EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project

3002000717

Final Report June 2013

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*This document was **not** developed under a 10CFR50 Appendix B program.*

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ACKNOWLEDGMENTS

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This report describes research sponsored by EPRI.

EPRI would also like to acknowledge the Participatory Peer Review Panel (W. Arabasz – Chairman, B. Chiou, R. Quittmeyer, and R. Whorton), who reviewed the technical and process aspects of the project, and GEOVision, Inc., with The University of Texas, who conducted the shear-wave-velocity measurements at seismic recording stations. The ground-motion experts and seismologists, listed in Table 2.1-1, who participated in the due diligence review of the EPRI (2004, 2006) Ground-Motion Model, in interviews conducted by the TI Team (Appendix C), and in the October 17, 2012, workshop (Table 2.2.6-1) are also acknowledged. The value of the Updated EPRI (2004, 2006) GMM has been enhanced through productive cooperation from the Pacific Earthquake Engineering Research (PEER) Center, members of the NGA-East Project, and the U.S. Geological Survey (USGS). Some of the analyses and graphics contained in this report were prepared using **R** (R Development Core Team, 2012). EPRI thanks R. Chambers, G. Moore, and N. Sutherland of AMEC Environment & Infrastructure, Inc., for their assistance with the preparation of the report.

ABSTRACT

This report describes the Electric Power Research Institute (EPRI) (2004, 2006) Ground-Motion Model (GMM) Review Project, which developed an updated GMM for the Central and Eastern United States (CEUS) for use by licensees of nuclear generating plants to respond to the U.S. Nuclear Regulatory Commission's (NRC's) Request for Information to Title 10 of the Code of Federal Regulations 50.54(f), Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident, dated March 12, 2012.

The scope of this study was to determine whether the currently accepted existing EPRI (2004, 2006) GMM required updating, considering currently available data and seismological understanding of ground motions in the CEUS, and if determined to require updating, to update the model using accepted current practice contained in present-day NRC's seismic regulatory guidance. The team assembled to conduct the study was composed of distinguished subject-matter experts from industry, government, and academia. The study was carried out properly using a Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 process and the activities of evaluation and integration, the principal activities of any SSHAC study, were carried out properly and documented thoroughly. The activities of evaluation considered present-day data, models, and methods. The activities of integration captured the center, body, and range of technically defensible interpretations informed by the evaluation process (i.e., informed by evaluations of existing data, models, and methods).

The project solicited and evaluated inputs from recognized experts in the larger technical community, obtained ongoing process and technical review by a participatory peer review panel (PPRP), and solicited feedback from staff of the NRC throughout the study. The resulting Updated EPRI (2004, 2006) GMM is thus based on a comprehensive and traceable process, implemented in accordance with SSHAC guidelines in NUREG/CR-6372, *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts.* Considering current NRC guidance for updating an accepted existing hazard model, contained in NUREG-2117, *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*; the study used an enhanced SSHAC Level 2 assessment process. Therefore, the updated model can be used with confidence to calculate ground-motion response spectra at existing nuclear power plant (NPP) sites with assurance that the spectra properly represent current technical knowledge.

The study was conducted in two phases. Phase 1 consisted of assembling an up-to-date database and determining whether the EPRI (2004, 2006) GMM should be updated, and Phase 2 consisted of updating the EPRI (2004, 2006) GMM by integrating up-to-date data, models, and methods. As part of the project, shear-wave-velocity measurements were made at 33 seismic recording stations. In addition, the U.S. Geological Survey provided shear-wave-velocity measurements at 24 seismic recording stations. The project also obtained shear-wave-velocity profiles compiled

from the literature available in the NGA-East profile database. These shear-wave-velocity data were used to establish uniform reference conditions for evaluating ground-motion-prediction equations (GMPEs). The study established the technical basis for evaluating GMPEs and for updating the EPRI (2004, 2006) GMM by reviewing the current literature and conducting interviews and a workshop with ground-motion experts and seismologists. The study also developed the analytical approach for adjusting ground motions to CEUS reference-rock conditions. Computation of GMPE weights using empirical site class factors was an important part of the study, along with the update of the EPRI (2006) aleatory variability model based on results from NGA-West 1 (2008) and the NGA-West 2 (2012) studies.

The decision to proceed with the update of the EPRI (2004, 2006) GMM was based on the following information obtained during the Phase 1 review:

- Seven of the 13 developers of the GMPEs evaluated for development of the EPRI (2004, 2006) GMM now recommend that their GMPEs be replaced.
- Three new GMPEs were developed by ground-motion experts during the past 10 years.
- Eighty percent of the earthquake records in a new ground-motion database provided by the NGA-East Project are from earthquakes that occurred after the development of the EPRI (2004) GMM.
- The EPRI (2004, 2006) GMM was determined to over predict ground motions at some magnitude-distance and spectral frequency ranges important to NPP probabilistic seismic hazard assessments (PSHAs).

Computation of ground-motion response spectra for existing NPPs in the CEUS to support licensees' responses to the NRC's 50.54(f) letter dated March 12, 2012 requires use of present-day seismic regulatory guidance. This includes use of up-to-date, well-founded ground-motion and seismic-source models. The EPRI/DOE/NRC (2012) CEUS SSC model provides the required up-to-date seismic source model. Phase 2 of the study updated the EPRI (2004, 2006) GMM providing an up-to-date GMM for calculation of the GMRS at existing NPPs in the CEUS. The EPRI (2004, 2006) GMM was updated for both the Midcontinent and Gulf Regions.

The updated model was obtained through a structured evaluation of the range of diverse technical interpretations from the larger technical community and a full assessment and incorporation of uncertainties using an up-to-date database. Using the Updated EPRI (2004, 2006) GMM, test seismic hazard results for rock conditions were computed at the seven CEUS test sites for which test hazard results were computed as part of the EPRI/DOE/NRC (2012) CEUS SSC study. The hazard results obtained using the updated model were compared with the those developed in the 2012 CEUS SSC study, which used the EPRI (2004, 2006) GMM. The use of the Updated EPRI (2004, 2006) GMM, combined with the 2012 CEUS SSC model, resulted in reductions in seismic hazard at all frequencies except peak ground acceleration. The Updated EPRI (2004, 2006) GMM described in this report is suitable for use by licensees for development of responses the NRC's 50.54(f) letter and should be considered for other seismic regulatory purposes pending completion of the NGA-East Project.

Keywords

ground-motion model (GMM)

ground-motion prediction equations (GMPEs)

probabilistic seismic hazard analysis (PSHA)

Central and Eastern United States (CEUS)

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EXECUTIVE SUMMARY

The EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project was conducted during the period from March 8, 2012, to May 31, 2013, to provide the nuclear industry with an update to the EPRI (2004, 2006) GMM for use in conducting probabilistic seismic hazard analyses (PSHAs) to respond to the U.S. Nuclear Regulatory Commission's (NRC's) Request for Information (RFI) for existing nuclear facilities dated March 12, 2012. A Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 study process with a number of Level 3 process enhancements was used (NUREG-2117) considering present-day NRC guidance for updating an accepted existing seismic hazard model and balancing project-specific factors such as technical complexity, regulatory requirements, and resource limitations with the need to ensure with a high level of confidence that the updated model represents present-day technical knowledge. The purpose of providing an extended executive summary is to convey the extended scope of the project in somewhat greater detail.

This project was motivated by significant technical advances in predicting earthquake ground motion during the past 10 years, triggering the need to review the EPRI (2004, 2006) GMM and, if necessary, to update the model for use by licensees of nuclear plants located in the Central and Eastern United States (CEUS) in developing their responses to Near-Term Task Force (NTTF) Recommendation 2.1: Seismic. A key objective in planning the project was to implement a structured, unbiased process that included broad participation of the present-day GMM technical community, the regulator, and oversight groups to (1) define current seismological understanding of ground motion in the CEUS since the SSHAC study that developed the EPRI (2004, 2006) GMM, which began in 2002; (2) compile an up-to-date ground-motion database; and (3) evaluate whether the EPRI (2004, 2006) GMM required updating in light of the up-to-date database and present-day advances in the development of ground-motion-prediction equations (GMPEs).

For the purpose of defining the present-day state-of-practice for GMM, insights and perspectives from recognized ground-motion experts and from ongoing GMM projects were obtained. This was accomplished by means of conference calls, interviews, and a meeting at the offices of the U.S. Geological Survey (USGS). Table 2.1-1 lists the dates for these contacts and the professionals who participated, some of whom had participated in the SSHAC studies that developed the EPRI (2004, 2006) GMM. The observations and recommendations concerning the current state of practice for GMM in the CEUS that came from these activities were the basis for development of the EPRI (2004, 2006) GMM Review Project Plan described in Chapter 2.

These due diligence activities were conducted during the period from October 2011 to March 2012. During this period, interactions with the Pacific Earthquake Engineering Research (PEER) Center's NGA-East Project and the USGS National Seismic Hazard Mapping Project took place to establish processes for productive cooperation with these important ongoing projects throughout this study. The level of confidence that the Updated EPRI (2004, 2006) GMM represents present-day ground-motion-modeling practice has been enhanced by the broad participation of recognized seismologists and ground-motion experts from industry, government, and academia and by productive cooperation from participants in the PEER NGA-East Project and the USGS National Seismic Hazard Mapping Project.

The EPRI (2004, 2006) GMM Review Project implemented an enhanced SSHAC Level 2 study in order to provide a high level of assurance that the present-day data, models, and methods of the ground-motion modeling technical community were considered and that the center, body, and range of technically defensible interpretations have been properly represented in the updated model. The SSHAC process ensures thorough consideration of present-day knowledge and uncertainties of the larger technical community within a robust and transparent evaluation and assessment framework. Guidance for implementation of a SSHAC study is detailed in the NRC's NUREG/CR-6372, *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*, and NUREG-2117, *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies.*

The SSHAC methodology is accepted in present-day NRC's seismic regulatory guidance (Regulatory Guide 1.208) for ensuring that proposed seismic-design-basis ground motions properly represent uncertainties in data and scientific knowledge in compliance with the requirements of the seismic regulation 10 CFR Part 100.23 ("Geologic and Seismic Siting Criteria"). Therefore, the goal of the SSHAC methodology is the proper and complete representation of knowledge, data, and modeling uncertainties in the seismic-source characterization (SSC) and ground-motion characterization (GMC) inputs to the PSHA. Regulatory Guide 1.208 accepts the CEUS SSC and ground-motion characterization (GMC) models for the CEUS to be the starting basis for site-specific PSHAs at sites within the region and provides guidance for site-specific implementation. A SSHAC Level 3 study is required for development of a regional SSC or GMC model to be accepted as an element of the NRC's seismic regulatory guidance. A Level 2 study may be used for evaluating whether an existing accepted regional model requires updating for a specific application and, if determined to be required, for updating the model for PSHA at a specific site or another specific use.

A SSHAC assessment process consists of two core sequential activities: *evaluation* and *integration.* For a Level 2 study, these activities, which are conducted by a Technical Integration (TI) Team under the leadership of a TI Lead and the Project Manager, are described in NUREG-2117 as follows:

> The fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration, defined as:
>
> *Evaluation:* The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.
>
> *Integration:* Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods.

Implementation of each of the assessment and model-building activities of the EPRI (2004, 2006) GMM Review Project was carried out consistent with the evaluation and integration steps of a SSHAC Level 2 process. The specific roles and responsibilities of all project participants were defined in the Project Plan (EPRI, 2012). The technical assessments were made by the TI Team, which had the principal responsibility of evaluation and integration. The Database Manager and other technical support individuals assisted in the development of work products. Consistent with the SSHAC Level 2 implementation guidance, Resource and Proponent Experts participated in interviews. They continued technical interchange with the TI Team throughout the project. Also, the Resource and Proponent Experts presented their data and current models and interpretations at the workshop on October 17, 2012. The Participatory Peer Review Panel (PPRP) provided continuous interactive review of both the SSHAC Level 2 process implementation and the evolving technical assessments. Project communication with stakeholder observers assured proper integration of the activities of all participants.

For this project, the SSHAC Level 2 assessment process was enhanced by the implementation of a number of SSHAC Level 3 study processes. For example, the PPRP was engaged at project inception, including for development of the Project Plan and participation in the feedback workshop. Both the PPRP and the Resource and Proponent Experts provided extensive feedback. A comparison of the activities conducted during the EPRI (2004, 2006) GMM Review Project with those recommended in the SSHAC guidelines shows that the current standards of practice for a SSHAC Level 2 process were fully met and the activities of evaluation and integration were completely documented. The SSHAC Level 2 assessment process and implementation are discussed in depth in Chapter 3 of this report.

The objective of the project was to review the EPRI (2004, 2006) GMM and, if necessary, to update the model. Both the evaluation of whether the existing GMM should be updated and the implementation of the update study were carried out retaining the conceptual-structural framework of the EPRI (2004, 2006) GMM. The following steps were implemented:

1. Development of an up-to-date database.
2. Testing the EPRI (2004, 2006) GMM using the up-to-date database to determine whether it required updating.
3. Evaluation: Consideration of current data, models and methods that have been proposed by the larger technical community using the up-to-date database.
4. Integration: Assessment and incorporation of uncertainties representing the center, body, and range of technically defensible interpretations.
5. Adoption of new approaches to systematically document input from the larger technical community and to evaluate all data considered in order to increase transparency.
6. Engagement of all stakeholders and a robust peer review.

Highlights of the EPRI (2004, 2006) GMM review and update project are presented below.

STUDY AREA

The project study region (Figure 1) is the same as the region for the 2012 CEUS SSC model (EPRI/DOE/NRC, 2012). For the GMM, the project study region is divided into two sub-regions: the Midcontinent Region and the Gulf Region. The Updated EPRI (2004, 2006) GMM is applicable to all sites within the project study region. The western boundary is located approximately along the foothills of the Rocky Mountains at longitude 105°W. On the north, the study region extends a minimum of 322 km (200 mi.) beyond the U.S.-Canadian border. On the east and south, only areas that lie within the continental crust are included. The GMM does not apply to areas outside the study region boundaries, including the Western United States (WUS), Canada, most of Mexico, and the Caribbean Plate boundary area.

PRODUCTS OF THE PROJECT

Updated EPRI (2004, 2006) Ground-Motion Model

The Updated EPRI (2004, 2006) GMM was developed retaining the conceptual framework of the EPRI (2004) GMM for the Midcontinent Region and Gulf Region shown on Figure 1. The updated assessment was accomplished with the following major steps:

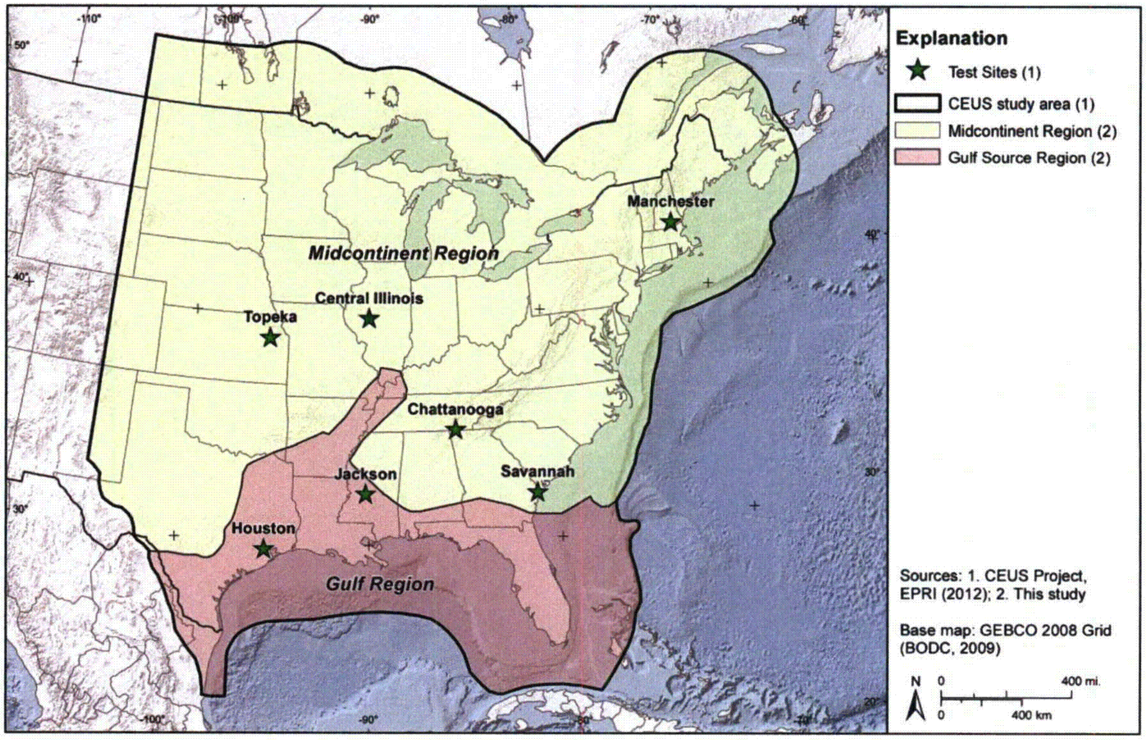

Figure 1
Study area showing ground-motion model sub-regions and test sites

- Prepare an up-to-date database of ground-motion recordings for use in testing the available Central and Eastern North America (CENA) GMPEs, using as a starting point the ground-motion database assembled by the NGA-East Project.
- Process the assembled database to ensure uniformity parameters and correction for near-surface site classifications throughout the study region, check the consistency of corrected data, and adjust, if necessary.
- Identify GMPEs and assign GMPEs to clusters by reviewing the literature, conducting interviews, and holding a workshop with current ground-motion experts.

- Establish analytical and empirical approaches for adjusting recording-site conditions using shear-wave-velocity measurements at strong-motion recording sites.
- Compute GMPE and cluster weights.
- Evaluate the epistemic uncertainty.
- Update the EPRI (2006) aleatory variability model.

The paragraphs that follow provide summaries regarding the evaluation and integration activities performed for development of the Updated EPRI (2004, 2006) GMM and describing additional products of the project.

Hazard Input Document

The hazard input document (HID) in Appendix G provides the documentation necessary for users to implement the Updated EPRI (2004, 2006) GMM in a PSHA. The HID contains all the information required for a future use of the model within a PSHA, but it does not include the technical basis or justification for the elements of the model. The purpose of the HID is to ensure that the expert assessments made by the TI Team are captured fully and are accurately and transparently communicated for use by the designated hazard analyst in a PSHA for a specific site. As part of this EPRI (2004, 2006) GMM Review Project, the HID was used by the hazard analyst, a member of the TI Team, to carry out hazard calculations at seven demonstration sites.

Documentation of Literature Reviews, Expert Interviews, and PPRP Correspondence

In order to demonstrate the structured and systematic evaluation of the range of diverse interpretations from the larger technical community in a structured and systematic way, the TI Team conducted literature reviews and both interviewed Resource and Proponent Experts, some of whose work was either not published or was awaiting publication. Appendix B provides the documentation for literature reviews, including literature review tables that document the results of the reviews by the TI Team. Appendix C provides the documentation for the interviews conducted by the TI Team with Resource and Proponent Experts who are working on CEUS ground-motion modeling. The TI Team obtained information from copies of papers under review or in press, as well as from updates about these experts' ongoing work. Appendix H and the PPRP Final Report present the PPRP input throughout the project.

Project Database

The EPRI (2004, 2006) GMM Review Project database was developed to compile, organize, and document the data sets and resources that have been utilized during the course of this project. Development of the project database began at the inception of the project and provided TI Team members with the current version of the NGA-East ground-motion database, the shear-wave-velocity database for seismic recording stations, and an up-to-date set of data, maps, and figures. The Database Manager established a File Transfer Protocol (FTP) site for the TI Team, Project Manager, and other participants in the study to access the project database. Appendix A provides details regarding the project database.

Shear-Wave-Velocity Measurements at Seismic Recording Stations

Shear-wave-velocity measurements were obtained for a suite of seismic recording sites in the CEUS from which usable recordings were available; the measurements were used for uniformly correcting the updated database. EPRI (2013a) describes the investigations conducted from May 15 and July 19, 2012, to develop S-wave velocity (V_S) models to a depth of 30 m (or more) and to estimate the average shear-wave velocity of the upper 30 m (V_{S30}) at 33 seismic recording stations located in the CEUS from which seismic recordings were available.

Additionally, the USGS measured shear-wave velocity at 24 seismic recording stations during 2011 and 2012 (Kayen et al., 2013). The results of these measurements were provided to the EPRI (2004, 2006) GMM Review Project as part of the productive cooperation between EPRI and the USGS established for the project. A summary of results from each of the recording site locations is provided in Chapter 4.

Based on these investigations, including overlapping shear-wave-velocity measurements at stations ET.SWET and US.CBN, the following results were obtained for support of ground-motion modeling in the CEUS.

- Shear-wave velocity for hard rock sites in general are, lower than the CEUS reference-rock velocity of 2,800 m/s, which is assumed for developing GMPEs; shear-wave velocities approaching or equal to the reference-rock velocity were encountered at depths greater than 30 m at some sites.
- Velocity inversions exist at some sites (i.e., shear-wave velocity of rock over a depth interval in the profile can be higher than that for an interval that is immediately below it).
- Information on the depth of seismograph instrument emplacement was obtained for the recording stations.
- The near-surface geology at the recording stations can be highly variable and lateral velocity variation is an important issue at many sites.
- The effects of different configurations of the velocity measurement instrumentation, lateral variation in the properties of near-surface strata, and local variation in the depth of water table must be taken into account in evaluating V_{S30} measurements.

The NGA-East profile database was also used. This database contains V_{S30} estimates compiled from existing literature.

EPRI (2004, 2006) GROUND-MOTION MODEL (GMM)

Framework

The Updated EPRI (2004, 2006) GMM retained the structural framework developed for the EPRI (2004) GMM development. The EPRI (2004) study essentially updated a study performed by EPRI almost 20 years earlier, in 1993, to evaluate and quantify uncertainty in ground-motion modeling in the CEUS and to develop a CEUS GMM that incorporated both epistemic and aleatory uncertainty in seismological aspects of ground-motion prediction given the database available at that time. Although the study preceded publication of the SSHAC Guidance (Budnitz et al., 1997), it was conducted following a process comparable to a SSHAC Level 3 assessment.

Consistent with the SSHAC Guidance for a Level 3 assessment, the EPRI (2004) GMM project team consisted of a three-person TI Team, including experienced ground-motion-modeling experts, a six-person expert panel, and a PPRP. The expert panel consisted of proponent GMPE development experts who broadly represented the range of seismological attributes of the-existing proponent GMPEs. The PPRP included nationally recognized experts in ground-motion modeling for engineering application, as well as in seismic hazard modeling applicable to seismic regulation.

Also consistent with the SSHAC Guidance, a series of three workshops was held for development of the EPRI (2004) GMM. TI Team working meetings took place as needed between workshops. An important outcome of Workshop 1 was consensus that simply weighting the technically defensible GMPEs based on the degree to which each predicts the available data would not adequately capture epistemic uncertainty. Considering approaches for structuring the evaluation and integration of the GMM to more fully understand and capture epistemic uncertainty, a structure evolved from the workshop of grouping the GMPEs into four clusters based on similar seismological attributes (primarily representation of the earthquake source). This structure permitted evaluation and assessment of within-cluster epistemic uncertainty, as well as epistemic uncertainty based on an assessment of the seismologic attributes of the four clusters. Implementation of the cluster structure resulted in four model clusters, defined as Single-Corner Stochastic (Cluster 1), Double-Corner Stochastic (Cluster 2), Hybrid (Cluster 3) and Finite-Source/Green's Function (Cluster 4). The 13 technically defensible GMPEs at the time were grouped into the four clusters shown in Table 1. EPRI (2004) GMM regionalization of the CEUS is shown on Figure 2.

Table 1
EPRI (2004) Ground-Motion Models Grouped by Cluster

Cluster	Model Type	Models[1]
1	Single-Corner Stochastic	Hwang and Huo (1997) Silva et al. (2002) – SC-CS Silva et al. (2002) – SC-CS-Sat Silva et al. (2002) – SC-VS Toro et al. (1997) Frankel et al. (1996)
2	Double-Corner Stochastic	Atkinson and Boore (1995) Silva et al. (2002) DC Silva et al. (2002) – DC-Sat
3	Hybrid	Abrahamson and Silva (2002) Atkinson (2001) and Sadigh et al. (1997) Campbell (2003)
4	Finite-Source /Green's Function	Somerville et al. (2001)

[1] SC = single-corner; DC = double-corner; CS = constant stress; VS = variable stress; Sat = saturation.

EPRI (2006) Aleatory Model Study: Update of the EPRI (2004) Aleatory Model

The standard deviation (sigma) developed in the EPRI (2004) ground-motion study was much larger than shown by later studies that used large western data sets of ground-motion measurements. In consequence, EPRI performed a study for the purpose of assessing the proper aleatory variability (sigma) to assign to CENA GMMs (EPRI, 2006). That study, which updated the EPRI (2004) study, was conducted using a SSHAC Level 2 assessment process. The preliminary results available from NGA-West 1 constituted the primary data for the study. The study concluded that empirically based estimates of sigma using data from active tectonic regions are appropriate with proper adjustment for the CEUS region. In the EPRI (2006) study, alternative models for the total standard deviation (combined intra-event and inter-event) were developed and applied to the CEUS.

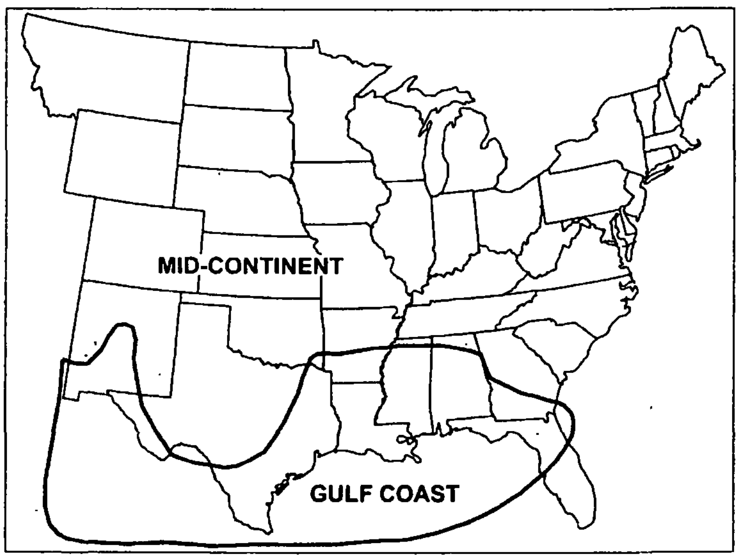

Figure 2
EPRI (2004) regionalization

Discussion of EPRI (2004, 2006) GMM Update

The TI Team for the EPRI (2004, 2006) GMM Review Project concluded that the model should be updated for the following reasons:

- Seven of the 13 GMPEs underlying the EPRI (2004, 2006) GMM are no longer supported by their developers.
- Three new GMPEs for CENA have been developed since the completion of the EPRI (2004) work. Furthermore, these 3 GMPEs are currently in their second generation of development, which suggests that they are robust.
- The CENA ground-motion database is significantly larger now than it was when the EPRI (2004) study was completed. This is a consequence of the occurrence of a number of earthquakes during the last decade (including the Mineral, Virginia, Sparks, Oklahoma, Val des Bois, Quebec, and Mt. Carmel, Illinois, earthquakes), and it is also due to the data

collection efforts of the NGA-East Project. In fact, the NGA-East CENA database available to this project is five times larger than the EPRI (2004) database.

- Comparisons to the database described above indicate that the EPRI (2004, 2006) GMM over predicts ground motions at some magnitude-distance and structural frequency ranges that are important to nuclear power plant (NPP) PSHA.
- The aleatory portion of the EPRI (2004, 2006) GMM was based primarily on preliminary models from the NGA-West 1 study (Power et al., 2008). These preliminary models have been superseded by the final NGA-West 1 model released in 2008 and by the preliminary results of the ongoing NGA-West 2 model study (Bozorgnia et al., 2012).

Based on the reviews and discussions with researchers, the continued use of each of the GMPEs included in the EPRI (2004) study was evaluated and new candidate GMPEs were identified. The results of these evaluations are shown in Table 2 where the Updated EPRI (2004, 2006) GMM clusters, models, and weights are shown.

Table 2
Updated EPRI (2004, 2006) GMM Clusters and Models

Cluster	Model Types and Cluster Weights (repeated large-magnitude earthquake sources/area earthquake sources)	Models
1	Single-Corner Brune Source (0.15/0.185)	Silva et al. (2002) – SC-CS-Sat[1] Silva et al. (2002) – SC-VS[1] Toro et al. (1997) Frankel et al. (1996)
2	Complex/Empirical Source ~R^{-1} Geometrical spreading (0.31/0.383)	Silva et al. (2002) – DC-Sat Atkinson (2008) with 2011 modifications (A08')
3	Complex/Empirical Source ~$R^{-1.3}$ Geometrical spreading (0.35/0.432)	Atkinson-Boore (2006) with 2011 modifications (AB06') Pezeshk et al. (2011)
4	Finite-Source /Green's Function (0.19/0)	Somerville et al. (2001); slightly different models for rifted and nonrifted (not used for distributed seismicity sources with large contribution from **M** < 6)

SC = single-corner; DC = double-corner; CS = constant stress; VS = variable stress; Sat = saturation.

[1] Treated as one model for calculation of weights.

KEY ELEMENTS OF THE UPDATED EPRI (2004, 2006) GMM

The following is an overview of the methodology used to develop the Updated EPRI (2004, 2006) GMM. Clusters 1-4 for the Updated EPRI (2004, 2006) GMM are described in Table 2. Chapters 5 through 7 provide details.

SSHAC Study Level

Because this study is an update to an accepted existing SSHAC Level 3 GMM, a SSHAC Level 2 assessment process was selected as the appropriate level. A number of SHHAC Level 3 features were also implemented in this project, such as the engagement of a PPRP from the start of the project, review and acceptance of the Project Plan, and an in-person feedback workshop. Both the PPRP and the Resource and Proponent Experts provided extensive feedback in formal interviews and in an interactive workshop.

Data

This project took advantage of two significant data collection efforts, namely, the NGA-East Project effort, which included the uniform processing of strong-motion and seismograph data, and the EPRI-sponsored effort, which characterized site conditions at a number of recording stations (the latter supplemented by a parallel USGS effort that provided data for additional stations). Chapter 4 provides the shear-wave-velocity data from both collection efforts. The station site data were used to adjust the strong-motion data to reference site conditions, using two alternative approaches. Appendix A provides details regarding the database for this study. Chapter 6 of this report describes development and corrections to the database, and Section 7.2 describes the development of the final ground-motion database used in this study, including details of the NGA-East database and the processing steps applied to develop the final project database used for the update to the EPRI (2004, 2006) GMM.

Structure of the Updated GMM

The Updated GMM retained the structure of the EPRI (2004) GMM, which grouped the candidate GMPEs into four clusters according to their seismological characteristics, weighting the GMPEs within each cluster according to their consistency with the data, representing each cluster by three fitted GMMs (5th percentile, median, and 95th percentile), and assessing cluster weights based on consistency with observed data and seismological attributes of the GMMs within each cluster.

There are some differences in implementation in the Updated GMM, however. Some of these differences represent adjustments for advances in ground-motion prediction; others represent improvements in methodology for model development. In particular, the set of candidate GMPEs has changed to because (1) some of the GMPEs considered by the EPRI (2004) study are no longer supported by their developers and proponents, and (2) new GMPEs are currently available. The new GMPEs necessitated updating the definition of Clusters 2 and 3 because the most salient grouping of the candidate GMPEs for these clusters was their difference in geometrical spreading. Also, the calculation of consistency with the data was changed to a likelihood-based formulation, which is more flexible (e.g., it allows for consideration of single-station correlation in adjustment factors) and has a strong basis in theory. In addition, the characterization of within-cluster epistemic uncertainty was modified to avoid unquantified correlations, and to take advantage of the more abundant data in constraining the predictions at low magnitudes, and to account for uncertainty in magnitude scaling in a more direct manner. The clusters and weights (for area sources and repeated large-magnitude-earthquake sources, respectively) for the Updated EPRI (2004, 2006) GMM are shown in Table 2.

Model for Aleatory Uncertainty

The EPRI (2006) model for aleatory uncertainty (sigma) was based on preliminary NGA-West 1 models for sigma (Power et al., 2008) from the WUS, adjusted to account for differences in properties of the earth's crust between WUS and CEUS. The updated model for this study incorporates nearly final NGA-West 2 aleatory models (Bozorgnia et al., 2012), with the same adjustments for differences between WUS and CEUS. In that sense, the updated model for aleatory uncertainty represents a straightforward update to the EPRI (2006) aleatory model, where elements that have been superseded are replaced by their natural successors. The aleatory variability model developed by Atkinson et al. (2012) for updating the seismic hazard map of Canada is compared with the model developed in this study on Figure 3. A comparison of the total aleatory variability for the EPRI (2004) GMM and the Updated EPRI (2004, 2006) GMM is shown on Figure 4.

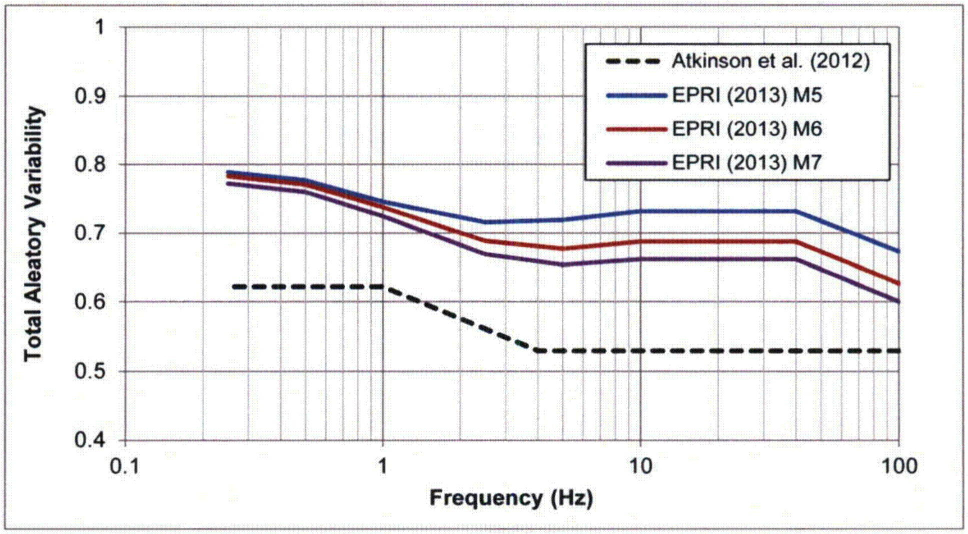

Figure 3
Comparison of aleatory variability model developed by Atkinson et al. (2012) with the model developed from this study

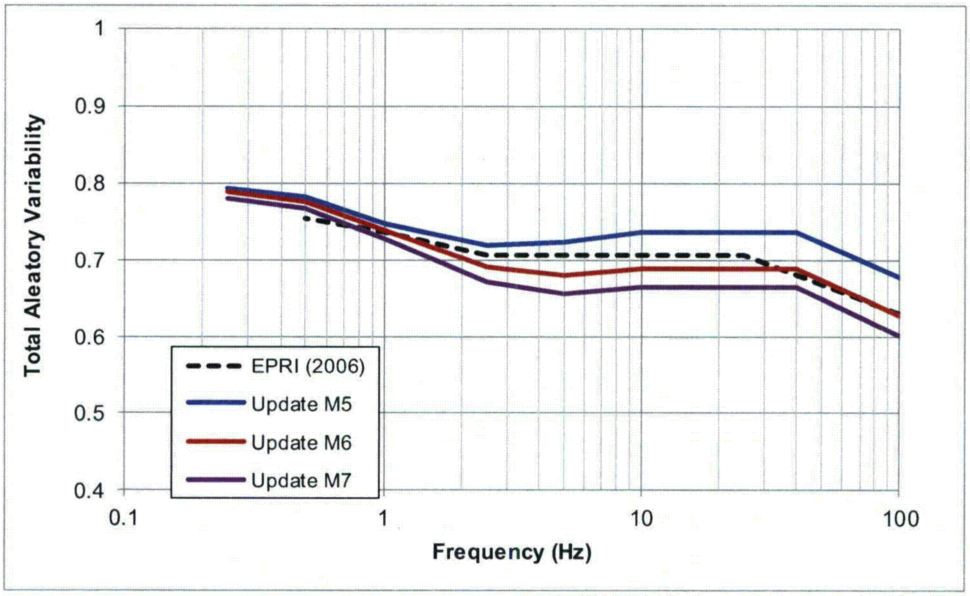

Figure 4
Total aleatory variability for EPRI (2006) GMM and Updated EPRI (2004, 2006) GMM

Model for Gulf Region

Section 7.11 documents procedures for modifying the Updated GMM for site-seismic source geometries where seismic wave travel paths are primarily through Gulf Coast. This modification accounts for differences in anelastic attenuation between the Midcontinent and the Gulf Coast sub-regions and updates the approach developed by EPRI (1993), which was adopted for the EPRI (2004) GMM. The updated geographical boundary between the Midcontinent and Gulf Regions is shown on Figure 1; the geographical boundary used for the EPRI (2004) GMM is shown on Figure 2.

In cases where a seismic source defined in the CEUS SSC Model (EPRI/DOE/NRC, 2012) is wholly or partially within one region and the site for which PSHA is to be performed is within the other, the selection between the Midcontinent and Gulf model is not straightforward. It is recommended that the hazard analyst select the region that contains the majority of the travel path, defined by the minimum distance from the source to the site. It is also appropriate to pro-rate the Midcontinent and Gulf ground-motion amplitudes, taking into account the fraction of the source-site path that is contained within each region.

SEISMIC HAZARD CALCULATIONS AT TEST SITES

Overview

The Updated EPRI (2004, 2006) GMM was used to calculate seismic hazard at the seven test sites examined under the CEUS SSC Project (EPRI/DOE/NRC, 2012). Comparisons of hazard results shown in Chapter 8 of this report illustrate differences in hazard between the EPRI (2004, 2006) GMM and the Updated EPRI (2004, 2006) GMM. All the calculations described in this chapter were made for demonstration purposes only and should not be used for design or analysis decisions for any engineered facility.

The seismic hazard calculated for comparative purposes are for CEUS reference-rock conditions. CEUS reference rock is defined by shear-wave velocity of 2,800 m/s (9,200 ft/s) and kappa of 0.006 seconds. Locations of the seven test sites are shown on Figure 1.

When the geometry of the earthquake rupture is defined, the Updated EPRI (2004, 2006) GMM uses distance to the surface projection of the rupture (Joyner-Boore distance) and closest distance to the rupture (depending on the specific equation within the model). When (for seismic hazard calculations) the rupture geometry is unknown and the earthquake is represented as a point, the EPRI (2004) report includes correction terms for the distance measures and for the aleatory standard deviation, in order to modify these parameters for point-source conditions. These modifications were implemented within the seismic hazard calculations, for both the EPRI (2004, 2006) GMM and the Updated EPRI (2004, 2006) GMM.

The seismic hazard calculations performed for this report were made with the LCI THAZ software code. This software is different from the software used to calculate and report results in the CEUS SSC Project (EPRI/DOE/NRC (2012), but it gives seismic hazard results that are very close to those in that project. Any differences in the results observed are attributable to differences in the ground-motion equations.

Observations

The following observations are based on comparisons of the seismic hazard curves in Chapter 8.

- There is a decrease in ground motion hazard at all spectral frequencies, but not at peak ground acceleration (PGA), for the test sites in both the Midcontinent Region and Gulf Region when the Updated EPRI (2004, 2006) GMM is used with the 2012 CEUS SSC model. For PGA, equations for the Updated EPRI (2004, 2006) GMM indicate a range of seismic hazards similar to the range of seismic hazards obtained using the EPRI (2004, 2006) GMM.
- The amount of reduction in ground motion varies by spectral frequency and test site.
- At test sites located in the Gulf Region, some of the difference in hazard can be attributed to the updated geometry of the Gulf Region, compared with the geometry defined in the EPRI (2004, 2006) GMM. Chapter 8 provides details of the changes between the EPRI (2004, 2006) GMM and the Updated EPRI (2004, 2006) GMM for the seven test sites.

All results from the seismic hazard calculations for each of the seven test sites, including a detailed discussion, are provided in Chapter 8. Details of differences in hazard between the EPRI (2004, 2006) GMM and the Updated EPRI (2004, 2006) GMM for the seven test sites are also provided in Chapter 8.

CONCLUSIONS

The conclusions from the EPRI (2004, 2006) GMM Review Project are as follows:

1. The EPRI (2004, 2006) GMM Review Project demonstrates that a SSHAC Level 2 process update of an accepted existing SSHAC Level 3 study is feasible by maintaining the conceptual/structural framework of the original SSHAC Level 3 study.
2. The Updated EPRI (2004, 2006) GMM was developed using the conceptual structure developed for the EPRI (2004) GMM and updating the model considering technically defensible present-day GMPEs and the present-day ground-motion database, 80% of which was obtained after the EPRI (2004) study.
3. Each of the steps in the SSHAC Level 2 process was followed along with several enhancements performed for this study.
4. The center, body, and range (CBR) of technically defensible interpretations (TDI) have been captured and appropriately represented in the Updated EPRI (2004, 2006) GMM.
5. Participation of recognized seismologists and ground-motion experts from industry, government, and academia, engagement of the PPRP from the beginning of the study, and the productive cooperation from the PEER Center, members of the NGA-East Project, and the USGS contribute to assurance that the Updated GMM properly represents present-day state of practice.

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PPRP FINAL REPORT #7
EPRI GMM REVIEW PROJECT

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Gentlemen:

Reference: *EPRI (2004, 2006) Ground Motion Model Review Project:* Participatory Peer Review Panel Final Report (PPRP Report #7)

This letter constitutes the final consensus report of the Participatory Peer Review Panel (PPRP)[1] ("the Panel") for the *EPRI (2004, 2006) Ground Motion Model Review Project* (the "GMM Review Project" or "the Project").

The four Panel members (Walter J. Arabasz, Brian Chiou, Richard C. Quittmeyer, and Robert B. Whorton) participated in the Project in a manner fully consistent with the SSHAC Guidance[2] for a participatory peer review. The Panel was continually engaged in all phases and key activities of the Project's implementation.

CONCLUSIONS

1. The exemplary implementation of a Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 process in this Project allows us to confidently endorse its procedural aspects.
2. We concur that the full ranges of relevant data, models, and methods proposed by the larger technical community have been duly considered by the Technical Integration (TI) Team in their assessment and development of an Updated EPRI (2004, 2006) Ground Motion Model (GMM).

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[1] All acronyms used in this report are defined in the Appendix.

[2] Budnitz, R. J., G. Apostolakis, D. M. Boore, L. S. Cluff, K. L. Coppersmith, C. A. Cornell, and P. A. Morris, 1997. *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and the Use of Experts* (known as the "Senior Seismic Hazard Analysis Committee Report," or the "SSHAC Guidance"). NUREG/CR-6372, U. S. Nuclear Regulatory Commission. TIC; 235076. Washington, DC.

3. We concur that, in responding to our review comments on the draft Project Report, all technical assessments have been adequately defended and documented by the TI Team.
4. Based on our observation of the implementation of the SSHAC Level 2 process and our review of the technical bases and justifications provided by the TI Team, the PPRP concurs that the Updated EPRI (2004, 2006) GMM, developed to be consistent with the conceptual framework of the existing EPRI (2004, 2006) GMM, appropriately captures the center, body, and range (CBR) of technically-defensible interpretations (TDI).

BACKGROUND

Summary of PPRP Engagement

Consistent with the SSHAC Guidance for a participatory peer review, the Panel engaged in continual peer-review activities throughout the entire project period—from development of the Project Plan (March–June 2012) through production of draft and final versions of the Project Report (April–May 2013). The Panel, collectively and individually, fully understood the SSHAC Guidance for a structured participatory peer review and the requirements for a SSHAC Level 2 assessment process. We interacted extensively with the TI Team and Project Manager throughout the Project, and diligent efforts were made by the Project Manager to keep us appropriately informed.

The Panel provided written and oral peer-review comments on both technical and process aspects at several stages of the Project's evolution. Our written comments are documented in six PPRP reports reproduced in Appendix H of the Project Report.

Key PPRP activities included the following:

- Detailed review of the draft Project Plan (PPRP Report #1)
- Participation as observers, and occasionally as resource experts when requested by the TI Team and Project Manager, in each of the TI Team's five formal working meetings, held between March and August 2012
- Critical review of information and arguments presented by the TI Team and Project Manager at Working Meeting #5 on August 14, 2012, and PPRP agreement with the TI Team's recommendation to update the EPRI (2004, 2006) GMM (PPRP Report #2)
- Involvement in the October 17, 2012, Project Workshop: "Interactions with Technical Community"—including advising in the planning stage, participating collectively as a review panel during the workshop (and individually as resource experts when requested by the TI Team and Project Manager), and submitting a written report of the Panel's observations and recommendations following the workshop (PPRP Report #3)
- Peer-review and written comments on the draft updated GMM presented at the PPRP Closure Briefing on February 13, 2013, together with general comments on the TI Team's Intermediate Document of January 18, 2013 (PPRP Report #4)
- Multiple interactions with the TI Team and Project Manager, following on the PPRP Closure Briefing, leading to a final version of an Updated EPRI (2004, 2006) GMM in

late March 2013 along with PPRP concurrence with the Updated GMM (PPRP Report #5)

- Extensive, critical peer-review of the draft Project Report in May 2013 (PPRP Report #6)
- In addition to the workshop and five working meetings noted above, direct PPRP interaction with the TI Team and Project Manager in more than 13 conference calls, all providing opportunities for timely comments on technical and process issues

Responsibilities of the PPRP at Closure

Upon closure of the Project, the PPRP has the responsibility, under SSHAC guidelines, to address the following (see, for example, section 3.6.8 of NUREG-2117[3]):

- Whether the Project has conformed to the recommendations of a SSHAC Level 2 assessment process
- Whether the full ranges of data, models, and methods have been duly considered in the TI Team's assessment
- Whether all technical assessments have been adequately defended and documented by the TI Team
- Whether the updated GMM captures the CBR of TDI

DISCUSSION

Implementation of a SSHAC Level 2 Process

Chapter 3 of the Project Report provides a full description of how a SSHAC Level 2 assessment process was implemented in the Project. The summary reflects evident attention to ensuring compliance with SSHAC guidelines. The SSHAC Level 2 process implemented for the Project has been exemplary, in our judgment. The PPRP has also been impressed with the execution of the Project in terms of adherence to schedule and the timely completion of tasks.

The decision by the Project Manager and the Sponsor to enhance the SSHAC Level 2 process by involving a PPRP has contributed significantly, in our view, to the Project's success. We thank the Project Manager and the TI Team for actively seeking, respecting, and duly acting upon our comments and recommendations relating both to process and technical issues throughout the Project.

Evaluation of Data, Models, and Methods

We observed that the TI Team adopted a structured systematic approach to perform the SSHAC *evaluation* activity of considering the complete set of relevant data, models, and methods proposed by the larger technical community. The evaluation activity notably included multi-stage interactions with the larger technical community—including interviews, conference calls

[3] U.S. Nuclear Regulatory Commission (NRC), 2012. Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies, NUREG-2117, Rev. 1, NRC Office of Nuclear Regulatory Research.

and meetings during the pre-Project "due diligence" stage that helped shape the Project Plan; close coordination with the NGA-East Project and the U.S. Geological Survey's National Seismic Hazard Mapping Project; a thorough literature review; one-on-one interviews by members of the TI Team with 11 resource and proponent experts; and the October 2012 interaction workshop together with follow-up feedback.

It is germane to note that for the purpose of updating the EPRI (2004, 2006) GMM, the TI Team adopted an approach intended to be consistent with the conceptual framework of the *existing* EPRI GMM. Based on our observations of the process involved in the Project, including direct comments made by ground motion experts at the October 2012 workshop, we are confident that the TI Team has duly considered and evaluated all available data, methods, and models that are relevant.

Documentation—the Project Report

The SSHAC Guidance emphasizes the critical importance of thorough and adequate documentation of the Project's process and results—for understanding and use by others in the technical community, by later analysis teams, and by the project sponsor. The Panel was committed to ensuring (1) that the documentation of technical details associated with the Project Report was clear and complete and (2) that process aspects of the Project were transparent and accurately described in the Project Report. The PPRP also has the companion responsibility to ensure that all of the TI Team's technical assessments have been adequately defended and documented. To be clear, the SSHAC Guidance charges the PPRP to judge the adequacy of the documented *justification* for the Updated GMM and its associated logic-tree weights; *intellectual ownership* of the Updated GMM and its inputs belongs to the TI Team.

The Panel completed a rigorous review of the draft Project Report. We provided a lengthy compilation of review comments on the entire report, including appendices (PPRP Report #6), and we also provided marked-up Microsoft Word files with extensive editorial comments and suggestions for improving the report. Further, we held a conference call with the TI Team and Project Manager to ensure a clear understanding of our review comments. Our formal review comments were designated as either *mandatory* (to be addressed by the TI Team in finalizing the Project Report) or *non-mandatory* (to be handled by the TI Team as feasible and at their discretion).

Production of the final Project Report faced a firm deadline. Before submitting this PPRP Final Report, the Panel had the opportunity to examine revised versions of Chapters 5–8 of the Project Report—the critical chapters describing the technical bases of the Updated EPRI (2004, 2006) GMM. A conference call was held with the TI Team and Project Manager to confirm that the PPRP's mandatory comments had been suitably resolved. Also, a member of the PPRP was on site for one day to assist in final technical editing of these chapters as the Project Report was being prepared for publication. It is on this basis that we affirm that the TI Team has adequately justified, defended, and documented its technical assessments supporting the Updated GMM.

Updated GMM vis-à-vis the CBR of TDI

Here, we revisit an assessment of this issue that we made in PPRP Report #5 regarding the TI Team's *integration* activity, i.e., how they evaluated existing data, models, methods and ultimately how their Updated GMM represents the CBR of TDI. To clarify the issue at hand: "The SSHAC process seeks to capture the center, the body, and the range on each component of the hazard study. . . . If the correlations between these component distributions are also captured, this in turn will then result in capture of the center, the body, and the range of seismic hazard estimates, which is the ultimate objective of the process" (NUREG-2117, section 3.1, p. 33).

For clarification of terminology, we refer further to NUREG-2117:

> Once a group of geological, seismological, and geotechnical experts have made their evaluations of all of the available data, the center of these interpretations can be thought of as the best estimate or central value (median) of the distribution of possible outcomes as determined by that group. The term "body" can be thought of as the shape of the distribution of interpretations that lie around this best estimate and capture the major portion of the mass of the distribution. The term "range" refers to the tails of this distribution and the limiting credible values. (NUREG-2117, section 3.1, p. 33)

Importantly, the excerpt from NUREG-2117 reproduced above points out how the *center* of TDI is achieved—in effect, it results from determinations of the TI Team. Whereas the *body* and *range* of TDI can be compared to the available views of the larger technical community, the *center* of TDI is more fundamentally linked to the TI Team's informed judgment.

Based on our observation of the implementation of the SSHAC Level 2 process and our review of the technical bases and justifications provided by the TI Team in the Project Report, we concur that the Updated EPRI (2004, 2006) GMM appropriately captures the CBR of TDI. In particular, we note the following:

- The multi-stage engagement by the TI Team of resource and proponent experts from the larger technical community gives us assurance that the TI Team's decisions to eliminate some older ground motion prediction equations (GMPEs) and to substitute/include more up-to-date GMPEs, which predict lower mean ground motions than the older GMPEs, are well founded and not just reflections of the TI Team's own experience and opinions.
- Despite the great increase in available ground-motion recordings in the central and eastern U. S. (CEUS) since the development of the EPRI (2004, 2006) GMM, the TI Team's recognition of the limitations of these data for predicting future ground motions in critical magnitude-distance ranges is an important element of the Updated GMM. Significantly, the TI Team has (1) abandoned an earlier decision to give greater weight to data consistency and (2) added a contribution to epistemic uncertainty that aims to capture increased uncertainty due to the relative lack of empirical data and knowledge of magnitude scaling for earthquakes of magnitude 5 and greater in the CEUS.
- Ground motion data used to evaluate GMPEs are adjusted to take into account site conditions of the recording stations. Uncertainties in the adjustments are incorporated appropriately. The adjustments mitigate a known bias in the use of the ground motion data to test GMPEs developed for a nominal site condition of 2800 m/s.

- The characterization of aleatory variability, updating the approach used for the existing EPRI GMM, is based on the published NGA-West1 models and preliminary results of the NGA-West2 project.
- The model updates the characterization of ground motion for the Gulf Coast region to incorporate current data and technical results, including NUREG-2115[4] and studies based on data recorded by regional network stations of the Advanced National Seismic System (ANSS) and by EARTHSCOPE Transportable Array stations.
- Demonstration hazard calculations at the seven (7) test sites for both the existing EPRI (2004, 2006) GMM and the Updated GMM provide a level of assurance of consistency in final results achieved, when compared to the existing model.

We are pleased to confirm that implementation of the GMM Review Project conformed with the SSHAC Guidance and that the resulting Updated GMM properly meets the SSHAC goal of representing the center, body, and range of technically-defensible interpretations.

This concludes our PPRP Final Report for the *EPRI (2004, 2006) Ground Motion Model Review Project*.

Walter J. Arabasz, Chairman

Brian Chiou

Richard C. Quittmeyer

Robert B.Whorton

Copy: Gabriel R. Toro, TI Team Lead

[4] Electric Power Research Institute, U.S. Department of Energy, and U.S. Nuclear Regulatory Commission (EPRI/DOE/NRC), 2012. Technical Report: *Central and Eastern United States Seismic Source Characterization for Nuclear Facilities*, NUREG-2115.

APPENDIX — ACRONYMS

ANSS	Advanced National Seismic System
CBR	Center, Body, and Range
CEUS	Central and Eastern United States
EARTHSCOPE	An earth science program funded by the U.S. National Science Foundation
EPRI	Electric Power Research Institute
GMM	Ground Motion Model
GMPE	Ground Motion Prediction Equation
NGA-East	Research project to develop a new ground motion characterization (Next-Generation Attenuation) model for Central and Eastern North America
NGA-West1, NGA-West2	NGA project(s) for Western North America
NRC	U.S. Nuclear Regulatory Commission
NUREG	NRC Nuclear Regulation Report
NUREG/CR	NRC Nuclear Regulation Contractor's Report
PPRP	Participatory Peer Review Panel
SSHAC	Senior Seismic Hazard Analysis Committee
TDI	Technically Defensible Interpretations
TI Team	Technical Integration Team

ABBREVIATIONS AND SYMBOLS

A08′	Atkinson (2008) GMPE with 2011 revisions (see *GMPE* below)
AB06′	Atkinson and Boore (2006) GMPE with 2011 revisions
AIC	Akaike Information Criteria
ANSS	U.S. Advanced National Seismic System
BA08′	Boore and Atkinson (2008) GMPE with revisions of Atkinson and Boore (2011)
BIC	Bayesian Information Criteria
CBR	center, body, and range
CENA	Central and Eastern North America
CERI	Center for Earthquake Research and Information
CEUS	Central and Eastern United States
CFR	Code of Federal Regulations
COL	combined construction and operating license
COLA	Combined Operating License Application
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
ECC-GC	extended continental crust – Gulf Coast region seismotectonic zone
ENA	Eastern North America
EPRI	Electric Power Research Institute
EPRI-SOG	Electric Power Research Institute – Seismicity Owners Group
EQID	Earthquake identification number
ERM-N	Eastern rift margin – north
ERM-S	Eastern rift margin – south
ESP	Early Site Permit
EUS	Eastern United States
FEL	Frankel et al. (1996) GMPE

FTP	File Transfer Protocol
ft.	foot or feet
ft/s	feet per second
GC	Gulf Coast
GHEX	Gulf Coast Highly Extended Crust seismotectonic zone
GIS	geographic information system
GMC	ground-motion characterization
GMM	ground-motion model
GMPE	ground-motion-prediction equation
GMRS	ground-motion response spectrum (or spectra)
GPS	global positioning system
GV	GEOVision, Inc.
HEM	hybrid empirical method
HID	hazard input document
Hz	hertz
IRIS	Incorporated Research Institutes for Seismology
IRVT	inverse random vibration theory
ITC	informed technical community
km	kilometer(s)
κ	kappa: represents near-surface anelastic attenuation
LRSM	Long-Range Seismic Measurements
m	meter(s)
M	moment magnitude
MALW	multichannel analysis of Love waves
MSF	magnitude scaling factor
MASW	multichannel analysis of Rayleigh waves
mi.	mile(s)
MIDC	Midcontinent
MidC	Midcontinent-Craton (seismotectonic zone)
M_{max}	maximum magnitude
m/s	meter(s) per second

NGA	Next Generation Attenuation
NMFS	New Madrid fault source
NPP	nuclear power plant(s)
NRC	U.S. Nuclear Regulatory Commission
NTTF	Near-Term Task Force
NUREG	NRC Nuclear Regulation Report
ϕ	intra-event component of aleatory variability standard deviation
PEER	Pacific Earthquake Engineering Research Center
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
PM	Project Manager
PPRP	Participatory Peer Review Panel
PSA	pseudo-spectral acceleration
PSHA	probabilistic seismic hazard analysis
PZT	Pezeshk et al. (2011) GMPE
Q	Quality factor (used for quantifying anelastic attenuation)
QWL	quarter-wavelength method
ρ	mass density
R	distance
R_{JB}	Joyner-Boore distance
R_{Rup}	rupture distance
RFI	request for information
RLME	repeated large-magnitude earthquake
RR	Reelfoot Rift seismotectonic zone
RR-RCG	Reelfoot Rift – Rough Creek Graben seismotectonic zone
RSTN	Regional Seismic Test Network
RVT	random vibration theory
Σ	covariance matrix (also called variance matrix)
σ	total aleatory variability standard deviation
SA	spectral acceleration

SASW	spectral analysis of surface waves
SEL	Somerville et al. (2001) GMPE
SDC	Silva et al. (2002, 2003) double-corner GMPE (also denoted as DC)
SDCS	Silva et al. (2002, 2003) double-corner with saturation GMPE (also denoted as DC-Sat)
SSCCS	Silva et al. (2002, 2003) single-corner constant stress GMPE (also denoted as SC-CS)
SSCCSS	Silva et al. (2002, 2003) single-corner constant stress with saturation GMPE (also denoted as SC-CS-Sat)
SSCVS	Silva et al. (2002, 2003) single-corner variable stress GMPE (also denoted as SC-VS)
SSC	seismic source characterization
SSHAC	Senior Seismic Hazard Analysis Committee
τ	inter-event component of aleatory variability standard deviation
TA	EarthScope Transportable Array
TC	technical community
TDI	technically defensible interpretations
TEL	Toro et al. (1997) GMPE
TIP	Trial Implementation Project
TI	Technical Integration (*also* Technical Integrator)
UHRS	uniform hazard response spectra
USGS	U.S. Geological Survey
UT	The University of Texas
Vp	compressional wave (P-wave) velocity
V_S, β	shear-wave (S-wave) velocity
V_{S30}	time-averaged shear-wave velocity to a depth of 30 m
WNA	Western North America
WUS	Western United States