or greater) occurrence during a specific time period is risk.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
2	Jim Beavers	**Page i, Paragraph 2.** Last sentence it is stated: “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	**Page i, Starting in Paragraph 3.** Line 16 it states: “There is a mathematical error in the . . .” This discussion is continued through paragraph 4.	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 on PSHA and SHA. There are also several references on these.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
4	Jim Beavers	**Page 1, Paragraph 1.** Line 13, it 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 Cell report for Site A had a peak ground motion design value of 0.48g. The CERCLA Cell project was stopped for political reasons not technical.	This statement reflects the fact that Kentucky Solid Waste Division refused to issue the permit by citing the USGS hazard estimate.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
5	Jim Beavers	**Page 1, Paragraph 2.** Line 4, it is stated: Currently, the highest building design PGA used in California (UBC-97) is capped at about 0.4g.	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 attenuation relationships (near-source saturation), this cap (0.4g) may still be valid.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
6	Jim Beavers	Page 1, Paragraph 2. Line 12 it is stated: “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 (NMSZ) 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 EPRI and LLNL 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 it 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	Page 3, Paragraph 1.	This paragraph is right on target.		

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
8	Jim Beavers	**Page 3, Paragraph 2.** First line it is stated: "Objectives of this project are . . ."	I would think one objective would be to clearly show why the PSHA approach overstates the seismic hazard.	PSHA approach may understates the seismic hazard. For example, the ground motions with 500-year 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 it is a high or low estimate.	
9	Jim Beavers	**Page 4, Paragraph 1.** First sentence it is stated: "Two methods . . ."	I currently do not believe that both PSHA and DSHA are commonly used today. I think the use of PSHA for outweighs the use of DSHA. In a recent correspondence with from 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."	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
10	Jim Beavers	**Page 4, Paragraph 4.** Last sentence states; “Wang (2004) . . .”	I assume Wang (2004) is Wang, Z. (in press) reference document at bottom of page 53 or is it Wang et al. 2004. Also on page 53 you have a Wang 2003 with no title or reference. In addition, I would suggest you list your reference 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 site SRL Vol. 63 which should be Vol. 68.	These will corrected.	
11	Jim Beavers	. **Page 5, Paragraph 2.** Second sentence it states: “The probability that no earthquake will . . .”	Suggest this say: “The probability that no such earthquakes will . . .”	Revised	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
12	Jim Beavers	• Page 5, Paragraph 2. Fourth sentence it 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 in the introduction and stick with that notation throughout the document. See Comment on Item 1. What you are calling seismic risk I still see as frequency because a 10% 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." 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	Document / Section or Page #	Comment	Response to Comment	Resolution
13	Jim Beavers	. **Page 5 Paragraph 2 continued on page 6.** Last sentence it 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 some place to get my design values. In the old days we put it right under our site.		
14	Jim Beavers	**Page 6, Paragraph** 2. General	I basically agree with this paragraph assuming your Gutenburg – Richter curve represents the earthquake activity of the NMSZ. However, when I got to pages 16 through 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	**page 6, ragraph 2.** st sentence states: he risk sed by . .	This is still frequency to me.	By common definition, a frequency is used to describe how often an event occurs, is not a probability to occur over a time period.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
16	Jim Beavers	**Page 6, Paragraph 3.** First sentence states: "In practice . . ."	To me this is where the spatial aspects come into the equation.	agree	
17	Jim Beavers	**Page 6, Paragraph 3 continued on Page 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	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
18	Jim Beavers	. **Page 6, Paragraph 3 continued on Page 7.** Seventh sentence states: “Similarly, the ground motion and their MRI’s at a site . . .”	Here you are going from Equation (3), which you justified on page 5 as the probability of earthquakes equal to or greater than a specific size (*M*) with *X* percent PE 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 a simple mathematics. From equation (6), $\ln(Y) = f(M,R) + n\sigma_{\ln,Y}$, (6) We have $M = g(R, \ln Y, n\sigma_{\ln Y})$. (16) Combining equation (16) with equation (15) $\tau = \frac{1}{N} = e^{-2.303a+2.303bM}$ (15) Results in $\tau = \frac{1}{N} = e^{-2.303a+2.303bg(R,\ln Y, n\sigma_{\ln Y})}$ (17)	
19	Jim Beavers	**Page 6, Paragraph 3 continued on Page 7.** Seventh sentence it 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, the equation (17).	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
20	Jim Beavers	• **Page 6, Paragraph 3 continued on Page 7.** Eighth sentence it 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 be considered 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	• **Page 6, Paragraph 3 continued on Page 7.** The eleventh 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 #18	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
22	Jim Beavers	. **Page 8, Paragraph 1.** Third sentence it 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	. **Page 8, Paragraph 1.** Fourth Sentence it 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 on 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 Comment 12 and 15.	See response to comment #18	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
24	Jim Beavers	. **Page 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 cost $500 I don not have a high seismic risk. This is why there are no nuclear power plants within a 120 mile radius of the NMSZ.	This is good example showing that lower exposure (building) gives you lower risk even though hazard is high.	
25	Jim Beavers	. **Page 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, like the flood risk.	
26	Jim Beavers	. **Page 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 NMSZ.	The comparisons in the report are based on the same exposure. Higher exposure makes the comparison more valid.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
27	Jim Beavers	. **Page 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 0.97g." It is then stated: "This PGA (0.97g) 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 0.97g if each of the three earthquakes occur." In my view it means that the probability of exceedance of a 0.97 PGA will occur on the average once every 2500 years over hundreds of thousands of years.	In the Wang and Ormsbee 2005 EOS paper it is stated: "Figure 2 shows that PGA with 2% PE in 50 years is 0.97g." It is then stated: "This PGA (0.97g) 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 0.97g if each of the three earthquakes occur." A probability of 0.0835, 0.0294, or 0.0086 that PGA will exceed 0.97g if each of the three earthquakes occurs does not mean this will occur.	
28	Jim Beavers	. **Page 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	Document / Section or Page #	Comment	Response to Comment	Resolution
29	Jim Beavers	• **Page 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 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 BSSA are using the M 6.0 Parkfield event to clearly show the uncertainty of ground motion for any earthquake. In reality I know that both the ground motion are 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 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), in comparison with the distance being measured for a point source. We agree with that "In reality I know that both the ground motion are 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 results in different formulation for hazard calculation. In other words, current PSHA has a mathematical problem.	
30	Jim Beavers	• Page 11, Equation 10.	Below this equation you describe σ_{source} and σ_{path} and do not describe $\sigma_{modeling}$ is there a reason for this? I do not have EPRI 2003 to verify.	$\sigma_{modeling}$ describes modeling uncertainty.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
31	Jim Beavers	· **Page 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 in 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 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 exceed 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 exceed while T is the return period of the characteristic earthquake. See earlier comments 13, 18, 21 and 23.	These equations show the fundamentally difference between the recurrence interval (T) of an earthquake and the return period (Trp) of a ground motion that is generated by the 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 period from a single recurrence interval.	
32	Jim Beavers	· **Page 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 because the spread is one order of magnitude based on the M 6.0 at Parkfield.	The term *ergodic* assumption was defined by Anderson Brune (1999).	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
33	Jim Beavers	**. Page 15, First Paragraph.** Fifth sentence that starts with: "This interpretation fundamentally . . ."	I agree that in the discussion above that it kind of gets ludicrous when we go talking about a 100-million year earthquake. However, I really do not think you are changing the physical and statistical meanings except maybe to the lay person. 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 year return period in flooding or a 100 million return period in earthquakes. I guess a 100 million year 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.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
34	Jim Beavers	. **Page 15, First Paragraph.** Eighth and ninth sentences that both start with: "Figure 9 shows . . ."	It is quite clear to me that if you have a M 7.7 that has an MRI of 500 years in the NMSZ and the uncertainty does exist per Campbell (June 2003), BSSA, that you will have the uncertainty show in Figure 9and if the median PGA is 0.36 g then the probability of exceeding 0.36 g, given the earthquake occurs, is (1/500)x0.5 or 0.001 annual frequency or an event that has a return period of 1000 years of during the 50 year life of a building there is a 5% chance the building will experience that kind of ground motion. In past designs, the rule was to design for a 10% chance in 50 years which is the "500 year earthquake" in better words (more accurate) an earthquake that might occur from the characteristic fault that could cause the building experience at PGA of 0.36g or more in its life time.	Good comments. These show the differences between PSHA and the proposed approach.	
35	Jim Beavers	. **Page 15, First Paragraph.** Last sentence where it 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 years as being the ground motion occurs at least once in 2,500 years? They should be interpreting it as: "on average, over hundreds of thousands of years, this ground motion will be exceeded once every 2,500 years.	According to McGuire (2004), 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 exactly that way.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
36	Jim Beavers	. Page 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 you discussion in the first paragraph. See earlier comments 13, 18, 21, 23, 33, 34, and 35.	Temporal and spatial measurements are two the most fundamental elements of the world. Mixing them one way or the other would cause problem.	
37	Jim Beavers	. Page 15, Second Paragraph. Second sentence that starts with: “Temporal and spatial . . .”	I am confused. Here like you are saying that the temporal measurements (M) and spatial measurements (ground motions) are two intrinsic independent characteristics of and 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.	
38	Jim Beavers	. Page 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 lay person or engineer that 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 that are not familiar with seismic design.	Unfortunately, it happens all the times.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
39	Jim Beavers	• Pages 16 through 18. Section 2.2 New Approach–Seismic Hazard Assessment.	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 (REI 99)) and my use of the USGS methodology I had access to the deaggregations. The deaggregations for both (McGuire and USGS) show that a magnitude M 7.5 or 8 was driving the PSHA ground motions 20 kilometers (km) from the PDGP. The 20 km is based on (Johnston and VanAresdale, Appendix to REI 99). So I said: “Ok, let’s have a DSHA earthquake of M 8.0 occur 20 kilometers from the PGDP and let’s also be more realistic and have an M 8.0 occur 60 km from the PGDP 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 years, the ground motion generated by the earthquake at a site must also occur every 500 years.	
40	Jim Beavers	• Pages 16 through 18. Section			

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
41	Jim Beavers	. Page 22. Last paragraph.	In this paragraph it appears that you reference Wheeler 1997 in support the NMSZ extending northeastward toward the PGDP and site Wheeler 1997 in support of it not extending toward the PGDP. 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.	These will clearified.	
42	Jim Beavers	. **Page 20. Last paragraph.** Last sentence which starts out as: “This can be seen clearly . . .”	As an engineer when I look at Figure13 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 et al. 97 it looks to me like Johnston and VanAresdale (REI 99) have a justification for the northeast extension.	Will revise	
43	Jim Beavers	. **Page 21. First paragraph.** Sixth sentence where it 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 NMSZ?	In terms of stress field and focal dept.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
44	Jim Beavers	. **Page 21. Second paragraph.** Last sentence that starts with: "Thus, there is no evidence . . ."	I think the jury is still out on this.		
45	Jim Beavers	. **Page 21. Last paragraph.** Last sentence where it states: "In this report, we used the location . . ."	I agree with using a maximum magnitude of M 7.5.		
46	Jim Beavers	. Pages 24-28. Section 3.2.	I have read this section and am not going to comment as I feel it has little bearing on PGDP.		
47	Jim Beavers	. Page 29. First paragraph.	I don not have a copy of Peterson 2005 although I was at the workshop.	It is summary for a meeting between KGS and USGS in Lexington.	
48	Jim Beavers	. **Page 29. First paragraph.** Fourth sentence that starts with: "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).	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
49	Jim Beavers	. **Page 32. First paragraph.** Last sentence that starts with 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 NMSZ.	Will correct it.	
50	Jim Beavers	. **Page 32. Last paragraph.** Fifth sentence that starts with: “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.	
51	Jim Beavers	. **Page 37. Last paragraph continuing on to Page 38.** Ninth sentence that starts with: “As shown in the Figure, Frankel . . .”	The figure actually shows Frankel attenuation curve at near source similar to Campbell (2003). It is AB06 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-DC-S	The comparison should be at distance between 10 and 40 km. Frankel and others (1996) did not provide values less than 10 km.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
52	Jim Beavers	. **Page 40. Last paragraph.** First sentence that starts with: "Figure32, 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 us 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 0.2s and 1.0s response accelerations of the four attenuation relationships for an M7.5 earthquake in the central United States.	
53	Jim Beavers	. **Page 40. Last paragraph.** Last sentence that starts with: "Tables 7, 8 and 9 list the 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% probability of being exceed during its assumed life. The assumed life was 50 years. For a 10% probability of exceedence in 50 years represents an event that occurs every 475 years to be exact or 500 years 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, page18 that the mean PGA would be 0.44g so how could your mean PGA ground motions in Table 7 be below 0.3g. You need to have more discussion in you report on how you got these numbers and the justification for it.	0.44g is the median PGA for a site at 30 Km distance. Table 7 is for PGAs at a site of 45 km.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
1	Ken Campbell	General Hazard vs. 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 if 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 a 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),"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 frequency. At each throwing, 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). Earthquake and its ground motion at a site are analog to throwing a dice.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
2	Ken Campbell	Temporal vs. Spatial	I think that the distinction between temporal and spatial descriptions of hazard 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 mumber 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 non-temporal 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 the most fundamental elements of the world. Mixing them one way or the other will cause problem. Any activity or event is always associated with a time and space. See response to comment #1 on frequency vs. probability.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
3	Ken Campbell	Frequency vs. Probability vs. Return Period	Whether from temporal or non-temporal 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 lognormal distribution (or BPT, 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 of 0.01 of, for example a flood event, is often referred to as the 100-year 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 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 misconcept 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 one year) or the theoretical frequency that corresponds to that probability.	First, frequency and probability are different (see response to comment #1) and can not 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 can not be compared.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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 non-temporal 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 lognormal), (2) should this distribution be truncated at its upper end (this truncation is usually taken as 2-3 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 CEUS 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 Distributio n.	The lognormal 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 lognormal 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	Document / Section or Page #	Comment	Response to Comment	Resolution
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 lognormal 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 arbitrarily.	
7	Ken Campbell	Aleatory vs. 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 NGA 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 the ENA can be assumed to be the same as that in WNA, 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 CEUS.	
8	Ken Campbell	Biased Median Estimate	In my view, many of the theoretically derived attenuation relationships in ENA 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 ENA 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.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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" (SHA) 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 analysis and technically sound. The definition of hazard and risk used in this report follows the accepted convention, particularly in engineering (hydraulic, flood, wind, and snow). These definitions are also consistent with those of McGuire (2004) and Reiter (1990). A better explanation on the methods used and the assumptions made will be addressed.	
2	Leon Reiter	Specific comment #1 (P 1, 2nd 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 one week? During one 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	Specific comment #2 (P 4, 1st paragraph)	DSHA does not (as stated in (2)) require the determination of earthquake occurrence frequencies.	True.	
4	Leon Reiter	Specific comment #3 (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	Document / Section or Page #	Comment	Response to Comment	Resolution
5	Leon Reiter	Specific comment #4 (P 5, Section 2.1.1)	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 is it 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. (continue to next page)	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 (MRI) 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 defined 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, the larger magnitude, the higher potential to cause harm, a magnitude *M* or greater with a MRI is seismic hazard. Similarly, MMI or ground motion at a site is a property of an earthquake, MMI VIII (or PGA 0.25-0.30g) or greater with a return period is seismic hazard. MMI VIII is described to have a considerable damage to ordinary buildings. Consequently, a 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 described 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 (*M* or greater) occurrence during a specific time period is risk.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
6			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 why they chose these definitions and 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. The exposure time is a normal life time 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	Specific comment #5	Figure 2 and Figure 23. Vertical axis should be "N" not "Log (N)"	Will revise.	
8	Leon Reiter	Specific comment #6 (P 7)	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 the specific comment #4	
9	Leon Reiter	Specific comment #7 (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? (response to the specific comment #4)	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
10	Leon Reiter	Specific comment #8 (P 11)	1st 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 Eq. 4 is to account for the uncertainty of focal point (distribution). The uncertainty of focal point is accounted in part by the uncertainty of ground motion because R is measured as a single distance (rupture, JB, or seismogenic) regardless focal distance. Eq.4 counts the distance uncertainty, at least some portion, twice. Similarly, $f_M(m)$ in Eq. 4 is to account for the uncertainty of magnitude (distribution). Also similarly, the ground motion standard deviation is dependent of M. Again, Eq.4 counts the magnitude uncertainty, at least some portion, twice. These will be fully discussed at the review meeting.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
11	Leon Reiter	Specific comment #9 (P 12)	1st 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 CEUS. This will be discussed at the meeting.	
12	Leon Reiter	Specific comment #10 (P 15)	1st paragraph, first sentence. The authors state that geologic records of earthquakes are limited to the past 11,000 years (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 thousand of years.	But not hundreds of million of years.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
13	Leon Reiter	Specific comment #11 (P 15)	1st paragraph, last line (see also statements in the middle of the first paragraph.) I can't find the statement in Frankel (2005) which says that ground motion with a 2500 year return period **will** [authors' emphasis] occur at least once in 2500 years. On the contrary, Frankel (2005) talks about the ground motion being exceeded once **on average** [my emphasis] over 2500 years. Also, in a response to Wang and Ormsbee (2005), Holzer (2005) clearly states that the 2500 year PGA is **not guaranteed** [my emphasis] to occur in 2500 years. How important is this to the authors' criticism of PSHA?	Figures 1 and 2 in Frankel (2005) shows that (which is the acceleration that will be exceeded). Frankel's explanation is a "deterministic" interpretation. An event with a 63% probability of occurrence may not occur, but was interpreted and shown to occur.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
14	Leon Reiter	Specific comment #12 (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 mixing 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	Document / Section or Page #	Comment	Response to Comment	Resolution
15	Leon Reiter	Specific comment #13 (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 0.1g (and whose 16th percentile is about 0.04g and whose 84th percentile is about 0.22g). Ground motion contributions at 0.1g 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). Also the data base used for determining flood 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. If there are only two characteristic earthquakes, M5.5 and M7.5, with 0.004/yr and 0.002/yr (Fig. 2) both at 30 km. At 0.22g, the confident level is 84% (16% PE) if M5.5 occurs, and 16% (84% PE) if M7.5 occurs. Here, ground motion with a confident level of 84% is compared with the one with a confident level of 16%. This comparison may not be statistically correct. Comparison for two statistic datasets should be based on the same level of confident. Equation (17) describes a hazard curve in terms of **ground motion and its MRI** [my emphasis] at a site has a clear physical meaning. The hazard curve directly converted from G-B curve (Eq. 15) and ground motion attenuation (Eq.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 meanings, the way how the curves are constructed and used. In fact, PSHA was originally developed from 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.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
16	Leon Reiter	Specific comment #14 (Fig. 10)	Figure 10. What would the mean seismic hazard be? In the title 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 Fig. 10.	
17	Leon Reiter	Specific comment #15 (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.	
18	Leon Reiter	Specific comment #16 (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 is the New Madrid fault 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.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
19	Leon Reiter	Specific comment #17 (P. 21)	1st 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 fault, the proposed northwest-trending structure, and discuss their significance. They could also show the plots of micro-seismicity (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 2002, Risk Engineering, 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	Specific comment #18 (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 be the same as the New Madrid faults shown in Figure 31? What are the blue boxes trending NNW supposed to represent?	The blue lines represent New Madrid faults (SW, BL, NE, W, and thrust-box) and rift boundaries (ER and WR) by Johnston and Schweig (1996). The faults in Fig. 31 are the same as those of Johnston and Schweig (1996), except the thrust fault presenting by northern edge.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
21	Leon Reiter	Specific comment #19 (P. 24)	1st paragraph. The authors refer to Figure 10. Do they mean Figure 15?	Yes, Fig. 15.	
22	Leon Reiter	Specific comment #20 (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 12 above). Do the authors mean to say "areal" rather than "aerial?" (see also "aerial" in paragraph 1 of p. 40)	The Figures 15 and 16 were taken from other reports. The references will be cited. It should be “areal”.	
23	Leon Reiter	Specific comment #21 (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	Specific comment #22 (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 Figs. 18 and 19, large earthquakes (M=7.0 to 7.5) in the background zone was used in the national mapping. The recurrence interval of the large earthquake is in 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 Fig. 20. In other words, the large earthquakes were introduced, but have no effect on hazard calculation. Some people, even seismologists, have used Fig. 19 to generate ground motion hazard maps to show the general public and policy makers. This is clearly confusion. Fig. 20 was used to show that there is no contribution to the hazard from the large background earthquakes. Magnitude 6 and 6.5 earthquake shown in Fig. 20 was 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).	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
25	Leon Reiter	Specific comment #23 (Fig. 21)	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 boundary.	
26	Leon Reiter	Specific comment #24 (P. 32)	1st 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	Specific comment #25 (P. 32)	2nd 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 the1811-1812 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 vs. mean recurrence interval (or return period for ground motion). The cluster events are considered through the cumulative effect.	
28	Leon Reiter	Specific comment #26	Figure 22. Is the red curve a line drawn through individual seismicity data points?	It should be, but directly cited from Frankel and others (1996).	
29	Leon Reiter	Specific comment #27 (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	Specific comment #28	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	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
31	Leon Reiter	Specific comment #29 (P. 37)	1st paragraph. Contrary to what is stated, Table 6 contains five, not six attenuation relationships, the lowest value of which is 0.69g, not 0.46g. Also I am not clear what range of standard deviations *the authors* are assuming for the central U.S. Is it 0.6 to 0.8?	Errors will be corrected. 0.6 to 0.8 is the range of standard deviation for all attenuations in CUS. Exactly number used are based on each attenuation.	
32	Leon Reiter	Specific comment #30 (P. 37)	2nd 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 (USGS/NRC Workshop, 2005)." I contacted someone from the NRC who was at the workshop and the USGS organizer of the workshop and they do not remember this statement about a consensus.	There is video CD for the workshop.	
33	Leon Reiter	Specific comment #31	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	Specific comment #32 (P. 39)	1st paragraph. Why did the authors choose these 4 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 a “outlier”	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
35	Leon Reiter	Specific comment #33 (P. 40)	1st paragraph. Re 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 (round-up to 15) km. Higher background earthquake will have (and should have) significant effect on hazard calculation. But the large background earthquakes have no effect because the way they were treated in a PSHA study. See response to comment #22 for further explanation.	
36	Leon Reiter	Specific comment #34	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 Fig. 31 are the same in Fig. 12. See response to comment #18.	
37	Leon Reiter	Specific comment #35 (P. 43)	Tables 7, 8, and 9, when compared to Figures 27 to 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 13.	For a single characteristic source, SHA is equivalent to a deterministic scenario. See explanations to comments #8, 12, and 13.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
38	Leon Reiter	Specific comment #36 (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	Specific comment #37 (P. 44-45)	There are many important issues raised here. Comments 4, 8, 9,11, 12, 13, 14, 35, and 36 address these issues and the content of pp. 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 (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	Specific comment #38 (P. 44)	1st 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, 1st paragraph.	See explanations to comment #4.	
41	Leon Reiter	Specific comment #39 (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 in terms of mean and median hazards. These will be addressed and discussed at the meeting.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated February 2007
April 2007

Comment on *"Seismic hazard assessment for Paducah gaseous diffusion plant" by Z. Wang and E. Woolery*

Mai Zhou
Department of Statistics
849 Patterson Office Tower
University of Kentucky
Lexington, Kentucky 40506
E-mail: mai@ms.uky.edu

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

$$\begin{aligned}\gamma(y) &= \sum vP[Y \geq y] \\ &= \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln(\xi) - g(m,r))^2}{2\sigma^2_{\ln,y}}] d(\xi)\} f_M(m) f_R(r) dmdr \\ &= \sum \iint [1 - \Phi(\frac{\ln(y) - g(m,r)}{\sigma_{\ln,y}}) f_M(m) f_R(r) dmdr\end{aligned} \tag{3}$$

where *v* is the activity rate, $f_M(m)$ and $f_R(r)$ are the probability density function (PDF) of earthquake magnitude *M* and site-to-source distance *R*, respectively, and *g*(*m,r*) and $\sigma_{ln,y}$ are the median and standard deviation at *m* and *r*, Φ(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 needs caution and a through review is perhaps needed.

1. Whether the error distribution is normal or not? Even it is normal, whether the variance of the error distribution remains a constant, as *M* and *R* changes? The systematic change of the variance, called variance structure, do not affect the estimation of the regression function *g*(*m*,*r*) too badly. But for 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 there is other systematic influence on the regression being ignored, then often the discrepancy in the regression functions are treated as error and regulated to *E*, thus inflating the $\sigma_{ln,y}$. For example, site condition is not considered in the model. Also, if the distance *R* are measured with large error, the changes in ground motion due to these factors may be mixed with the intrinsic variability of *E*.

3. The probability density function (PDF) $f_M(m)$ and/or $f_R(r)$. The form and accuracy of these two densities affects the exceedance probability a great deal. How confident we are 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 for estimating the regression function $g(M,R)$. Since the least squares method used in the estimation of regression function is also consistent when the error follows other type 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, R. Only when M, R, and E are independent random variables, the joint probability density function of M, R, and E can be written as a product

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

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

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

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

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

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

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

As demonstrated above, equation (3) is derived from the pre-condition that *only if* M, R, and E are independent random variables. However, if the ground-motion variability E depends on M and R, then hazard calculation, equation (3), in PSHA is not correct.

Appendix D – Review Comments and Responses for the Final Report (May 2007)

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated May 2007
June 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
1	Roy Van-Arsdale		An appendix illustrating your calculations for both PSHA and DSHA.	PSHA calculation is straight forward, but very time consuming (long). We decided not to include it. DSHA calculation is shown in table 8 though 11.	
2	Roy Van-Arsdale		A brief discussion in your conclusion section point out the differences between your values and the USGS values.	This has been added.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated May 2007
June 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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 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. 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 (eg. 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 highlighted in yellow. All suggested changes are straightforward to implement. With the highlighted comments addressed as suggested, the report will then form a good assessment of the seismic hazard at Paducah.	Responses are only provided to the highlighted (yellow) ones. Others have been revised accordingly.	
2	Gail Atkinson	20.2	The use of Mx=6.8 in Wabash is inconsistent with the estimated range of M6.2 to 7.3 for paleoseismic events. The Mx for WVSZ should be at least 7.3, and possibly 7.5. See also Figure 18, which also shows higher magnitudes for paleo events.	We used mean values (best estimate) for any set of parameters throughout this report. Fig. 18 was the old estimate and used by the USGS (Frankel and others, 2002).	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated May 2007
June 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
3	Gail Atkinson	21.8	The treatment of the background source is not satisfactory. You cannot justify a low Mx (in the M5 range) anywhere in the world. Most global studies suggest Mx~7 for stable craton regions (eg. Johnston et al., 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 WVSZ, which are handled in the PSHA.	As discussed in Wang (2003a), there is no contribution from those large background earthquakes because (1) a large-area source zone and (2) a longer recurrence interval (more than 10,000 years). Use of the large background earthquake only causes confusion.	
4	Gail Atkinson	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. Fig. 20 shows the earthquakes that was 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.	Rrup was used throughout this report.	
6	Gail Atkinson	37.3	The sentence, and corresponding approach "We used a point source at 15 km with a maximum magnitude of M5.0 to account for the local earthquake" is not justified. A proper areal source zone with the magnitude recurrence relation as defined from Fig. 21 should be defined and included in the PSHA, with a suitable Mx (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 WVSZ areal sources are defined for the PSHA.	The local zone (background) is a point source at 15 km. WVSZ is an areal source shown in Fig. 30.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
8	Gail Atkinson	38.1	The most important uncertainties for a logic tree in this case are the GMPEs 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 singe Mx 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 Mx. 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 Mx and distance can be used to quantify hazard at a site in NMSZ (Frankel, 2004; Petersen, 2005). The background seismicity was treated in a similar way to the USGS mapping (Frankel and others, 1996, 2002).	
9	Gail Atkinson	Table 6	What weights were used for the GMPEs? Does Table 7 and Figs 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 GMPEs. Table 7 and Figs 31-33 refer to the mean hazard. No sensitivity to alternative models was carried out in this study.	
10	Gail Atkinson	44.8	Delete the entire paragraph under Table 15. You consider only probabilities to 1/2500 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.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated May 2007
June 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
1	Jim Beavers		Zhenming, per our conversation today with regard to your PSHA PGA number (0.49g)on hard rock (USGS Type A foundation) at 2500 years we talked about three things that brought the number down from the 0.8g PGA I had calculated from the USGS (1996) B-C boundary of 1.2g and the corresponding 0.8g Risk engineering had calculated. These three things were These all make sense to me, as a result, the 0.49g seems realistic to me knowing these three items changed. To convince others that 0.49g is the right number for this study I would run a sensitivity analysis. For example, run your PSHA with just using Frankel's attenuation and see how much it raises the 0.49g. 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 0.8g. This will give you a feel for what is contributing to the reduction. The only other variable that may cause the 0.49g to go up is the lower return period 500 verses 1000, but you used that anyway. In McGuire's and Frankel's 0.8g was an M 8.0 and R of 1000. 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 PGDP, which is highly likely to occur for the upcoming DOE CERCLA Waste Disposal Facility.	The three things are: 1) the location of the New Madrid faults (further west), 2) a smaller mean magnitude (M7.5 vs. M7.7) for the characteristic earthquake in the New Madrid Seismic Zone, and 3) use of lower ground motion attenuation relationships.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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 sec. and 7.3-1c for 1 sec. We did not do a 0.2 sec curve. The CERCLA will have longer period motions, probably around 1 sec. It looks like your 0.49g will lower the long period motions. I took a quick look at the Bechtel-Jacobs report and with a hard rock PGA of 0.49g 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 0.1sec at top of soil of 1.2, and from figure 7.3-1c I get an amplification factor at 1 sec 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 the 0.1 sec because of the PGA being 0.49g, But when you get out to the 1 sec period we had a 25% higher amplification because our hard rock PGA was 0.8g or 0.71g after refinement of my earlier calculations in the Bechtel-Jacobs report.	Soil amplification is not part of this project.	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated May 2007
June 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
1	Ken Campbell	General #1	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 appendix.	
2	Ken Campbell	General #2	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 (NMSZ) and the maximum magnitude earthquakes on the Wabash Valley Seismic Zone (WBSZ) and the Local Source Zone (LSZ) located at specific distances to the PGDP 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 PGDP site than was assumed. Of course, there would be some floating earthquakes within the LSZ that would also occur closer to the PGDP 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 on the seismic hazard assessment at the Paducah Gaseous Diffusion Plant and its surrounding area, and 2) to communicate the hazard information more effectively to the users and policy makers.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
3	Ken Campbell	General #3	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 WVSZ and LSZ). 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 is to perform a PSHA with some discussions for improvements. This report reflected that. More analyses, including sensitivity analysis, could be done, but there is a time constrain.	
4	Ken Campbell	General #4	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 (NSHMP) 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 CEUS. We had tried our best in this report.	
5	Ken Campbell	General #5	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. DHSA also has weaknesses and strengths, but comments throughout the report tend to emphasize its strengths while emphasizing the weaknesses in PSHA.	Text has revised to address the weaknesses of DSHA.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
6	Ken Campbell	Page 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 CEUS (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% 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 (0.6g and 0.8g) were reduced by a 1.5 factor.	
7	Ken Campbell	Page 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 CEUS, and the lower rate of attenuation in the CEUS.	This has been revised.	
8	Ken Campbell	Page 8.	Deaggregation methods were developed to overcome the disadvantage in the PSHA methodology that was identified by NRC (1988) and has now been accepted by practitioners and regulators alike as a valid means of developing one or more design earthquakes from PSHA results.	De-aggregation is an effort in PSHA to try seeking the "design earthquake." (revised)	
9	Ken Campbell	Page 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., ≥ 2% probability of exceedance in 50 years). Even Figure 4 shows that the contribution of uncertainty caps out at 2-3 standard deviations for probabilities constrained to such levels.	The ground-motion uncertainty is an integral part of PSHA, a cap on it may not statistically sound.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
10	Ken Campbell	Page 10.	There seems to be a clear bias against PSHA, since only its disadvantages are listed, whereas only advantages are listed for DSHA. See General 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	Page 11.	References for the possible causes of seismicity in the NMSZ 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. However, those could cause confusion.	
12	Ken Campbell	Page 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 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	Page 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 PGDP site.	It is shown in Figs. 7 and 30.	
14	Ken Campbell	Page 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 WVSZ. These alternative source zones would have made a valid epistemic uncertainty model.	Different names have been used for the zone in the literature. WVSZ was used throughout this report.	
15	Ken Campbell	Page 21.	The characterization of the LSZ in terms of magnitude, distance, and focal depth distributions seems arbitrary and needs to be justified. For example, as discussed in the review meeting, Mmax (Mw) = 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 PGDP site. Based on a worldwide study, EPRI proposed that Mw = 6.3 ± 0.2 represented a reasonable estimate of maximum magnitude in non-rifted SCR crust. Alternatively, one could look at a much large region of the CEUS (and possibly eastern Canada) with tectonic conditions similar to the region around the PGDP site to come up with a more reasonable estimate of Mmax.	A M8.0 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	Document / Section or Page #	Comment	Response to Comment	Resolution
16	Ken Campbell	Page 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 years for such large events. The 1,000-year recurrence interval used previously by the USGS and others would appear to be longer justified.	Here is one reference published recently: Holbrook, J., Autin, W.J., Rittenour, T.M., Marshak, S., and Goble, R.J., 2006, Stratigraphic evidence for millennial-scale temporal clustering of earthquakes on a continental-interior fault: Holocene Mississippi River floodplain deposits, New Madrid Seismic Zone, USA: Tectonophysics, v. 420, p. 431-454. There are some GPS studies available, but were not used in this report. Mark Zoback also suggested 1,000 year recurrence interval at a recent EarthScope workshop.	
17	Ken Campbell	Page 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	Page 28-29.	There is no reference to studies (e.g., the recent NGA studies; Boore et al., 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 CEUS.	As the way it is being modeled (finite source and global data), ground-motion uncertainty is a dependence of magnitude and distance.	
19	Ken Campbell	Page 31.	The range of median PGA values from Table 5 is 0.69-1.20, not 0.46-1.20.	revised	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
20	Ken Campbell	Page 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 et al. (1996) is not that different from many of the other relationships in the distance range 10-100 km, so I don't understand the statement to the contrary. Furthermore, the Frankel et al. relationship represents NEHRP B site conditions and, using the USGS conversions 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 site. The distance is Rrup. No distance conversion was done. Frankel's ground motion values was corrected by the factor 1.53.	
21	Ken Campbell	Page 38.	As mentioned in General Comment 2, Table 6 does not represent a true PSHA, since it does not include: (1) epistemic uncertainty in Mchar and Mmax, (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 fault 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 the general comment #2.	
22	Ken Campbell	Page 38.	Why were the specific attenuation relationships selected for use in the study? For example, why was the Silva DC-S model chosen over the other three that he has developed and used to characterize epistemic uncertainty? Was the hard rock or NEHRP BC 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 DC-S model provides a reasonable value. Others represent different models, i.e., composite, double-corner, and hybrid.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
23	Ken Campbell	Page 38.	I don't see the justification for giving the 1,000-year recurrence interval on the New Madrid fault 25% 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	Page 43.	Using an estimated value of PGA from an estimated value of MMI at the PGDP site for the 7 February 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 years for determining design ground motions for the PGDP site. New relationships between PGA and MMI, some developed specifically for the CEUS, 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, 2006) was added.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
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.[1] 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 specific comments #2, 17, 20, 21, 23, 32, 33, and 36 **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. The specific comments #2, 17, 20, 21, 23, 32, 33, and 36 for the early version have also been addressed in some degree.	

---

[1] Please note that my review represents my own views and not necessarily those of my past employers, the Nuclear Regulatory Commission and the U.S. Nuclear Waste Technical Review Board.

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
2	Leon Reiter	Comments on section 6 (Results) 1.	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 (NMSZ), Wabash Valley (WVSZ), and local source zones, were the only ones considered in the analysis. Only one magnitude (Mmax) 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 WVSZ were allowed to occur anywhere within that zone. The NMSZ allowed two different recurrence intervals for the controlling earthquake, while the WVSZ 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 NMSZ and local source zone, the recurrence intervals for the controlling earthquakes in the WVSZ and local source zone. Also the effects of earthquakes smaller than Mmax 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 NMSZ 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 a site-specific. The main purposes are to gain better understanding on the seismic hazard assessment at the Paducah Gaseous Diffusion Plant and its surrounding area.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
3	Leon Reiter	Comments on section 6 (Results) 2.	The introduction of a two level design basis represents a positive step. The choice of a 1,000-year 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	Comments on section 6 (Results) 3.	There is some confusion between the use of the terms "mean" and "median." Based upon my understanding of the revised report the PSHA results 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.	Median is only applied to each ground motion attenuation relationship. Mean is for all others.	
5	Leon Reiter	Specific comment #1 (P 2, Fig.1)	Identify the location of the centers (0 km, 0 km) of the seismicity plots.	The map is a schematic and cited from Stain and others (2003). No reference point was given.	
6	Leon Reiter	Specific comment #2 (P 4) third paragraph	This paragraph implies that the SSE and the OBE for nuclear power plants are only determined through DSHA. This is not true. The OBE 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." USNRC Regulatory Guide 1.165 describes how PSHA can be used to determine the SSE.	Although these terms originally have a clear meaning, they are confused. All those could cause confusion have been deleted.	

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
7	Leon Reiter	Specific comment #3 (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 page 5.	
8	Leon Reiter	Specific comment #4 (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?	De-aggregation is an effort in PSHA to try seeking the "design earthquake." (revised)	
9	Leon Reiter	Specific comment #5 (P. 8, Second Paragraph)	Reiter (2004) does not appear in the list of references.	It is an abstract and deleted from the references	
10	Leon Reiter	Specific comment #6 (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.	These have been revised to use the background seismicity only.	
11	Leon Reiter	Specific comment #7 (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 that PSHA needs to improve.	
12	Leon Reiter	Specific comment #8 (P. 30, Figure 23)	If the report does include this figure (see discussion above), the title should mention and explain the use of REPI and RRUP in the figure.	Rrup is used throughout this report (revised)	

Review Comments and Reponses
Report on Seismic Hazard Assessment for Paducah Gaseous Diffusion Plant, Dated May 2007
June 2007

Comment Number	Reviewer	Document / Section or Page #	Comment	Response to Comment	Resolution
13	Leon Reiter	Specific comment #9 (P. 34, First paragraph)	The final report states that ground motion at near-source has been over-predicted 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 AB06 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 on 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	Specific comment #10 (P. 34, Second paragraph)	The basis for picking the four attenuation relationship and excluding others (e.g., Frankel) needs to presented.	These attenuation relationships represent different approaches (i.e., finite source/green function, double-corner, and hybrid methods).	