Central and Eastern United States Seismic Source Characterization for Nuclear Facilities

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ABSTRACT

This report describes a new seismic source characterization (SSC) model for the Central and Eastern United States (CEUS). It will replace the *Seismic Hazard Methodology for the Central and Eastern United States*, EPRI Report NP-4726 (July 1986) and the *Seismic Hazard Characterization of 69 Nuclear Plant Sites East of the Rocky Mountains,* Lawrence Livermore National Laboratory Model, (Bernreuter et al., 1989). The objective of the CEUS SSC Project is to develop a new seismic source model for the CEUS using a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 assessment process. The goal of the SSHAC process is to represent the center, body, and range of technically defensible interpretations of the available data, models, and methods. Input to a probabilistic seismic hazard analysis (PSHA) consists of both seismic source characterization and ground motion characterization. These two components are used to calculate probabilistic hazard results (or seismic hazard curves) at a particular site. This report provides a new seismic source model.

Results and Findings

The product of this report is a regional CEUS SSC model. This model includes consideration of an updated database, full assessment and incorporation of uncertainties, and the range of diverse technical interpretations from the larger technical community. The SSC model will be widely applicable to the entire CEUS, so this project uses a ground motion model that includes generic variations to allow for a range of representative site conditions (deep soil, shallow soil, hard rock). Hazard and sensitivity calculations were conducted at seven test sites representative of different CEUS hazard environments.

Challenges and Objectives

The regional CEUS SSC model will be of value to readers who are involved in PSHA work, and who wish to use an updated SSC model. This model is based on a comprehensive and traceable process, in accordance with SSHAC guidelines in NUREG/CR-6372, *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*. The model will be used to assess the present-day composite distribution for seismic sources along with their characterization in the CEUS and uncertainty. In addition, this model is in a form suitable for use in PSHA evaluations for regulatory activities, such as Early Site Permit (ESPs) and Combined Operating License Applications (COLAs).

Applications, Values, and Use

Development of a regional CEUS seismic source model will provide value to those who (1) have submitted an ESP or COLA for Nuclear Regulatory Commission (NRC) review before 2011; (2) will submit an ESP or COLA for NRC review after 2011; (3) must respond to safety issues resulting from NRC Generic Issue 199 (GI-199) for existing plants and (4) will prepare PSHAs to meet design and periodic review requirements for current and future nuclear facilities. This work replaces a previous study performed approximately 25 years ago. Since that study was

completed, substantial work has been done to improve the understanding of seismic sources and their characterization in the CEUS. Thus, a new regional SSC model provides a consistent, stable basis for computing PSHA for a future time span. Use of a new SSC model reduces the risk of delays in new plant licensing due to more conservative interpretations in the existing and future literature.

Perspective

The purpose of this study, jointly sponsored by EPRI, the U.S. Department of Energy (DOE), and the NRC was to develop a new CEUS SSC model. The team assembled to accomplish this purpose was composed of distinguished subject matter experts from industry, government, and academia. The resulting model is unique, and because this project has solicited input from the present-day larger technical community, it is not likely that there will be a need for significant revision for a number of years. See also Sponsors' Perspective for more details.

Approach

The goal of this project was to implement the CEUS SSC work plan for developing a regional CEUS SSC model. The work plan, formulated by the project manager and a technical integration team, consists of a series of tasks designed to meet the project objectives. This report was reviewed by a participatory peer review panel (PPRP), sponsor reviewers, the NRC, the U.S. Geological Survey, and other stakeholders. Comments from the PPRP and other reviewers were considered when preparing the report. The SSC model was completed at the end of 2011.

Keywords

Probabilistic seismic hazard analysis (PSHA)
Seismic source characterization (SSC)
Seismic source characterization model
Central and Eastern United States (CEUS)

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EXECUTIVE SUMMARY

The Central and Eastern United States Seismic Source Characterization for Nuclear Facilities (CEUS SSC) Project was conducted over the period from April 2008 to December 2011 to provide a regional seismic source model for use in probabilistic seismic hazard analyses (PSHAs) for nuclear facilities. The study replaces previous regional seismic source models conducted for this purpose, including the Electric Power Research Institute–Seismicity Owners Group (EPRI-SOG) model (EPRI, 1988, 1989) and the Lawrence Livermore National Laboratory model (Bernreuter et al., 1989). Unlike the previous studies, the CEUS SSC Project was sponsored by multiple stakeholders—namely, the EPRI Advanced Nuclear Technology Program, the Office of Nuclear Energy and the Office of the Chief of Nuclear Safety of the U.S. Department of Energy (DOE), and the Office of Nuclear Regulatory Research of the Nuclear Regulatory Commission (NRC). The study was conducted using Senior Seismic Hazard Analysis Committee (SSHAC) Study Level 3 methodology to provide high levels of confidence that the data, models, and methods of the larger technical community have been considered and the center, body, and range of technically defensible interpretations have been included.

The regional seismic source characterization (SSC) model defined by this study can be used for site-specific PSHAs, provided that appropriate site-specific assessments are conducted as required by current regulations and regulatory guidance for the nuclear facility of interest. This model has been designed to be compatible with current and anticipated ground-motion characterization (GMC) models. The current recommended ground-motion models for use at nuclear facilities are those developed by EPRI (2004, 2006a, 2006b). The ongoing Next Generation Attenuation–East (NGA-East) project being supported by the NRC, DOE, and EPRI will provide ground-motion models that are appropriate for use with the CEUS SSC model. The methodology for a SSHAC Level 3 project as applied to the CEUS SSC Project is explained in the SSHAC report (Budnitz et al., 1997), which was written to discuss the evolution of expert assessment methodologies conducted during the previous three decades for purposes of probabilistic risk analyses. The methodological guidance provided in the SSHAC report was intended to build on the lessons learned from those previous studies and, specifically, to arrive at processes that would make it possible to avoid the issues encountered by the previous studies (NRC, 2011).

The SSHAC assessment process, which differs only slightly for Level 3 and 4 studies, is a technical process accepted in the NRC's seismic regulatory guidance (Regulatory Guide 1.208) for ensuring that uncertainties in data and scientific knowledge have been properly represented in seismic design ground motions consistent with the requirements of the seismic regulation 10 CFR Part 100.23 ("Geologic and Seismic Siting Criteria"). Therefore, the goal of the SSHAC assessment process is the proper and complete representation of knowledge and uncertainties in the SSC and GMC inputs to the PSHA (or similar hazard analysis). As discussed extensively in the SSHAC report (Budnitz et al., 1997) and affirmed in NRC (2011), a SSHAC assessment process consists of two important sequential activities, *evaluation* and *integration.* For a Level 3 assessment, these activities are conducted by the Technical Integration (TI) Team under the leadership of the TI Lead. As described in NRC (2011),

> 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).

Each of the assessment and model-building activities of the CEUS SSC Project is associated with the evaluation and integration steps in a SSHAC Level 3 process. Consistent with the requirements of a SSHAC process, the specific roles and responsibilities of all project participants were defined in the Project Plan, and adherence to those roles was the responsibility of the TI Lead and the Project Manager. The technical assessments are made by the TI Team, who carry the principal responsibility of evaluation and integration, under the technical leadership of the TI Lead. The Database Manager and other technical support individuals assist in the development of work products. Resource and proponent experts participate by presenting their data, models, and interpretations at workshops and through technical interchange with the TI Team throughout the project. The Participatory Peer Review Panel (PPRP) is responsible for a continuous review of both the SSHAC process being followed and the technical assessments being made. The project management structure is headed by the Project Manager, who serves as the liason with the sponsors and the PPRP and manages the activities of all participants. The SSHAC Level 3 assessment process and implementation is discussed in depth in Chapter 2 of this report.

Each of the methodology steps in the SSHAC guidelines (Budnitz, 1997) was addressed adequately during the CEUS SSC Project. Furthermore, the project developed a number of enhancements to the process steps for conducting a SSHAC Study Level 3 project. For example, the SSHAC guidelines call for process steps that include developing a preliminary assessment model, calculating hazard using that model in order to identify the key issues, and finalizing the model in light of the feedback provided from the hazard calculations and sensitivity analyses. Because of the regional nature of the project and the multitude of assessments required, four rounds of model-building and three rounds of feedback were conducted. These activities ensured that all significant issues and uncertainties were identified and that the appropriate effort was devoted to the issues of most significance to the hazard results. A comparison of the activities conducted during the CEUS SSC Project with those recommended in the SSHAC guidelines themselves (Section 2.6) led to the conclusion that the current standards of practice have been met for a SSHAC Study Level 3 process—both those that are documented in the SSHAC report and those that resulted from precedents set by projects conducted since the SSHAC report was issued.

The catalog of past earthquakes that have occurred in a region is an important source of information for the quantification of future seismic hazards. This is particularly true in stable continental regions (SCRs) such as the CEUS where the causative mechanisms and structures for the occurrence of damaging earthquakes are generally poorly understood, and the rates of crustal deformation are low such that surface and near-surface indications of stresses in the crust and the buildup and release of crustal strains are difficult to quantify. Because the earthquake catalog is used in the characterization of the occurrence of future earthquakes in the CEUS, developing an updated earthquake catalog for the study region was an important focus of the CEUS SSC Project. The specific goals for earthquake catalog development and methods used to attain those goals are given in Chapter 3.

The earthquake catalog development consists of four main steps: catalog compilation, assessment of a uniform size measure to apply to each earthquake, identification of dependent earthquakes (catalog declustering), and assessment of the completeness of the catalog as a function of location, time, and earthquake size. An important part of the catalog development process was review by seismologists with extensive knowledge and experience in catalog compilation. The result is an earthquake catalog covering the entire study region for the period from 1568 through the end of 2008. Earthquake size is defined in terms of the moment magnitude scale (Hanks and Kanamori, 1979), consistent with the magnitude scale used in modern ground-motion prediction equations (GMPEs) for CEUS earthquakes. A significant contribution of the CEUS SSC Project is the work conducted to develop an updated and consistent set of conversion relationships between various earthquake size measures (instrumental magnitudes and intensity) and moment magnitude.

The conceptual SSC framework described in Chapter 4 was developed early in the CEUS SSC Project in order to provide a consistent approach and philosophy to SSC by the TI Team. This framework provides the basic underpinnings of the SSC model developed for the project, and it led to the basic structure and elements of the master logic tree developed for the SSC model. In considering the purpose of the CEUS SSC Project, the TI Team identified three attributes that are needed for a conceptual SSC framework:

1. A systematic, documented approach to treating alternatives using logic trees, including alternative conceptual models for future spatial distributions of seismicity (e.g., stationarity); alternative methods for expressing the future temporal distribution of seismicity (e.g., renewal models, Poisson models); and alternative data sets for characterizing seismic sources (e.g., paleoseismic data, historical seismicity data).
2. A systematic approach to identifying applicable data for the source characterization, evaluating the usefulness of the data, and documenting the consideration given to the data by the TI Team.
3. A methodology for identifying seismic sources based on defensible criteria for defining a seismic source, incorporating the lessons learned in SSC over the past two decades, and identifying the range of approaches and models that can be shown to be significant to hazard.

Each of these needs was addressed by the methodology used in the project. For example, the need for a systematic approach to identifying and evaluating the data and information that underlie the source characterization assessments was met by the development of Data Summary and Data Evaluation tables. These tables were developed for each seismic source to document the information available at the time of the CEUS SSC assessments (the Data Summary tables) and the way those data were used in the characterization process (the Data Evaluation tables). Given the evolution of approaches to identifying seismic sources, it is appropriate to provide a set of criteria and the logic for their application in the CEUS SSC Project. In the project, unique seismic sources are defined to account for distinct differences in the following criteria:

- Earthquake recurrence rate
- Maximum earthquake magnitude (Mmax)
- Expected future earthquake characteristics (e.g., style of faulting, rupture orientation, depth distribution)
- Probability of activity of tectonic feature(s)

Rather than treat these criteria as operating simultaneously or without priority, the CEUS SSC methodology works through them sequentially. Further, because each criterion adds complexity to the seismic source model, it is applied only if its application would lead to hazard-significant changes in the model. In this way, the model becomes only as complex as required by the available data and information.

The CEUS SSC master logic tree is tied to the conceptual SSC framework that establishes the context for the entire seismic source model. The master logic tree depicts the alternative interpretations and conceptual models that represent the range of defensible interpretations, and the relative weights assessed for the alternatives. By laying out the alternatives initially, the subsequent detailed source evaluations were conducted within a framework that ensures consistency across the sources. Important elements of the master logic tree are as follows:

- Representation of the sources defined based on paleoseismic evidence for the occurrence of repeated large-magnitude earthquakes (RLMEs, defined as two or more earthquakes with $\mathbf{M} \geq 6.5$).
- Alternatives to the spatial distribution of earthquakes based on differences in maximum magnitudes (Mmax zones approach).
- Representation of uncertainty in spatial stationarity of observed seismicity based on smoothing of recurrence parameters.
- Representation of possible differences in future earthquake characteristics (e.g., style, seismogenic thickness, and orientation of ruptures), which lead to definition of seismotectonic zones in the logic tree (seismotectonic zones approach).

The methodologies used by the project to make the SSC assessments are discussed in Chapter 5. The heart of any SSC model for PSHA is a description of the future spatial and temporal distribution of earthquakes. Continued analysis of the historical seismicity record and network monitoring by regional and local seismic networks has led to acceptance within the community that the general spatial patterns of observed small- to moderate-magnitude earthquakes provide predictive information about the spatial distribution of future large-magnitude earthquakes. The analyses leading to this conclusion have focused on whether the observed patterns of earthquakes have varied through time; therefore, in effect, this is an assessment of uncertainty in whether small- to moderate-magnitude earthquakes have been relatively stationary through time. However, the available data on larger-magnitude earthquakes and their relationship to the spatial distribution of smaller earthquakes based on the observed record are quite limited. These data are not sufficient to allow confidence in the predictions generated by empirical spatial models. For this reason, geologic and geophysical data are needed to specify the locations of future earthquakes in addition to the observed patterns of seismicity.

Detailed studies in the vicinity of large historical and instrumental earthquakes, and liquefaction phenomena associated with them, coupled with field and laboratory studies of geotechnical properties, are leading to a stronger technical basis for (1) placing limits on the locations of paleoearthquakes interpreted by the distribution of liquefaction phenomena and (2) defining their magnitudes. In some cases, the paleoseismic evidence for RLMEs is compelling, and the TI Team has included the RLME source in the SSC model. The locations of RLME sources notwithstanding, the spatial distribution of distributed seismicity sources has advanced in PSHA largely because of the assumption of spatial stationarity, and the SSC and hazard community uses approaches to “smooth” observed seismicity to provide a map that expresses the future spatial pattern of recurrence rates. The CEUS SSC model is based largely on the assumption, typical in PSHA studies, that spatial stationarity of seismicity is expected to persist for a period of approximately 50 years.

Estimating Mmax in SCRs such as the CEUS is highly uncertain despite considerable interest and effort by the scientific community over the past few decades. Mmax is defined as the upper truncation point of the earthquake recurrence curve for individual seismic sources, and the typically broad distribution of Mmax for any given source reflects considerable epistemic uncertainty. Because the maximum magnitude for any given seismic source in the CEUS occurs rarely relative to the period of observation, the use of the historical seismicity record provides important but limited constraints on the magnitude of the maximum event. Because of the independent constraints on earthquake size, those limited constraints are used to estimate the magnitudes of RLME. For distributed seismicity source zones, two approaches are used to assess Mmax: the Bayesian approach and the Kijko approach. In the Bayesian procedure (Johnston et al., 1994), the prior distribution is based on the magnitudes of earthquakes that occurred worldwide within tectonically analogous regions. As part of the CEUS SSC Project, the TI Team pursued the refinement and application of the Bayesian Mmax approach becauses it provides a quantitative and repeatable process for assessing Mmax.

The TI Team also explored alternative approaches for the assessment of Mmax that provide quantitative and repeatable results, and the team identified the approach developed by Kijko (2004) as a viable alternative. While the Kijko approach requires fewer assumptions than the Bayesian approach in that it uses only the observed earthquake statistics for the source, this is offset by the need for a relatively larger data sample in order to get meaningful results. Both approaches have the positive attribute that they are repeatable given the same data and they can be readily updated given new information. The relative weighting of the two approaches for inclusion in the logic tree is source-specific, a function of the numbers of earthquakes that are present within the source upon which to base the Mmax assessment: sources with fewer earthquakes are assessed to have little or no weight for the Kijko approach, while those with larger numbers of events are assessed higher weight for the Kijko approach. In all cases, because of the stability of the Bayesian approach and the preference for "analogue" approaches within the larger technical community, the Bayesian approach is assessed higher weight than the Kijko approach for all sources.

A major effort was devoted to updating the global set of SCR earthquakes and to assessing statistically significant attributes of those earthquakes following the approach given in Johnston et al. (1994). In doing so, it was found that the only significant attribute defining the prior distribution is the presence or absence of Mesozoic-or-younger extension. The uncertainty in this assessment is reflected in the use of two alternative priors: one that takes into account the presence or absence of crustal domains having this attribute, and another that combines the entire CEUS region as a single SCR crustal domain with a single prior distribution. The use of the Bayesian—and Kijko—approach requires a definition of the largest observed magnitude within each source, and this assessment, along with the associated uncertainty, was incorporated into the Mmax distributions for each seismic source. Consideration of global analogues led to the assessment of an upper truncation to all Mmax distributions at 8¼ and a lower truncation at 5½. The broad distributions of Mmax for the various seismic source zones reflect the current epistemic uncertainty in the largest earthquake magnitude within each seismic source.

The CEUS SSC model is based to a large extent on an assessment that spatial stationarity of seismicity will persist for time periods of interest for PSHA (approximately the next 50 years). Stationarity in this sense does not mean that future locations and magnitudes of earthquakes will occur exactly where they have occurred in the historical and instrumental record. Rather, the degree of spatial stationarity varies as a function of the type of data available to define the seismic source. RLME sources are based largely on paleoseismic evidence for repeated large-magnitude ($M \geq 6.5$) earthquakes that occur in approximately the same location over periods of a few thousand years. On the other hand, patterns of seismicity away from the RLME sources within the Mmax and seismotectonic zones are defined from generally small- to moderate-magnitude earthquakes that have occurred during a relatively short (i.e., relative to the repeat times of large events) historical and instrumental record. Thus, the locations of future events are not as tightly constrained by the locations of past events as for RLME sources. The spatial smoothing operation is based on calculations of earthquake recurrence within one-quarter-degree or half-degree cells, with allowance for "communication" between the cells. Both *a*- and *b*-values are allowed to vary, but the degree of variation has been optimized such that *b*-values vary little across the study region.

The approach used to smooth recurrence parameters is a refinement of the penalized-likelihood approach used in EPRI-SOG (EPRI, 1988), but it is designed to include a number of elements that make the formulation more robust, realistic, and flexible. These elements include the reformulation in terms of magnitude bins, the introduction of magnitude-dependent weights, catalog incompleteness, the effect of Mmax, spatial variation of parameters within the source zone, and the prior distributions of *b*. A key assessment made by the TI Team was the weight assigned to various magnitude bins in the assessment of smoothing parameters (Cases A, B, and E). This assessment represents the uncertainty in the interpretation that smaller magnitudes define the future locations and variation in recurrence parameters. Appropriately, the penalized-likelihood approach results in higher spatial variation (less smoothing) when the low-magnitude bins are included with high weight, and much less variation (higher smoothing) in the case where the lower-magnitude bins are given low or zero weight. The variation resulting from the final set of weights reflects the TI Team's assessment of the epistemic uncertainty in the spatial variation of recurrence parameters throughout the SSC model.

The earthquake recurrence models for the RLME sources are somewhat simpler than those for distributed seismicity sources because the magnitude range for individual RLMEs is relatively narrow and their spatial distribution is limited geographically such that spatial variability is not a concern. This limits the problem to one of estimating the occurrence rate in time of a point process. The data that are used to assess the occurrence rates are derived primarily from paleoseismic studies and consist of two types: data that provide estimated ages of the paleoearthquakes such that the times between earthquakes can be estimated, and data that provide an estimate of the number of earthquakes that have occurred after the age of a particular stratigraphic horizon. These data are used to derive estimates of the RLME occurrence rates and their uncertainty.

The estimation of the RLME occurrence rates is dependent on the probability model assumed for the temporal occurrence of these earthquakes. The standard model applied for most RLME sources in this study is the Poisson model, in which the probability of occurrence of an RLME in a specified time period is completely characterized by a single parameter, λ, the rate of RLME occurrence. The Poisson process is "memoryless"—that is, the probability of occurrence in the next time interval is independent of when the most recent earthquake occurred, and the time between earthquakes is exponentially distributed with a standard deviation equal to the mean time between earthquakes. For two RLME sources (Reelfoot Rift–New Madrid fault system and the Charleston source), the data are sufficient to suggest that the occurrence of RLMEs is more periodic in nature (the standard deviation is less than the mean time between earthquakes). For these RLME sources a simple renewal model can also be used to assess the probability of earthquake occurrence. In making an estimate of the probability of occurrence in the future, this model takes into account the time that has elapsed since the most recent RLME occurrence.

The CEUS SSC model has been developed for use in future PSHAs. To make this future use possible, the SSC model must be combined with a GMC model. At present, the GMPEs in use for SCRs such as the CEUS include limited information regarding the characteristics of future earthquakes. In anticipation of the possible future development of GMPEs for the CEUS that will make it possible to incorporate similar types of information, a number of characteristics of future earthquakes in the CEUS are assessed. In addition to characteristics that might be important for ground motion assessments, there are also assessed characteristics that are potentially important to the modeling conducted for hazard analysis. Future earthquake characteristics assessed include the tectonic stress regime, sense of slip/style of faulting, strike and dip of ruptures, seismogenic crustal thickness, fault rupture area versus magnitude relationship, rupture length-to-width aspect ratio, and relationship of ruptures to source boundaries.

Chapters 6 and 7 include discussions of the seismic sources that are defined by the Mmax zones and the seismotectonic zones branches of the master logic tree. Because of convincing evidence for their existence, both approaches include RLME sources. The rarity of repeated earthquakes relative to the period of historical observation means that evidence for repeated events comes largely from the paleoseismic record. By identifying the RLMEs and including them in the SSC model, there is no implication that the set of RLMEs included is in fact the total set of RLMEs that might exist throughout the study region. This is because the presently available studies that locate and characterize the RLMEs have been concentrated in certain locations and are not systematic across the entire study region. Therefore, the evidence for the existence of the RLMEs is included in the model where it exists, but the remaining parts of the study region are also assessed to have significant earthquake potential, which is evidenced by the inclusion of moderate-to-large magnitudes in the Mmax distributions for every Mmax zone or seismotectonic zone.

In Chapter 6, each RLME source is described in detail by the following factors: (1) evidence for temporal clustering, (2) geometry and style of faulting, (3) RLME magnitude, and (4) RLME recurrence. The descriptions document how the data have been evaluated and assessed to arrive at the various elements of the final SSC model, including all expressions of uncertainty. The Data Summary and Data Evaluation tables (Appendices C and D) complement the discussions in the text, documenting all the data that were considered in the course of data evaluation and integration process for each particular seismic source.

Alternative models for the distributed seismicity zones that serve as background zones to the RLME sources are either Mmax zones or seismotectonic zones. The Mmax zones are described in Chapter 6 and are defined according to constraints on the prior distributions for the Bayesian approach to estimating Mmax. The seismotectonic zones are described in Chapter 7 and are identified based on potential differences in Mmax as well as future earthquake characteristics. Each seismotectonic zone in the CEUS SSC model is described according to the following attributes: (1) background information from various data sets; (2) bases for defining the seismotectonic zone; (3) basis for the source geometry; (4) basis for the zone Mmax (e.g., largest observed earthquake); and (5) future earthquake characteristics. Uncertainties in the seismotectonic zone characteristics are described and are represented in the logic trees developed for each source.

For purposes of demonstrating the CEUS SSC model, seismic hazard calculations were conducted at seven demonstration sites throughout the study region, as described in Chapter 8. The site locations were selected to span a range of seismic source types and levels of seismicity. The results from the seismic hazard calculations are intended for scientific use to demonstrate the model, and they should not be used for engineering design. Mean hazard results are given for a range of spectral frequencies (PGA, 10 Hz, and 1 Hz) and for a range of site conditions. All calculations were made using the EPRI (2004, 2006) ground-motion models such that results could be compared to understand the SSC effects alone. Sensitivity analyses were conducted to provide insight into the dominant seismic sources and the important characteristics of the dominant seismic source at each site. The calculated mean hazard results are compared with the results using the SSC model from the 2008 U.S. Geological Survey national seismic hazard maps and the SSC model from the Combined Operating License applications for new nuclear power reactors. The hazard results using the CEUS SSC model given in Chapter 8 are reasonable and readily understood relative to the results from other studies, and sensitivities of the calculated hazard results can be readily explained by different aspects of the new model. The TI Team concludes that the SSC model provides reasonable and explainable calculated seismic hazard results, and the most important aspects of the SSC model to the calculated hazard (e.g., recurrence rates of RLME sources, recurrence parameters for distributed seismicity sources, Mmax) and their uncertainties have all been appropriately addressed.

Presumably, the GMC model input to the PSHA calculations will be replaced in the future by the results of the ongoing NGA-East project. The calculated hazard at the demonstration sites in Chapter 8 comes from the regional CEUS SSC model and does not include any local refinements that might be necessary to account for local seismic sources. Depending on the regulatory guidance that is applicable for the facility of interest, additional site-specific studies may be required to provide local refinements to the model.

To assist future users of the CEUS SSC model, Chapter 9 presents a discussion on the use of the model for PSHA. The basic elements of the model necessary for hazard calculations are given in the Hazard Input Document (HID). This document provides all necessary parameter values and probability distributions for use in a modern PSHA computer code. The HID does not, however, provide any justification for the values, since that information is given in the text of this report.

Chapter 9 also describes several simplifications to seismic sources that can be made to increase efficiency in seismic hazard calculations. These simplifications are recommended on the basis of sensitivity studies of alternative hazard curves that represent a range of assumptions on a parameter's value. Sensitivities are presented using the test sites in this study. For applications of the seismic sources from this study, similar sensitivity studies should be conducted for the particular site of interest to confirm these results and to identify additional simplifications that might be appropriate. For the seismic sources presented, only those parameters that can be simplified are discussed and presented graphically. The sensitivity studies consisted of determining the sensitivity of hazard to logic tree branches for each node of the logic tree describing that source. The purpose was to determine which nodes of the logic tree could be collapsed to a single branch in order to achieve more efficient hazard calculations without compromising the accuracy of overall hazard results.

Finally, this report provides a discussion of the level of precision that is associated with seismic hazard estimates in the CEUS. This discussion addresses how seismic hazard estimates might change if the analysis were repeated by independent experts having access to the same basic information (geology, tectonics, seismicity, ground-motion equations, site characterization). It also addresses how to determine whether the difference in hazard would be significant if this basic information were to change and that change resulted in a difference in the assessed seismic hazard. This analysis was performed knowing that future data and models will continue to be developed and that a mechanism for evaluating the significance of that information is needed. Based on the precision model evaluated, if an alternative assumption or parameter is used in a seismic hazard study, and it potentially changes the calculated hazard (annual frequency of exceedence) by less than 25 percent for ground motions with hazards in the range 10^{-4} to 10^{-6}, that potential change is within the level of precision at which one can calculate seismic hazard. It should be noted, however, that a certain level of precision does not relieve users from performing site-specific studies to identify potential capable seismic sources within the site region and vicinity as well as to identify newer models and data. Also, this level of precision does not relieve users from fixing any errors that are discovered in the CEUS SSC model as it is implemented for siting critical facilities. In addition, NRC has not defined a set value for requiring or not requiring siting applicants to revise or update PSHAs.

Included in the report are appendices that summarize key data sets and analyses: the earthquake catalog, the Data Summary and Data Evaluation tables, the paleoliquefaction database, the HID, and documentation important to the SSHAC process. These data and analyses will assist future users of the CEUS SSC model in the implementation of the model for purposes of PSHA. The entire report and database will be provided on a website after the Final Project Report is issued.

The TI Team, Project Manager, and Sponsors determined the approach for quality assurance on the CEUS SSC Project in 2008, taking into account the SSHAC assessment process and national standards. The approach was documented in the CEUS SSC Project Plan dated June 2008 and discussed in more detail in the CEUS SSC Report (Appendix L). Beyond the assurance of quality arising from the external scientific review process, it is the collective, informed judgment of the TI Team (via the process of evaluation and integration) and the concurrence of the PPRP (via the participatory peer review process), as well as adherence to the national standard referred to in Appendix L, that ultimately lead to the assurance of quality in the process followed and in the products that resulted from the SSHAC hazard assessment framework.

October 24, 2011

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Gentlemen:

Reference: *Central and Eastern United States Seismic Source Characterization for Nuclear Facilities Project:* Participatory Peer Review Panel Final Report

Introduction

This letter constitutes the final report of the PPRP[1] ("the Panel") for the *Central and Eastern United States Seismic Source Characterization for Nuclear Facilities Project* (the "CEUS SSC Project" or "the Project"). The eight Panel members (Jon P. Ake, Walter J. Arabasz, William J. Hinze, Annie M. Kammerer, Jeffrey K. Kimball, Donald P. Moore, Mark D. Petersen, J. Carl Stepp) participated in the Project in a manner fully consistent with the SSHAC Guidance.[2] The Panel was actively engaged in all phases and activities of the Project's implementation, including final development of the Project Plan and planning of the evaluation and integration activities, which are the core of the SSHAC assessment process.

[1] Participatory Peer Review Panel
[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.

The Panel's involvement, described more fully later in this letter, also included review of analyses performed by the Project to support the evaluation and integration processes, review of interim evaluation and integration products, and review of the interim draft project report and the final project report. Additionally, panel members participated in specific analyses as resource experts, and panel members were observers in or participated as resource experts in eight of the eleven Technical Integrator Team (TI Team) working meetings held to implement the integration phase of the assessment process. We want to express our appreciation for the opportunity to participate in the CEUS SSC Project in this way.

In the remainder of this letter we provide our observations and conclusions on key elements of the project implementation process, and we summarize our reviews of the draft and final project reports. As we explain in our comments, assurance that the center, body, and range of the technically-defensible interpretations ("CBR of the TDI")[3] have been properly represented in the CEUS SSC Model fundamentally comes from implementing the structure and rigor of the SSHAC Guidance itself. We are aware that the SSHAC Guidance is accepted by the Nuclear Regulatory Commission and the Department of Energy for developing seismic hazard models that provide reasonable assurance, consistent with the seismic safety decision-making practices of these agencies, of compliance with their seismic safety policies and regulatory requirements. For these reasons, we describe aspects of the SSHAC Guidance to provide context for our observations and conclusions.

Project Plan: Conformity to the SSHAC Assessment Process

The SSHAC Guidance recognizes that observed data, available methods, models, and interpretations all contain uncertainties. These uncertainties lead to alternative scientific analyses and interpretations. In other words, experts in the broad technical community do not hold a single interpretation. Accepting this scientific situation, the SSHAC assessment process is designed to engage the scientific community in an orderly assessment of relevant data, methods, models, and interpretations that constitute current scientific knowledge as the basis for development of a seismic hazard model that represents the CBR of the TDI.

The assessment process is carried out by means of two main activities: *evaluation* and *integration*.[4] In implementation, the evaluation activities are structured to inform the integration activities. The evaluations are carried out by means of workshops in which the TI Team engages proponents of alternative interpretations that represent the range of relevant current community knowledge. Resource experts in the various relevant data sets are also engaged. The workshops have the dual purposes of, first, evaluating the degree to which alternative interpretations are supported by observed data and, second, defining uncertainties in the degree to which the interpretations are defensible, given the observed data. Integration is carried out by individual evaluator experts or evaluator expert teams (Level 4 process) or by a Technical Integrator (TI) Team (Level 3 process) who, informed by the evaluation activities, characterize the range of

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[3] See Section 2.1 in the CEUS SSC Final Report for discussion of concepts relating to the center, body, and range of the "technically-defensible interpretations" vs. the center, body, and range of the "informed technical community."

[4] For an excellent discussion of this two-stage process, see *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*, USNRC NUREG-XXXX, Draft for Review, Office of Nuclear Regulatory Research, May 2011.

defensible alternative interpretations in an integrated hazard model and assess the scientific uncertainty distribution. Based on our review of the Project Plan and our subsequent discussions with the Project Team, we concurred that the Plan conformed with the SSHAC Guidance, incorporating lessons learned from fourteen years experience using the Guidance, and that the planned implementation was structured to properly carry out the SSHAC assessment process for development of the CEUS SSC Model.

SSHAC Level 3 Assessment Process

The SSHAC Guidance describes implementation processes for four levels of assessment depending on the scientific complexity of the assessment and the intended use of the assessed hazard model. For an assessment such as the regional SSC model for the Central and Eastern United States, which will be used at many sites for making safety and licensing decisions for nuclear facilities, the SSHAC Guidance recommends using an assessment Level 3 or Level 4.

There are process differences between a Level 3 and Level 4 implementation, but the objective is the same: to obtain from multiple proponent experts information that supports an informed assessment of the range of existent relevant interpretations and associated uncertainties that together represent current community knowledge and to perform an informed assessment of the CBR of the TDI. We understand that within the SSHAC assessment process “technically defensible” means that observed data are sufficient to support evaluation of the interpretation and the corresponding uncertainty.

In a Level 4 assessment process a TI Team facilitates the assessment, identifying and engaging proponent and resource experts, performing supporting analyses, and conducting knowledge evaluation workshops and assessment integration working meetings. Multiple experts or teams of experts perform as evaluators of the range of existent interpretations and as integrators of the hazard model. The individual evaluator experts or evaluator expert teams take ownership of their individual or team assessments. In a Level 3 assessment all of these activities are consolidated under a single TI Team consisting of a TI Lead, multiple evaluator experts representing the scope of required scientific expertise, and experienced data and hazard analysts.

As we noted earlier in this report, assurance that the CBR of the TDI is properly represented in a hazard model comes from rigorously implementing the SSHAC assessment process itself. We note that an important lesson learned from multiple implementations of the SSHAC Guidance over the past fourteen years is that the Level 3 and Level 4 assessment processes provide comparably high assurance that the relevant scientific knowledge and the community uncertainty distribution are properly assessed and represented in the hazard model. The Level 3 assessment is significantly more integrated and cohesive and is more efficient to implement. These considerations led us to endorse use of the Level 3 assessment for implementation of the CEUS SSC Project in our Workshop No. 1 review letter. During the course of the Project we observed that the higher level of cohesiveness inherent in the Level 3 assessment process leads to significantly improved communication, facilitating the experts’ performance of their technical work.

Overall Project Organization

A complex project with multiple sponsors such as the CEUS SSC Project cannot be successful unless it is well organized and energetically managed so that the various participants understand the interconnectedness of their activities and perform their technical work as a cohesive group. In this regard the adopted project management structure allowed the Project Manager to provide integrated overall project leadership, manage the database development activities, and effectively maintain communication with the PPRP and project sponsors while allowing TI Team lead to concentrate on the structural and technical activities of the assessment as the Project unfolded. <u>We conclude that the project organization was effective overall and particularly so with regard to facilitating the TI Team's implementation of the assessment process.</u>

Implementing the SSHAC Level 3 Assessment Process

Irrespective of the level of implementation, evaluation and integration are the main activities of a SSHAC assessment. The evaluation activities aim to identify and evaluate all relevant available data, models, methods, and scientific interpretations as well as uncertainties associated with each of them. The integration activities, informed by the evaluations, aim to represent the CBR of the TDI in a fully integrated SSC model.

Evaluation

Consistent with the SSHAC Guidance the evaluation phase of the CEUS SSC project accomplished a comprehensive evaluation of the data, models, methods, and scientific interpretations existent in the larger technical community that are relevant to the SSC model. In significant part the process was carried out in three structured workshops, each focusing on accomplishing a specific step in the evaluation process.

The first workshop (WS-1) focused on evaluations of relevant geological, geophysical, and seismological datasets (including data quality and uncertainties) and on identification of hazard-significant data and hazard-significant SSC assessment issues. It became clear that a number of issues relating to the earthquake catalog, the paleoliquefaction data set, the potential-field geophysical data, updating procedures for assessing maximum earthquake magnitude, and development of procedures for assessing earthquake recurrence would require focused analyses. These analyses were appropriately carried out within the TI Team working interactively with appropriate resource experts recognized by the larger scientific and technical community.

WS-2 focused on evaluations of the range of alternative scientific interpretations, methods, and models within the larger scientific community and on corresponding uncertainties. WS-3 focused on evaluations of hazard feedback derived at seven representative test locations using a preliminary CEUS SSC model. Specifically, the workshop focused on the identification of the key issues of most significance to completing the SSC model assessment.

Experience has shown that evaluations to gain understanding of the quality of various data sets and uncertainties associated with them are essential for fully informing an SSC assessment. We observed that in WS-1 resource experts for the various data sets did a high-quality job of describing the data sets and giving their perspective about the data quality and associated uncertainties. <u>We conclude that the understanding of data quality and uncertainties gained in WS-1 together with continued interactions between the TI Team and data resource experts</u>

significantly informed the TI Team's evaluations. The TI Team's evaluations of the data quality and uncertainties are well documented in the innovative "Data Summary Tables" and "Data Evaluation Tables" included in the Project Report. Importantly, the TI Team continued to effectively engage data resource experts in productive analyses of potential-field geophysical data, the earthquake catalog, development of the paleoearthquake data set (including an integrated assessment of the paleoliquefaction data in order to extend the earthquake catalog), the development of methods for assessing maximum earthquakes, and the development of earthquake recurrence analyses. All of these focused analyses strongly informed the assessment process. Moreover, documentation of the analyses resulted in stand-alone products of the Project that will serve future users of the CEUS SSC Model.

The compilation and evaluation of potentially relevant methods, models, and alternative scientific interpretations representing the community knowledge and corresponding uncertainties must be considered the core process activity of any SSHAC assessment. This step was largely carried out in WS-2. Success in defining the community knowledge depends on fully engaging proponent experts representing the range of methods, models, and interpretations existent at the time. Full engagement means that the proponent experts completely and clearly describe their interpretations and the data that support them and provide their individual evaluations of corresponding uncertainties. We observed that the actions taken by the Project and TI Team to explain the workshop goals and to guide participants toward meeting those goals was very productive. We conclude that the workshop was highly successful in meeting the stated goals and that it fully met the expectation of the SSHAC Guidance with respect to evaluating the range of alternative scientific interpretations. The discussions during the workshop and between the TI Team and Panel following the workshop evolved the "SSC Framework" concept, which provided transparent criteria that framed the TI Team's systematic identification and assessment of seismic sources throughout the CEUS.

Feedback from hazard calculations and sensitivity analyses is an important step in a SSHAC assessment to understand the importance of elements of the model and inform the final assessments. For development of a regional SSC model to be used for site-specific probabilistic seismic hazard analyses (PSHAs) at many geographically distributed sites, feedback based on the preliminary model is particularly important. Following WS-2 a preliminary SSC model termed "the SSC sensitivity model," was developed and used for hazard sensitivity calculations that were evaluated in WS-3. While the SSC sensitivity model was clearly preliminary, the evaluation of sensitivity results that took place in WS-3 provided important feedback for completing analyses and for supporting the TI Team's development of the preliminary CEUS SSC model. The Panel was able to review the preliminary model and provide feedback in a subsequent project briefing meeting on March 24, 2010.

Together the three workshops provided the TI Team interactions with the appropriate range of resource and proponent experts. These experts were carefully identified to present, discuss, and debate the data, models, and methods that together form the basis for assuring that the CBR of the TDI have been properly represented in the hazard model. Experts representing academia, government, and private industry participated. The TI Team also reached out to a wide range of experts as they developed the database and performed the integration activities to develop the SSC model. The Panel participated throughout this process, and is satisfied that the TI Team fully engaged appropriate experts to accomplish the goals of a SSHAC Guidance.

Integration

Consistent with the SSHAC Guidance, integration is the process of assessing the CBR of the TDI and representing the assessment in the SSC model. Informed by the evaluation process, the integration process includes representation of the range of defensible methods, models, and interpretations of the larger technical community together with new models and methods developed by analyses during the evaluation and integration process.

For the CEUS SSC Project, development of the earthquake catalog, methods for assessing and representing maximum earthquake magnitudes, and methods for earthquake recurrence assessment continued during the integration process. The Panel reviewed all the analyses at various stages of development and provided comments and recommendations. The TI Team performed the integration process by means of eleven working meetings. Members of the Panel participated in most of these working meetings as observers or resource experts. The full Panel participated in the discussions during both feedback meetings and provided formal comments and recommendations following the meetings. <u>We observed that the integration process was thorough and that it acceptably complied with the SSHAC Guidance. Based on our participation and observations we conclude that the integrated CEUS SSC Model appropriately represents the center, body, and range of current methods, models and technically defensible interpretations.</u>

PPRP Engagement

Consistent with the SSHAC Guidance, the Panel was fully engaged in peer-review interactions with the TI Team and the Project Manager of the CEUS SSC Project throughout the entire project period—from development of the Project Plan in early to mid 2008 through production of the Final Project Report in mid to late 2011.[5] The Panel provided both written and oral peer-review comments on both technical and process aspects at many stages of the Project's evolution. Key PPRP activities, leading up to this final report, have included:

- Review of the Project Plan.
- Formulation of a PPRP implementation plan, specifically for the CEUS SSC Project, to ensure adherence to the general guidance provided by SSHAC and NUREG-1563 for the scope and goals of a PPRP review.
- Involvement in *each* of the three Project workshops, 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), providing timely comments on technical and process issues; and submitting a written report of the Panel's observations and recommendations following each workshop.
- Development and implementation of a process, together with the TI Team, to document the resolution of recommendations made in PPRP formal communications.
- Participation as observers (and occasionally as resource experts when requested by the TI Team) in eight of the TI Team's 11 working meetings.
- Peer-review and written comments, including several informal reports, on the TI Team's intermediate work products, particularly early versions of the CEUS SSC Model.

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[5] See CEUS SSC Final Report: Section 2.5, Table 2.2-1, and Appendix I

- Direct interaction with the TI Team and Project Manager in more than 20 teleconferences and four face-to-face briefings—in addition to the three workshops and eight working meetings of the TI Team noted above.
- Extensive, critical peer-review of the Project's 2010 Draft Report and 2011 Final Report.

The Panel, collectively and individually, fully understood the SSHAC Guidance for a structured participatory peer review and the requirements for a Level 3 assessment process; had full and frequent access to information and interacted extensively with the TI Team and Project Manager throughout the entire project; provided peer-review comments at numerous stages; and, as documented within the Final Project Report, was fully engaged to meet its peer-review obligations in an effective way.

Project Report

The SSHAC Guidance makes clear that adequate documentation of process and results is crucial for their understanding and use by others in the technical community, by later analysis teams, and by the project sponsors. The Panel understood what was needed to conform to the SSHAC requirements, and it was committed to ensuring that the documentation of technical details associated with the CEUS SSC Model in the Project Report was clear and complete. The Panel was equally committed to ensuring the transparency of process aspects of the project, both in implementation and in description in the Project Report.

The Panel provided lengthy compilations of review comments (see Appendix I of the Project Report) for both the 2010 Draft Report and the 2011 Final Report. These included hundreds of comments, categorized as general, specific, relating to clarity and completeness, or editorial. The massive amount of detail provided by the TI Team in the Project Report and the intensiveness of the Panel's review comments both reflect great diligence and a mutual understanding by the TI Team and the PPRP of the thoroughness and high quality of documentation expected in the Project Report.

The Project Manager and the TI Lead provided review criteria to the Panel for both the draft and final versions of the Project Report. The criteria for reviewing the Draft Report[6] covered the range of technical and process issues consistent with requirements of the SSHAC Guidance, including draft implementation guidance (see footnote #4). Key criteria, among others, include sufficiency of explanatory detail; adequate consideration of the full range of data, models, and methods—and the views of the larger technical community; adequate justification of the data evaluation process, logic-tree weights, and other technical decisions; proper treatment of uncertainties; and conformance to a SSHAC Level 3 assessment process. To be clear, the PPRP is charged with judging the adequacy of the documented *justification* for the CEUS SSC Model and its associated logic-tree weights. The TI Team "owns" the Model and logic-tree weights.

Criteria for reviewing the Final Report focused on reaching closure to comments made on the Draft Report and ensuring that no substantive issues remained unresolved. To that end, among its many review comments on the Final Report the Panel identified "mandatory" comments, which the TI Team was required to address in the final version of the Project Report.

[6] See PPRP report dated October 4, 2010, in Appendix I of CEUS SSC Final Report

The Panel made thorough, extensive efforts in its documented reviews of the 2010 Draft Report and the 2011 Final Report (as well as in many related interactions with the TI Team) to ensure a high-quality Project Report that fully meets SSHAC requirements for clear, complete, and transparent documentation of all aspects of the CEUS SSC Project. We are pleased to confirm that implementation of the CEUS SSC Project fully conformed with the SSHAC Guidance and that the resulting CEUS SSC Model properly meets the SSHAC goal of representing the center, body, and range of technically-defensible interpretations.

This concludes our PPRP Final Report for the CEUS SSC Project.

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Jeffrey F. Hamel was the EPRI Advanced Nuclear Technology Program Manager. Lawrence A. Salomone of Savannah River Nuclear Solutions, LLC, served as the Project Manager for the study. Kevin J. Coppersmith of Coppersmith Consulting Inc., served as the lead for the TI Team. J. Carl Stepp of Earthquake Hazards Solutions, and Walter J. Arabasz, Research Professor Emeritus of Geology and Geophysics at the University of Utah, served as Co-chairmen for the PPRP. The entire Central and Eastern United States Seismic Source Characterization Project Team and their roles are discussed in Section 2 and are shown on the project oganization chart (Figure 2.3-1) of the report.

The authors of the report wish to acknowledge the contributions of the following people: the resource experts who participated in Workshop 1, the proponent experts who participated in Workshop 2, and the technical experts who provided valuable insights, perspective, and references throughout the study. The names of all these contributors are listed in Table 2.2-2.

In addition, the authors of the report appreciate the support of Geraldine Moore-Butler as administrative assistant and Nancy L. Sutherland as technical editor for the project. This report was assembled at AMEC.

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SPONSORS' PERSPECTIVE

This report describes a new seismic source characterization model for the Central and Eastern United States (CEUS) for use in probabilistic seismic hazard analysis (PSHA) for nuclear facilities. PSHA has become a generally accepted procedure for supporting seismic design, seismic safety and decision making for both industry and government. Input to a PSHA consists of seismic source characterization (SSC) and ground motion characterization (GMC); these two components are necessary to calculate probabilistic hazard results (or seismic hazard curves) at a particular geographic location.

The 1986 Electric Power Research Institute and Seismicity Owners Group (EPRI-SOG) study included both an SSC and GMC component. Recent applications for new commercial reactors have followed U.S. Nuclear Regulatory Commission (NRC) regulatory guidance (RG 1.208) by using the EPRI-SOG source model as a starting point and updating it as appropriate on a site-specific basis. This CEUS SSC Project has developed a new SSC model for the CEUS to replace the SSC component of the EPRI-SOG study.

The CEUS SSC Project was conducted using a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 process, as described in the NRC publication, *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* (NUREG/CR-6372). The goal of the SSHAC process is to represent the center, body, and range of technically defensible interpretations of the available data, models, and methods. The CEUS SSC model is applicable to any site within the CEUS and can be used with the EPRI 2004/2006 GMC model to calculate seismic hazard at any site of interest. Long-term efforts to replace the EPRI 2004/2006 GMC model with the Next Generation Attenuation Relationships for Central and Eastern North America obtained from the NGA-East Project is scheduled for completion in 2014.

The updated CEUS SSC model provides industry and government with the following: a new model for the commercial nuclear industry to perform PSHAs for future reactor license applications; the NRC to support its review of early site permit (ESP) and construction and operating license (COL) applications; and the U.S. Department of Energy (DOE) to support modern PSHAs to meet design and periodic review requirements for its current and future nuclear facilities. Specific benefits of the model are as follows:

- **Consistency:** For many sites, seismic sources at distances up to 300 km (186 mi.) or more significantly contribute to hazard at some spectral frequencies. Consequently, seismic hazard models for many sites have significant geologic overlap. If done separately, there is a likelihood of conflicting assessments for the same regions. A regional source model allows for consistent input into a PSHA. An updated conceptual SSC framework that provides a consistent basis for identifying and characterizing seismic sources in the CEUS has been developed. The NRC will no longer need to review each time each applicant's regional SSC model when the accepted CEUS SSC model is used. This will avoid lengthy review of the regional SSC model in ESP and COL applications for sites within the CEUS that use the accepted regional CEUS SSC model to develop its site-specific SSC model.

- **Stability:** This CEUS SSC model was developed using the accepted state-of-practice SSHAC methodology that involved the following tasks:
  - Development of a comprehensive database and new tools for documenting the data consideration process.
  - Multiple workshops to identify applicable data, debate alternative hypotheses, and discuss feedback.
  - Multiple working meetings by the Technical Integration (TI) Team to develop the SSC model and fully incorporate uncertainties.
  - Technical advancements in a number of areas, such as developing a uniform earthquake catalog, developing an updated approach for assessing maximum magnitude, compiling data evaluation tables, incorporating paleoseismic data, and using spatial smoothing tools.
  - Participatory peer review, including four panel briefings, multiple interactions, and periodic formal feedback.
  - Proper documentation of all process and technical aspects of the project.

  Experience has shown that stability is best achieved through proper and thorough characterization of our knowledge and uncertainties, coupled with the involvement of the technical community, regulators, and oversight groups.

- **Greater Longevity:** An explicit goal of the SSHAC methodology is to represent the center, body, and range of the technically defensible interpretations of the available data, models, and methods. Using the SSHAC process provides reasonable assurance that this goal has been achieved. Representing the center, body, and range of interpretations at the time of the study means that as new information is acquired and various interpretations evolve as a result, the current thinking at any point is more likely to be addressed in the study. As new information becomes available, an existing SSC will require periodic reviews to evaluate the implications of the new findings. The need for updates to a particular study is now better understood as a result of findings of the CEUS SSC Project sensitivity studies to determine the significance of source characteristics.

- **Cost and Schedule Savings:** The CEUS SSC model can be used to perform a PSHA at any geographic location within the CEUS. It is applicable at any point within the CEUS, subject to site-specific refinements required by facility-specific regulations or regulatory guidance. Having stable, consistent input into a regional PSHA will reduce the time and cost required to complete a commercial nuclear site's ESP or COL licensing application, prepare a DOE site's PSHA, and develop design input for new commercial and DOE mission-critical nuclear facilities.

- **Advancement of Science:** The CEUS SSC Project provides new data, models, and methods. This information was shared at three workshops with international observers as a means to provide technology transfer for application in other regions. The CEUS SSC earthquake catalog, which merges and reconciles several catalogs and provides a uniform moment magnitude for all events, and the CEUS SSC paleoliquefaction database provide a new baseline for future research and updates. New approaches used in this project for spatial smoothing of recurrence parameters, assessment of maximum magnitude, and systematical documentation of all data considered and evaluated also benefit future research and PSHA updates.

The sponsors of the CEUS SSC Project are utilities and vendors on the EPRI Advanced Nuclear Technology Action Plan Committee, the DOE Office of Nuclear Energy, the DOE Office of the Chief of Nuclear Safety, and the NRC Office of Nuclear Regulatory Research. Technical experts from the DOE, NRC, U.S. Geological Survey (USGS), and Defense Nuclear Facility Safety Board (DNFSB) participated in the study as part of the TI Team or as members of the Participatory Peer Review Panel (PPRP).

The product of the CEUS SSC Project is a robust peer-reviewed regional CEUS SSC model for use in PSHAs. This model will be applicable to the entire CEUS, providing an important baseline for future research and updates. The CEUS SSC Project demonstrates that a SSHAC Level 3 approach can achieve the goals of considering the knowledge and uncertainties of the larger technical community within a robust and transparent framework. The value of the new CEUS SSC model has been enhanced by the participation of key stakeholders from industry, government, and academia who were part of the CEUS SSC Project Team.

Looking forward, the NRC will publish NUREG-2117 (2012), *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies* that provides SSHAC guidance on the need to update a regional model. The guidance covers updating both regional and site-specific assessments. It addresses the "refinement" process of starting with a regional model and refining it for site-specific applications.

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ABBREVIATIONS

AD	anno domini (in the year of the Lord)
AFE	annual frequency of exceedance
AIC	Akaike information criterion
ALM	Alabama-Louisiana-Mississippi (zone of possible paleoseismic features)
AM	Atlantic Margin (seismotectonic zone)
AHEX	Atlantic Highly Extended Crust (seismotectonic zone)
ANSS	U.S. Advanced National Seismic System
ANT	Advanced Nuclear Technology
APC	Action Plan Comittee
BA	Blytheville arch
BC	before Christ
BCFZ	Big Creek fault zone
BFZ	Blytheville fault zone
BL	Bootheel lineament
BMA	Brunswick magnetic anomaly
BP	before present
BPT	Brownian passage time
BTP	Branch Technical Position
CAD	computer-aided design

CBR	center, body, and range
CCFZ	Crittenden County fault zone
CDZ	Commerce deformation zone
CENA	Central and Eastern North America
CERI	Center for Earthquake Research and Information
CEUS	Central and Eastern United States
CFZ	Commerce fault zone
CFR	Code of Federal Regulations
CGL	Commerce geophysical lineament
CGRGC	Cottonwood Grove–Rough Creek graben
CI	confidence interval
CNWRA	Center for Nuclear Waste Regulatory Analysis
COCORP	Consortium for Continental Reflection Profiling
COCRUST	Consortium for Crustal Reconnaissance Using Seismic Techniques
COL	combined construction and operating license
COLA	combined operating license application
COMP	composite prior, composite superdomain
CON	contemporary (with earthquake occurrence)
COV	coefficient of variation
CPT	cone penetration test
CVSZ	Central Virginia seismic zone
D&G	Dewey and Gordon (1984 catalog)
DEM	digital elevation model

DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DWM	Division of Waste Management
ECC	Extended Continental Crust
ECC-AM	Extended Continental Crust–Atlantic Margin (seismotectonic zone)
ECC-GC	Extended Continental Crust–Gulf Coast (seismotectonic zone)
ECFS	East Coast fault system
ECFS-C	East Coast fault system—central segment
ECFS-N	East Coast fault system—northern segment
ECFS-S	East Coast fault system—southern segment
EC-SFS	East Coast–Stafford fault system
ECMA	East Coast magnetic anomaly
ECRB	East Continent rift basin
ECTM	Eastern Canada Telemetered Network
E[**M**]	expected moment magnitude listed in the CEUS SSC catalog for an earthquake
ENA	eastern North America
EP	Eau Plain shear zone
EPRI	Electric Power Research Institute
EPRI-SOG	Electric Power Research Institute–Seismicity Owners Group
ERM	Eastern rift margin
ERM-N	Eastern rift margin—north
ERM-RP	Eastern rift margin—river (fault) picks
ERM-S	Eastern rift margin—south

ERM-SCC	Eastern rift margin—south/Crittenden County
ERM-SRP	Eastern rift margin—south/river (fault) picks
ERRM	Eastern Reelfoot Rift Margin
ESP	early site permit
ESRI	Environmental Systems Research Institute
ETSZ	Eastern Tennessee seismic zone
EUS	Eastern United States
FAFC	Fluorspar Area fault complex
FGDC	Federal Geographic Data Committee
ft	foot or feet
FTP	file transfer protocol
ft/s	feet per second
ft/yr	feet per year
FWLA	Fugro William Lettis & Associates
FWR	Fort Wayne rift
Ga	billion years ago
GC	Gulf Coast
GCVSZ	Giles County, Virginia, seismic zone
GHEX	Gulf Coast Highly Extended Crust (seismotectonic zone)
GIS	geographic information system
GLTZ	Great Lakes tectonic zone
GMC	ground-motion characterization (model)
GMH	Great Meteor Hotspot (seismotectonic zone)

GMPE	ground-motion prediction equation
GMRS	ground-motion response spectra
GPR	ground-penetrating radar
GPS	global positioning system
GSC	Geological Survey of Canada
Gyr	gigayears (10^9 years)
HF	Humboldt fault
HID	hazard input document
I_0	maximum intensity
IAEA	International Atomic Energy Agency
IBEB	Illinois Basin Extended Basement (seismotectonic zone)
IPEEE	Individual Plant Examination for External Events
IRM	Iapetan rifted margin
ISC	International Seismological Centre
ITC	informed technical community
ka	thousand years ago
K-Ar	potassium-argon
km	kilometer(s)
km^2	square kilometer(s)
km/sec	kilometers per second
K-S	Kijko-Sellevoll
K-S-B	Kijko-Sellevoll-Bayes
kyr	thousand years

LDO	Lamont-Doherty Earth Observatory (catalog)
LHS	Latin hypercube sampling
LLNL	Lawrence Livermore National Laboratory
ln(FA)	logarithm of felt area (with felt area measured in km^2)
LS	least squares
LSA	La Salle anticlinal belt
LWLS	locally weighted least squares
m	meter(s)
M	magnitude
M, M_W	moment magnitudes
Ma	million years ago
MAR	Marianna (RLME source)
m_b	body-wave magnitude (short period)
m_{bLg}	body-wave magnitude determined from higher-mode (L_g) surface waves
M_C	coda magnitude
MCMC	Markov Chain Monte Carlo
M_D	duration magnitude
MESE	Mesozoic and younger extended crust
MESE-N	Mesozoic-and-younger extended crust or Mmax zone that is “narrow”
MESE-W	Mesozoic-and-younger extended crust or Mmax zone that is “wide”
mi.	mile(s)
$mi.^2$	square mile(s)
MIDC	midcontinent

MidC	Midcontinent-Craton (seismotectonic zone)
Mfa	felt-area magnitude
M_L	local magnitude
M_{max}, Mmax	maximum magnitude
MMI	modified Mercalli intensity
mm/yr	millimeters per year
M_N	Nuttli magnitude
M_o	Scalar seismic moment
MRS	Midcontinent rift system
m/s	meters per second
M_S	surface-wave magnitude
MSF	Meeman-Shelby fault
M_w	
Myr	million years
NAD83	North American Datum of 1983
NAP	Northern Appalachian (seismotectonic zone)
Nd	neodymium
NEDB	National Earthquake Database
NEI	Nuclear Energy Institute
NEIC	National Earthquake Information Center
NF	Niagara fault zone
NMESE	Non-Mesozoic and younger extended crust
NMESE-N	Mesozoic-and-younger extended crust or Mmax zone that is “narrow”

NMESE-W	Mesozoic-and-younger extended crust or Mmax zone that is “wide”
NMFS	New Madrid fault system
NMN	New Madrid North fault
NMS	New Madrid South fault
NMSZ	New Madrid seismic zone
NN	New Madrid north (fault segment as designated by Johnston and Schweig, 1996)
NOAA	National Oceanic and Atmospheric Administration
NPP	nuclear power plant(s)
NR	Nemaha Ridge
NRC	U.S. Nuclear Regulatory Commission
NRHF	Nemaha Ridge–Humboldt fault
NSHMP	National Seismic Hazard Mapping Project
NW	New Madrid west (fault segment as designated by Johnston and Schweig, 1996)
OKA	Oklahoma aulacogen (seismotectonic zone)
OKO	Oklahoma Geological Survey Leonard Geophysical Observatory (catalog)
OSL	optically stimulated luminescence
P_a	probability of activity (of being seismogenic)
PEZ	Paleozoic Extended Crust (seismotectonic zone)
PGA	peak ground acceleration
PM	Project Manager
PPRP	Participatory Peer Review Panel
PSHA	probabilistic seismic hazard analysis
PVHA	probabilistic volcanic hazard analysis

RCG	Rough Creek graben
RF	Reelfoot fault
RFT	Reelfoot thrust (fault)
RLME	repeated large-magnitude earthquake (source)
RR	Reelfoot rift zone
RS	Reelfoot South (fault segment)
SA	spectral acceleration
SCL	St. Charles lineament
SCML	south-central magnetic lineament
SCR	stable continental region
SCSN	South Carolina Seismic Network
SEUS	Southeastern United States (catalog)
SEUSSN	Southeastern United States Seismic Network
SGFZ	Ste. Genevieve fault zone
SHmax	maximum horizontal stress, compression, or principal stress
SLR	St. Lawrence rift (seismotectonic zone)
SLTZ	Spirit Lake tectonic zone
SLU	Saint Louis University (catalog)
SNM	Sanford et al. (2002 catalog)
SOG	Seismicity Owners Group
SPT	standard penetration test
SRA	Stover, Reagor, and Algermissen (1984 catalog)
SRTM	Shuttle Radar Topography Mission

SSC	seismic source characterization
SSE	safe shutdown earthquake
SSHAC	Senior Seismic Hazard Analysis Committee
Str&Tur	Street and Turcotte (1977 catalog)
SUSN	Southeastern United States Network
TC	technical community
TFI	technical facilitator/integrator
TI	technical integration
USGS	U.S. Geological Survey
USNSN	U.S. National Seismograph Network
UTC	Coordinated Universal Time
V_P/V_S	ratio of P-wave velocity to S-wave velocity
WES	Weston Observatory (catalog)
WIPP	Waste Isolation Pilot Project
WQSZ	Western Quebec seismic zone
WRFZ	White River fault zone
WUS	Western United States
WVFS	Wabash Valley fault system
WVSZ	Wabash Valley seismic zone
WWSSN	World-Wide Standardized Seismograph Network