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APPENDIX
WORKSHOP SUMMARIES

WORKSHOP 1: KEY ISSUES AND AVAILABLE DATA
July 22–23, 2008

Electric Power Research Institute
3420 Hillview Ave.
Palo Alto, California 94304

The Workshop on Key Issues and Available Data was the first in a series of workshops jointly sponsored by the Electric Power Research Institute (EPRI) Advanced Nuclear Technology (ANT) Program and the U.S. Department of Energy (DOE) in support of the Central and Eastern U.S. Seismic Source Characterization for Nuclear Facilities (CEUS SSC) Project. The objective of the CEUS SSC is to develop a comprehensive and up-to-date SSC for a probabilistic seismic hazard analysis (PSHA) that is appropriate for use at any site in the CEUS. The goals of this workshop were to (1) introduce the various participants in the project to the goals, expectations, and schedule for the CEUS SSC project; (2) review the SSHAC Level 3 methodology (Budnitz et al., 1997) to be used for the project; (3) identify the key issues that need to be addressed in the course of the seismic source characterization; (4) review the available data, including data quality; and (5) identify the path forward for the project.

DAY 1–TUESDAY, JULY 22

Workshop participants were welcomed by Mr. Jeffrey Hamel, the EPRI Project Manager for the CEUS SSC project. He stated the importance of this project to the nuclear industry and noted that applications for 15 nuclear power plant units are currently pending and that 9 additional applications are planned to be submitted in 2009. He showed a "prism" slide that indicated the potential roles of electric sector technologies, including the role of nuclear power, in lowering CO_2 emissions by the year 2030. He reviewed the status of the current fleet of nuclear power plants in the United States and cited EPRI projections of a total of ~24 GWe by 2020 and ~64 GWe by 2030 from the new fleet that will be deployed.

The EPRI program for supporting new nuclear power plants, the Advanced Nuclear Technology (ANT) program, was described briefly. The program efforts are focused around facilitating standardization across the new fleet, transferring technology to new plant designs, and ensuring top plant performance from the start of operations. ANT program activities characterized as emerging, growth (including the CEUS SSC project), mature and declining activities were described. The program is funded by more than 25 utilities, vendors, and government agencies interested in promoting light water reactors. In addition, there is substantial interest from utilities based in Europe, which reflects the growth of this technology outside the United States as well.

Next, Mr. Lawrence Salomone, Project Manager for the CEUS SSC project, welcomed everyone and expressed his appreciation for their participation in the project. He asked all workshop participants to introduce themselves and identify their affiliations. He began his talk by emphasizing that nuclear capabilities are essential as clean, safe options to achieve base load capacity increases, noting that 50 new units will provide 25 percent of the projected increased demand. To expedite the licensing of next-generation nuclear power plants, Mr. Salomone emphasized that we can do "more for less to achieve stability, with reduced risk through standardization and partnering." He described the industry and government plan to advance the science for nuclear technology, which includes using the CEUS SSC project to replace the previous EPRI-Seismicity Owners Group (EPRI-SOG, 1988) and Lawrence Livermore National Laboratory (LLNL; Bernreuter et al.1989) seismic hazard studies that were conducted in the 1980s.

Next, Mr. Salomone described the goals for the CEUS SSC project, which include developing a "commercially viable" approach for SSC model development with respect to cost and schedule that meets the expectations of sponsors, regulators, and oversight groups. He reviewed the Workshop 1 objectives, noting that a documentation package would be prepared for the workshop to be consistent with the objective of having a transparent project process. Next he reviewed the CEUS SSC project history to date and outlined industry and U.S. Department of Energy (DOE) expectations for the project. The primary expectations are to advance the science and obtain a PSHA update that is based on a stable and consistent SSC model, thereby expediting the licensing of the next generation of nuclear power plants.

Mr. Salomone then noted that the number of proposed sites for next-generation plants in the CEUS is increasing and that existing plants in the DOE complex require an updated PSHA. Such studies are time-consuming and costly if each utility prepares a PSHA independently; at the same time, regulators want to streamline the review process and be capable of moving forward quickly. In addition, the EPRI-SOG (1988) and LLNL (1989) seismic hazard studies need to be updated using new data and interpretations; also, a void exists for an SSC model that postdates 10CFR 100.23. Accordingly, assembling a single team of experts to develop a new and stable CEUS SSC model that incorporates a full range of uncertainty provides many benefits, thus industry and government agencies have been brought together to sponsor this project.

Next, the organization chart for the CEUS SSC project was described. The Program Managers have overall responsibility for the project. The Technical Integration (TI) team, which includes the TI staff, has responsibility for the technical assessments made during the project. The Participatory Peer Review Panel (PPRP) is responsible for reviewing the process and technical aspects of the project. Specialty contractors are involved in database, hazard input and calculation, and documentation support. Participants in each of the project workshops are important because they have databases and alternative interpretations that are valuable to the project. Project milestones were described for the next two years; the final milestone will be an EPRI Technical Report to be published in 2010. Mr. Salomone concluded his talk by summarizing the benefits of the project, which include (1) supporting a research and development program to advance the state of practice for seismic hazard assessment; (2) obtaining PSHA input based on a stable and consistent SSC model vetted by a wide range of experts; (3) avoiding unnecessary conservatism and reduction in design margins; (4) expediting approvals of the seismic design basis for nuclear facilities; and (5) yielding significant economic benefits by reducing PSHA update costs for individual sites.

Mr. Salomone then introduced Dr. Kevin Coppersmith (Coppersmith Consulting, Inc.), the lead of the TI team, to speak in more detail about the CEUS SSC project and the goals of the workshop. Dr. Coppersmith began by stating that 20 years have passed since the previous seismic hazard assessments for the CEUS were conducted (e.g., EPRI-SOG, 1988, and LLNL, 1989). The current project will provide an unbiased seismic hazard assessment that captures uncertainty by following the process specifically designed to achieve this objective by the Senior Seismic Hazard Analysis Committee (SSHAC) (Budnitz et al., 1997).

Dr. Coppersmith described SSC as fundamentally a scientific issue involving three questions: where will future earthquakes occur, how large will they be, and how frequently will they happen? He described some of the scientific assessments needed for SSC and stated that locations of observed events are based on historical and instrumental earthquakes, yet for a hazard analysis there is a need to assess the future pattern of seismicity. Spatial stationarity, seismogenic potential of geologic structures, the nature of boundaries between seismic zones, and other assessments needed for SSC were mentioned as he showed examples that included San Francisco Bay Area seismicity, the active Meers fault in Oklahoma, the New Madrid seismic zone, seismicity in Switzerland, and an isoseismal map of the 1356 Basel, Switzerland, earthquake. Scientific assessments of earthquake size, especially maximum magnitude (M_{max}), and recurrence, were also illustrated using examples. He described how uncertainties in seismic hazard assessments need to be captured through the use of logic tree structures and noted that these were new at the time the EPRI-SOG work was conducted.

Next, Dr. Coppersmith described the SSHAC methodology that provides a framework for incorporation of scientific assessments. In this methodology the views of the larger scientific community are captured as a "snapshot in time" of our knowledge and uncertainties. He described elements of the SSHAC methodology, including the goal of all probabilistic hazard analyses to represent the center, body, and range of technical interpretations that the larger, informed technical community could provide. To achieve this goal, expert roles and responsibilities have been defined. Experts must be "evaluators" who need to understand and evaluate information provided by "proponents." Stability and longevity are the larger goals of all PSHA methodologies, which are achieved in part from identifying and incorporating uncertainties. With these attributes a PSHA will have public and regulatory confidence that all hypotheses have been considered and the conclusions are not subject to significant change with each new scientific finding; new information can also be considered and incorporated into a PSHA.

Dr. Coppersmith then reviewed the SSHAC study levels 1 thru 4, which are designed to address increasingly difficult and contentious problems by processes that increase complexity. The CEUS SSC project is a Level 3 study and includes both a TI team and the active involvement of a participatory peer review team, led by Drs. J. Carl Stepp and Walter Arabasz as co-chairmen.

The CEUS SSC task schedule was reviewed next. Dr. Coppersmith emphasized that a ground motion assessment was not part of the current project, as new alternative models were recently developed for the CEUS (EPRI, 2004, 2006). He then described the goals of Workshop 1, which include identifying key hazard-significant SSC issues and the data sets available to address these

issues. He reviewed the ground rules for workshops, which are designed primarily for the TI team to exchange data, present interpretations, challenge and defend technical hypotheses, gain information on the project, interact, and ask questions. Observers will be provided with opportunities for questions/comments. Finally, he reviewed the roles of workshop participants, including expert roles of proponents and evaluators, and concluded his talk by reviewing the agenda for
Workshop 1.

After a short break, the workshop session titled "Key Hazard-Significant CEUS SSC Issues" commenced. The purpose of this session was to review and discuss the technical issues of importance to the CEUS SSC study in the context of preparation of a PSHA. Dr. Robin McGuire (Risk Engineering, Inc.) gave a talk titled "Perspectives on Seismic Hazard Sensitivity to Input Assumptions." He noted that the purpose of his comments was to illustrate the sensitivity of seismic hazard to input parameter choices, and he emphasized the importance of keeping aleatory and epistemic uncertainties separate. He reviewed the definitions of these types of uncertainties and gave an example of how they are used in characteristic magnitude distribution (i.e., the aleatory uncertainty is that successive characteristic earthquakes have different magnitudes [e.g., M 7.2-7.7] and the epistemic uncertainty is in the range of these magnitudes [e.g., M 7.2-7.7 or M 7.0-8.0]). He explained also that these represent a "snapshot in time" and that uncertainty tends to migrate from aleatory to epistemic as better models are developed.

Next Dr. McGuire showed some examples for a set of sites affected by faults that represented the New Madrid event by showing example parameters and uncertainties for these hypothetical sources from the SSHAC report (Budnitz et al., 1997). He discussed the relationships between earthquake magnitude and hazard, such that if beta goes down, hazard increases, especially at larger distances; at close distances smaller events may dominate the hazard. Also, he mentioned that seismic hazard may be more sensitive to changes in distance if M_{max} is low. For purposes of sensitivity analysis, he defined a significant change as a hazard result change of more than 20 percent, as a result of alternative parameter inputs. He illustrated this with examples from Group A sites and Group B sites. Most changes result in a change in hazard of less than 20 percent, and some have no sensitivity. The integration of hazard over many events with various parameters is not inconsistent with the finding that the occurrence of a particular rare event could cause lots of damage. Multiple interpretations of seismic sources are important; this is especially critical for specific sites, as hazard results could be very sensitive to the boundaries defined for a particular seismic source.

Dr. McGuire showed examples of the contribution of high- and low-frequency hazard to the magnitudes and distances of the earthquakes that contribute to hazard at a site within the area of influence of the 1886 Charleston event. He showed a series of plots with increasingly larger ground motions, which progressively showed an increased contribution from close-by, smaller events. Then he showed a set of plots for low-frequency hazard and the associated events that contribute to hazard. He provided an example in the Eastern Tennessee seismic zone (ETSZ), showing M_{max} distributions for the ETSZ from recently completed studies as well as a series of slides showing the source zones for this region defined by the six EPRI-SOG teams. These give multiple alternative source zone interpretations and a resulting range of a factor of 5 in hazard from curves produced at 10 hertz (HZ) (the individual team results were ultimately weighted equally to produce a single hazard curve). Some of the differences are related to different seismicity rates within the alternative zones, which are influenced by the approach used to smooth the historical seismicity. At low structural frequencies, the New Madrid seismic zone is a major contributor and there is a tighter hazard range across the teams. He also showed that at high frequencies there is low sensitivity to M_{max}, whereas at low frequencies there is increased sensitivity to M_{max}. Therefore, if M_{max} is low, it can be more important to hazard than if it is high.

Dr. McGuire then showed geometries of New Madrid seismic sources from a recent study, the earthquake magnitudes for the sources used in a cluster model, and the associated sensitivity of 1 Hz and 10 Hz spectral acceleration hazard. He showed plots of New Madrid seismic sources from the EPRI-SOG teams and the resulting differences in hazard at specific locations (e.g., moving a site 20 km could result in a 30 percent reduction in hazard). Next he showed examples of updated Charleston seismic source geometry alternatives and how these were merged with the EPRI-SOG team Charleston sources as revised ("doughnut hole") sources containing the updated Charleston source information. As with the examples shown previously, the sensitivity of the mean hazard varies as a function of ground-motion structural frequency. From a distribution of seismic hazard curves for the 85th, mean, 50th, and 15th fractile hazard, the hazard (15th to 85th) is known within a factor of 20; the mean of the hazard is known more precisely. There is a high level of sensitivity to the characteristic earthquake (M_{char}).

Seismicity parameters used in the EPRI-SOG project were the next topic discussed by Dr. McGuire. The EPRI-SOG seismicity parameters were determined by statistical analysis of historical seismicity and the parameters were calculated for each source per degree cell using smoothing options specified by each team. Alternative sets of seismicity parameters were weighted by each team. Dr. McGuire showed examples from the Bechtel team's source BZ5. He showed a visual representation of different smoothing assumptions used within the zone and plots of the sensitivity of hazard curves to smoothing. Next, he showed examples of the central Virginia seismic zone using alternative zone geometries selected by the EPRI-SOG teams and the range of related seismicity parameters. He looked at the effect of seismic hazard at three sites, and found that site location is extremely sensitive to these zones: a difference in hazard of more than a factor of two for two sites located about 30 km apart, which is a huge difference. His conclusion is that alternative zone boundaries or boundary treatments are essential, as defining only a single source could significantly affect the hazard results for sites located either just inside or outside the zone boundaries.

Next Dr. McGuire showed a CEUS region and the geometries of faults in the New Madrid seismic zone as modeled in a recently conducted PSHA. The hazard results for sites at three different locations in the region show that at a low frequency (1 Hz), there is a large contribution to hazard from New Madrid sources, but at 10 Hz, there is a greater contribution (two to three times) from local sources at each of the sites.

In a last set of examples, Dr. McGuire showed seismic sources defined in the Gulf of Mexico region by each of the EPRI-SOG teams. He stated that it will be important for the CEUS SSC study to consider earthquakes outside the United States. Seismicity maps for Central America and the Caribbean were shown; both areas have seismicity that may need to be included in models for sites in the southeastern United States. Also shown were EPRI-SOG seismic sources and hazard curves for Houston, Texas. The hazard curve for 1 Hz shows strange behavior, having a huge range of almost two orders of magnitude difference between the 15th and 85th fractiles. Dr. McGuire postulated that one particular ground motion equation that was used may be affecting the mean hazard curve.

Following a break for lunch, Dr. McGuire concluded his presentation. He described the Cumulative Absolute Velocity (CAV) model developed to calculate cumulative ground motions at a site. This model indicates a short-duration, high-frequency earthquake will have less effect on a site than a large, distant earthquake. Sites where small magnitude earthquakes contribute the most to the overall hazard have lower hazard as a result of application of a CAV filter.

Dr. McGuire closed by listing his recommendations regarding the relative significance of SSC issues in order of priority. Assessments of seismic sources having potentially large earthquake magnitudes (e.g., New Madrid and Charleston regions) are the most important in terms of characteristic magnitude distributions and source zone locations because so many sites are potentially affected by these sources. These sources should be given highest priority, and the details of the characterization will be important to many sites. Next in importance are seismic sources having moderate magnitudes; and the remaining zones are background sources away from the more active sources. At this point, Dr. McGuire turned the session over to Dr. Gabriel Toro (Risk Engineering, Inc.).

Dr. Toro began by describing the equations that allow comparisons between sensitivity products. These comparisons are important for focusing on situations with an important seismic source where high sensitivity is combined with high uncertainty. He showed an example from the PEGASOS study in Switzerland, in which hazard in the 10^{-4} to 10^{-5} range is important. Input parameters used by the four PEGASOS SSC teams were all approximately equal in importance (exclusive of ground motion issues). For some sites, a specific parameter dominated over other parameters, but in general all parameters were equally important.

Dr. Coppersmith opened the group discussion at the end of the session by noting that the TI team will interact with Risk Engineering to define and properly consider sensitivities. The group discussed seismic source zones with large magnitudes, especially the need to define the characteristics of zone boundaries (e.g., uncertainties in location, “fuzzy” boundaries) and develop alternatives to assess the hazard for a site located near a source boundary. It may be useful to define generalized zones for most sources but have alternative boundaries for use with close-in sites. Source zone definitions and logic tree complexity were discussed. Differences between the PSHA approaches used for the EPRI-SOG project and what is available now for the CEUS SSC project were discussed, including significantly increased information on tectonic environments, modeling approaches such as spatial smoothing, computing power, GIS tools, and alternative methods for incorporating uncertainties. The TI team will review alternative interpretations of data at Workshop 2, planned for February 2009.

The next session of the workshop focused on data that are available to conduct the CEUS SSC and that may be useful in addressing the key issues discussed in the previous session. Dr. William Lettis of William Lettis and Associates (WLA) began with a presentation titled “Database Development.” He stated that the group was brought together for Workshop 1 to identify what we do and (most importantly) do not know about seismic hazard in the CEUS, especially for capturing uncertainty. What data sets do we have that are needed, and can some be targeted for additional analysis that would be useful for this project? He noted that Dr. McGuire had described the parameters that are most sensitive for source zone characterization, and this information will help the TI team focus on what is most important. Dr. Lettis described the data compilation objectives, which include identifying critical data sets of geologic and geophysical coverage, and compiling COLA and ESP data as well as DOE PSHA and other data as available and relevant. A data compilation and documentation process is being established. This effort will include constructing a GIS platform to support TI alternative interpretations and establishing a data server to facilitate share of data and information. Dr. Lettis reviewed the presentation outline and indicated the speakers who would discuss the different aspects of database development.

Dr. Frank Syms (WLA) discussed the administrative issues for the data documentation process. He noted that it will be important to document exactly how data are evaluated and transcribed into GIS. He noted that there will be some sharing restrictions, as some data have to be purchased. Data quality will be assessed with help from the data experts. An FTP site will be established to store and share data, which will include all data sets plus the metadata summary sheet, ArcGIS shape files, and a PDF of ArcGIS coverage, as appropriate. The earthquake catalog for the project will be available. COLA and ESP data from relevant sites will be assembled and made available, as will relevant U.S. Nuclear Regulatory Commission (NRC) Request for Additional Information (RAI) data. He described the status of COLA and ESP data; nine COLAs for sites in the CEUS are currently under review by the NRC and six additional COLA's have been identified as in preparation. Additionally, relevant information is available for the DOE Savannah River Site, as well as for the Los Alamos National Laboratory, where information on the seismic source characteristics of the Rio Grande Rift will be important to the CEUS SSC project.

Dr. Randy Cumbest (WLA) spoke next. He showed text from the project plan about the database scope and coverage. The western boundary of the study region will be the foothills of the Rocky Mountains (about longitude 105^{o} W), except that it will include the Rio Grande Rift system; coverage will extend a minimum of 200 miles beyond the coastline and 200 miles from the U.S. borders with Canada and Mexico. Next he showed a series of slides with the database contents, which will include regional geophysics, including potential field, tectonic stress, and seismic reflection and refraction data; regional geology, including crystalline basement, tectonic features, crustal thickness, Quaternary faults, paleoliquefaction sites and dates; and the earthquake catalog for the project. Dr. Cumbest has already determined the availability of data sets by contacting many of the principal investigators. For the remainder of the talk he reviewed specific data sources from the list and noted for many items where coverage was currently complete or incomplete.

The group considered possible gaps in the list of available data sets. Items discussed included GPS data, mantle velocity information, Paleozoic and Mesozoic structural information, earthquake intensity and focal mechanism data, and shallow seismic reflection data. It was noted that many of the additional data sets mentioned by workshop participants would be discussed by presenters during the second day of Workshop 1.

Mr. Scott Lindvall (WLA) followed up with a list of logistical questions and issues. These included focus on the western boundary of the study region, defined at 105^{o} W longitude, but which also includes the Rio Grande Rift, although the 200-mile buffer zone also includes the rift zone. It was noted that seismic sources throughout the buffer zone could affect sites within the study region boundaries; this is particularly the case along the western boundary. However, the major focus of the CEUS SSC study needs to be seismic sources within the defined boundary region. Using source models from other studies, especially the U.S. Bureau of Reclamation studies for dams in some of the western states (e.g., Colorado and Wyoming) was mentioned as a possible source of information for the WUS buffer zone areas. Offshore there are earthquakes with epicenters on the continental slope that need to be included in the analyses. Earthquakes in Cuba could be important for a site located in southern Florida. The appropriate way to deal with study area boundary questions will continue to evolve. Mr. Lindvall also discussed the USGS Quaternary faults and folds database that needs to be updated by adding available Wheeler (2005) and Crone and Wheeler (2007) information, specifically, the Class C and D features. Finally, data sharing and copyright limitations were discussed for both GIS data and published papers.

After a break, Dr. Randy Keller (University of Oklahoma) described the on-land gravity database being developed by the scientific community. The initial compilation of gravity data for the conterminous United States is currently being expanded by merging data from many organizations for all of North America and including data from Canada and Mexico. The organizations contributing to the effort include the USGS, NASA, NSF, NOAA, and others. A number of corrections have been made to the database to remove duplicate points, bad points, and to terrain-correct the data. Dr. Keller showed maps of data available from 900,000 stations in 1999 and from 1,282,787 station locations in December of 2003. He described the processes used to remove duplicate points. Data sets of this type incorporate thousands of different data sets and he described methods used to remove bad points. He mentioned that a significant part of the database development effort is the creation of new standards for gravity data reduction; these standards are published in a Hinze et al. (2005) article in *Geophysics*. Next he showed a map that indicates the complexity of the upper crustal structure in the CUS. Basement structures are far from homogeneous and thus difficult to correlate with other geologic information. Dr. Keller showed a series of maps and identified the location of the Meers fault in Oklahoma, as well as other geologic features, that have clear gravity signatures. He noted that different filters can be used to display the data in different ways. Magnetic data are an obvious complement to the gravity database. GIS-type approaches allow for many types of data to be overlain and examined. He closed with an example of a desalinization plant in El Paso, Texas, and the search for a brine disposal site, ultimately found in a basin identified as a gravity low. Following his comments the group discussed the use of isostatic adjustments (i.e., the effect of topography removal), the association of lineaments with gravity data, and terrain corrections that can be made.

Magnetic data were discussed next by Dr. Dhananajay Ravat (University of Kentucky). He began by showing maps of North America displaying the magnetic anomaly databases in 1987 and 2002, developed from hundreds of different aeromagnetic data sets. The variations between the different data sets resulted in significant problems when they were compiled, so he has undertaken the process of compiling improved data products. The National Uranium Reconnaissance Evaluation (NURE) data obtained in the 1970s are an important source of data. Dr. Ravat has used CM (the Comprehensive Model of the Near-Earth Magnetic Field) to improve the NURE data products. Some gaps remain where data have been lost, but his colleagues in Egypt inserted North American Magnetic Anomaly Group (NAMAG) data segments to fill gaps. To identify problems, second vertical derivatives (filters) are used; short wavelength data integrity problems result, which are correctable but require a time-consuming effort. To obtain the best full-spectrum magnetic anomaly product possible in the short term for his presentation, he combined NURE and NAMAG data for the conterminous United States.

Next Dr. Ravat described interpretations of the data set using reduction-to-pole of NAMAG data, which is important for some applications. Most modern source interpretation techniques require high-quality first and second derivatives. He also briefly described methods for structural mapping, source edge complexity, and determining continuity of sources (e.g., the use of interpretive products).

Workshop participants discussed combining geologic maps with the magnetic data maps, although it was noted that for some regions, geologic maps have been directly derived from magnetic data. The major limitations for use of the new map developed for this study were also discussed. Dr. Ravat knows the resolution could be improved by fixing some NURE problems, and he described some of the corrections that can be made using second vertical derivatives. Data for many areas have been collected but are not available for use at this time (e.g., U.S. Navy and industry data).

Dr. Walter Mooney (USGS) gave the final presentation of the day, titled "Global Seismic Refraction Catalog (GSC)." The USGS is interested in building a global seismic refraction catalog containing the most up-to-date information available about the Earth's crust. The Global Seismic Refraction Catalog (GSC) is a Digital Earth crustal model derived from seismic refraction and other geophysical data. It is an important product for seismic hazard assessments, earthquake studies, and petroleum research. Dr. Mooney described key features of the GSC, which provides global coverage using a comprehensive set of data collected from 1939 through the present. Using these data, 10,200 data points have been digitized at 50 km intervals; recently, additional high-resolution data have become available and will be added to the database. The database consists of seismic refraction and other data captured from open-file and published scientific literature sources. Dr. Mooney's study began with comparisons of refraction data and laboratory experiments; velocity data have also been compiled. Dr. Mooney showed current coverage of the GSC database; there is a strong correlation of survey areas with areas where there is interest in oil and gas resources. He described what is included in data records (location, structure of crust, tectonic environment and experimental details, etc.) and he showed a sample data record. For North America there are more than 1,400 data points, containing varying amounts of information. North America data have not been added consistently to the database since 2002; many thousands of additional points have been identified and need to be added to the model.

Turning to products that can be developed using GSC data, Dr. Mooney showed various maps of North America that displayed sediment thickness, depth to the Moho, and shear-wave velocity maps. The data currently being collected by the Earthscope project will eventually provide additional valuable information for the catalog. Dr. Mooney gave examples of how the database can be queried to filter information such as maps and cross sections that indicate different layers of the crust and the structure of the crust-mantle contact. For the workshop, a cross section showing variations in crustal thickness and the location of the Moho was created across the United States from the Pacific to Atlantic oceans at 35° N. Next Dr. Mooney showed some average statistics for North American crust: average thickness of continental crust of 36.72 km and oceanic crust of 8.39 km; average P and S velocities, and other information. He then showed a histogram of crustal thickness for North America (the thinnest crust is in northern California; the thickest in the Great Basin) and stated that thickness values are much higher in the Alps, Andes, and Himalayas. Heat flow data were also discussed, and he noted that assumptions need to be made about radioactive element contributions to heat flow. There is about a 500-degree C range in temperatures within the crust; in colder areas there are fewer earthquakes. Heat flow data can also be used to estimate thickness of the lithospheric root: as the root thickens, fewer earthquakes are observed, as deformation tends to be concentrated in areas of thinner lithosphere.

Next, Dr. Mooney showed the "Bigfoot" array of broadband instrument stations that is being moved east across the United States; these data will not be available in time for use in the CEUS study area. He concluded his talk with examples of maps of the upper mantle from surveys in southern Africa.

Mr. Salomone opened the workshop to comments and questions from observers. Several workshop participants commented on the data sets that had been described or were on the agenda to be described the following day. The workshop was then adjourned for the day.

DAY 2–WEDNESDAY, JULY 23

Dr. Coppersmith welcomed the group to the second day of the workshop and reminded everyone that the time period of interest for the CEUS SSC study is the ~50-year period of operation typical for conventional nuclear power plants and that the annual hazard probabilities of interest will be in the 10^{-4} to 10^{-7} range. Dr. Randy Cumbest (WLA) then resumed leading the presentations and discussions in the "Available Data" session that began the previous day.

The first talk of the morning was given by Dr. Robert Hatcher (University of Tennessee, Knoxville). Dr. Hatcher's talk was titled "Available Data: Geologic Domains, Tectonic Features, Rifts," and he addressed the difficulties of understanding the origin of earthquakes within continental plates. He began by showing a series of geologic maps, tectonic maps, and maps of the assembly and dispersal of the supercontinent of Rodinia. He spoke in more detail about the series of geologic maps of the United States and the improvements made in the level of detail through time. Next he showed magnetic and residual isostatic gravity anomaly maps of North America and pointed out structural trends and features of interest, including accreted terrains and suture zones. He noted that integrating geophysical data with geologic data was essential for understanding the geologic domains and tectonic features of the CEUS. Interpretations of geologic features based on a variety of geophysical data sets, including residual isostatic gravity anomaly data, magnetic data, and seismic reflection data, were discussed.

Next Dr. Hatcher discussed rifting processes. He described how Africa collided with North America at the end of the Paleozoic, and then showed geologic maps that provide the evidence for the collision sequence. He also described the New Madrid area and indicated the boundaries of the Reelfoot Rift; instrumentally recorded seismicity is not completely within the rift and therefore is not clearly associated with it. The crust-forming processes and features that began to form in the late Proterozoic and into the Mesozoic were described.

Dr. Hatcher then described EUS earthquake frequency and magnitude patterns. He discussed the eastern Tennessee seismic zone, in which earthquakes are occurring at depths of 7 to 25 km, and stated that there is no apparent structure in the lower crust or apparent offset of the basement that could be associated with this seismicity. He postulated that the Farallon Plate may extend below the EUS and is a possible cause of earthquakes such as the New Madrid events. In his concluding remarks he stated that old structural boundaries may concentrate stress and produce earthquakes, but they do not provide answers about why they occur where they do. Incomplete data sets, especially for information about the mantle, are a major handicap in understanding the seismic setting of the CEUS.

The next talk was given by Dr. W.R. Van Schmus (University of Kansas), titled "Major Tectonic Features of the Precambrian Basement in the Midcontinent Region, USA." Dr. Van Schmus reviewed available data sources, including outcrop, drillhole (core and cuttings), magnetic, and gravity maps, that allow interpretation of the geology of the midcontinent. He commented that outcrop availability is quite limited and drill cores can be useful when extended into granitic basement. Geologic maps can be developed from all available data. Next Dr. Van Schmus reviewed Archean-Proterozoic continental growth in the CEUS and showed maps of the accretionary belts and rock provinces that were emplaced progressively towards the south and southeast over a time span of about three billion years. Major boundaries between various terrains, the timing of their formation, and fundamental differences in the crust in various areas were described. Dr. Van Schmus traced the boundaries of some of the terranes and noted the difficulties in interpreting the associated histories, as some boundaries may be erosional and not tectonic in origin. Next he described the Eastern Granite-Rhyolite Province and Southern Granite-Rhyolite Province, both of which contain isolated plutons, juvenile basement, and stratified rock in older basement. He also described aspects of the Midcontinent Rift system, a large gravity feature that contains many faults.

Dr. Mark Zoback (Stanford University) was the next speaker, and he presented results of work conducted with Dr. Mary Lou Zoback (Risk Management Solutions). His talk was titled "In Situ Stress and Earthquake Focal Mechanisms in the Central and Eastern U.S.–An Update." First he reviewed the state of stress in the CEUS as it was understood in the early 1980s. At that time, regional ENE-WSW compression over a large area was recognized, and detailed information about the New Madrid zone was starting to become available. Next he compared the state of understanding in the late 1980s with that of the early 1980s and noted that dramatic changes occurred in interpretations as a result of a great increase in data on the state of stress in the United States. Most significantly, data were becoming available from wellbore breakouts, which are the best indicators available of stress orientation because they are uniform and consistent. The improved database also included earthquake focal mechanisms, which indicate that faulting in the northern part of the EUS ranges from strike-slip to strike-slip-reverse to reverse faulting along a NE-trending gradient. Subsequently, structural information on faults became available and these data are consistent with the regional stress field. Dr. Zoback noted that the current view of the state of stress in the CEUS is essentially the same as that presented in 1989.

Next Dr. Zoback noted that there are relatively uniform stress orientations across many complex geologic boundaries. He emphasized that intraplate earthquakes resulting from the contemporary stress field are acting on pre-existing faults. No evidence has been found for localized sources of stress in intraplate seismic zones such as New Madrid and Charleston. Dr. Zoback continued his talk by stating that several hypotheses considered in the mid-1980s for identifying seismic source zones are no longer valid. These hypotheses include reactivation of Triassic basin bounding faults and low-angle normal faulting in the Appalachian decollement, which appears unlikely because of the depths of earthquakes beneath the decollement and other factors. Faults slip in response to regional stress, thus the greatly improved stress orientation and relative magnitude databases improve the geologic bases for zonation. Dr. Zoback noted that where good data are available (e.g., in Japan), a remarkable correlation is apparent between maximum horizontal stress and strain, indicating that intraplate deformation is occurring in a coherent way. A key question about the New Madrid region is how to reconcile the fast Holocene rate of deformation with the extremely slow Cenozoic rate. Also, he stated that we now understand some of the real physical bounds on rates of deformation and other processes, and these data are helpful for defining source zone boundaries.

Following Dr. Zoback's talk the group discussed some of the data from studies in various regions of the EUS and how to explain the indicated stresses. Aspects of the data sets, including data quality, were discussed. The availability of industry data was discussed. The discussion continued about the degree to which rocks are close to being in a breaking state. Dr. Zoback noted that in general, rocks in the EUS are close to breaking and will respond to driving stress; what distinguishes an active area from a craton is not the state of stress in the brittle crust (even when rocks are near failure) but the strain rate. He stated that cratons are characterized by cold temperatures and low strain; in areas of higher heat flow, earthquakes occur more frequently. He also noted that when rocks in the upper crust creep, they are not at the state of brittle failure; the crystalline basement below, however, will likely be brittle.

Dr. Andrew Newman (Georgia Institute of Technology) spoke next with a talk titled "The State of Strain in the Eastern US: Can We See It?" His talk focused on strain fields in the EUS and he stated that GPS data is the best way to obtain strain information. He noted that because a significant amount of time is involved in processing GPS databases, differences can arise; recently, however, more stable results are being obtained. Since GPS data are derivative, he prefers to use the term "velocity field" when discussing strain. He noted that high strain rates do not necessarily equal high seismic hazard, as strain may be a result of discontinuity or poor data. He discussed rigid body motion of a plate on a sphere, the residual GPS velocity field for North America when plate motions are removed, and a model for glacial unloading of North America. No significant strain fields are recognized in the EUS except for glacial rebound areas.

To provide contrast Dr. Newman showed a map of the Chinese GPS field and stated that China has a large range of velocities and transitions across structural boundaries. He compared the strain rates between China and North America. He noted the strain localization indicated around the New Madrid seismic zone. He also stated, however, that geologic maps indicate the Eastern coastal plain has poor bedrock coupling, thus GPS instruments may not be firmly attached to bedrock and may not reflect tectonic motion. Since the New Madrid zone is very close to the Eastern coastal plain boundary, there could be some inaccuracies in the strain measurements. He noted that results of GPS campaigns in 1991, 1993, and 1997 showed no discernable motion (<2.4 mm/yr) in the New Madrid area. He compared velocity information with what is known from paleoseismic data and found that these data sets are consistent. Recently collected GPS data indicate rapid convergence is occurring at two sites near Reelfoot Lake. Dr. Newman checked and replotted these data. He believes that some New Madrid aftershocks are still occurring, and he identified different strain results from instruments at varying distances from the linear trend of seismicity. The apparent differences, however, may also be a result of instruments that are not all located on a homogenous medium. In his concluding remarks he stated that it is better to discuss bulk velocity fields rather than strain rates and that no large-scale tectonic deformation is yet observable in the EUS. Then he asked a final question of the workshop group: will we ever observe Chinese-style tectonic deformation in the EUS?

The group discussed this question and strain information for the EUS. Plate movement in China was discussed; it is not clear if some blocks are rigid. The extremely low strain rates in the EUS

(10^{-7}/yr) were also considered. It was noted that Holocene strain rates have been very high, but the Cenozoic rate overall is low. It is possible that we are currently in an earthquake cluster, but GPS data are not adequate to resolve this question. The limited amount of information available on the pre-1811/1812 earthquakes in the New Madrid area was discussed. Limitations inherent in available data sets, including the short time period in which GPS measurements have been made in the New Madrid area and gathering paleoliquefaction data in the soft sediment of the Mississippi Basin embayment, were discussed.

After a short break, two speakers gave presentations on paleoliquefaction in the CEUS. Before these speakers began, Dr. Ross Hartleb (WLA) gave a brief introduction about paleoliquefaction data sets, which are fundamentally important for assessing seismic hazards in the CEUS. Past large or moderate earthquakes can be identified by paleoliquefaction information, but we also need to answer questions about where, when, how often, and how large these events are. Paleoliquefaction data are difficult to correlate across space and time. Also, it is difficult to identify if these features were associated with one large event or multiple moderate events, and whether or not they were seismically induced. He noted that a comprehensive database of paleoliquefaction information is currently not available but developing such a database is a goal of this project.

Mr. Steve Obermeier (USGS, retired) gave the first talk, beginning by briefly describing his background, which includes significant geotechnical engineering experience. He gave a short overview of paleoliquefaction studies, noting that it is not known what controls the abundance of features so it is necessary to look at many miles of exposures. When he begins a study in a new area, he identifies localities where the water table is shallow and susceptible deposits are present, then he concentrates on examining exposures. He described why paleoliquefaction studies are useful and gave an overview of factors involved in conducting studies. He always begins with an air photo study to identify the features to be field-checked. Many streams are ideal for study, as extensive exposures are needed because features can be 1,000 feet or more apart. Mr. Obermeier stated that the New Madrid area is in an optimal setting for observing paleoliquefaction because of the high water table and a continuous Holocene sedimentary record. The Wabash Valley is a close second, but conditions there are more problematic. The principal questions to be answered in making interpretations include liquefaction susceptibility (based on factors such as grain size, packing, cementation, and thickness of units), density of sands as reflected by blow counts, depth to water table, age of sediments, and an assessment as to whether or not deformation is of seismic liquefaction origin. The experience level of the investigator is also important. Mr. Obermeier noted the optimal conditions for liquefaction, including a water table depth of 0 to a few meters, and then described techniques for assessing ages of sediments. Finally, he noted that artesian conditions, thrown trees, and chemical weathering can all result in features that look similar to paleoliquefaction.

Mr. Obermeier continued by discussing assessments of magnitude and showed a map with the extent of liquefaction features associated with large prehistoric earthquakes in the Wabash Valley region. Based on the severity and areal extent of liquefaction associated with the New Madrid earthquakes, he believes they had magnitudes in the high 7 range. He concluded his talk by describing five regions in the CEUS where he has worked and suggesting areas where additional information could be collected.

A second talk on paleoliquefaction was given by Dr. Martitia (Tish) Tuttle (M. Tuttle and Associates), who focused on data and databases. She acknowledged Dr. Kathy Tucker (CERI) and Dr. Buddy Schweig (USGS), who contributed to the work described in her presentation. She began by showing a map of locations in the CEUS where liquefaction studies have been conducted, identifying whether or not features were found and which sites had features that were equivocal. She described how she began developing a paleoliquefaction database with very limited experience and that the lessons learned will be of benefit to the CEUS SSC project. A database must be designed after considering how data will be used, queried, and displayed, both currently and in the future. She showed the process of converting data in an Excel spreadsheet to ArcGIS data and ArcMap plots. She also described work done in the New Madrid area, showing a map with estimates of sediment ages and the thickness of sandblows.

Next Dr. Tuttle described an archaeological site with an associated sand blow for which a well-constrained age could be determined using radiocarbon dating and artifact analysis. She described another area in which well-constrained ages of numerous large and broadly distributed sand blows allowed recognition of two events in 1,200 years. Next she showed example map queries by location, attribute, thickness, and age. She provided a list of data fields recommended to be included in a database. She concluded her talk with a list of lessons learned. She emphasized that it is important to carefully consider how to query and use data and that a uniform identification convention should be used for locality names. Her concluding statement was that paleoseismology can provide ground truth for seismic hazard assessments.

The group discussed preservation patterns of paleoliquefaction features in the geologic record and uncertainties associated with interpretations. Dr. Tuttle stated that for some features, geologic evidence including weathering patterns and fining upwards sedimentary sequences can clearly indicate a hiatus in deposition and allow separate events to be resolved within a few months.

Following a lunch break, Mr. Salomone asked the resource experts to send their lists of references to lawrence.salomone@srs.gov and syms@lettis.com . After this announcement the final session of the workshop, whose topic was the seismicity catalog, commenced; presentations and discussions in the session were led by Dr. Robert Youngs (AMEC Geomatrix). Dr. Youngs gave the first presentation, titled "Development of Earthquake Catalog for Seismic Source Characterization." He began by stating that the catalog would contain events compiled for the period 1600 to 2008 and that event sizes would be defined in terms of moment magnitude. Uncertainties in size and location will be defined for incorporation into a hazard model. The primary sources from which the catalog will be compiled include the EPRI-SOG (1988) catalog; the NCEER-91 revision of EPRI-SOG; the USGS seismic hazards mapping catalog, and the Canadian seismic hazard mapping catalog. Studies for ESP and COL applications in the CEUS will provide useful information, as will special studies of individual earthquake events or regions. Dr. Youngs described the catalog development process in which data from all sources will be summarized for earthquakes larger than magnitude ~3. The compiled information will be reviewed with a team of experts to select preferred values, assign uncertainties, and classify nontectonic events. Dr. Youngs explained the data needs for development of moment magnitude estimates for each event; these include moment magnitude estimates from other catalogs and special studies for instrumentally recorded earthquakes, plus intensity/felt area data for both instrumentally recorded as well as historical earthquakes.

Next, Dr. Youngs presented a series of slides on macroseismic data for the CEUS prepared by Ms. Margaret Hopper (USGS), who was unable to attend the workshop and be a presenter. Her slides provided information on a database of over 150 earthquakes in the CEUS for which intensity data are available. This database will be useful for the CEUS SSC project.

Dr. Youngs concluded his talk by describing the processes planned to identify dependent events within the catalog and to assess catalog completeness. The workshop group then discussed the possible compilation of earthquake focal mechanisms for the project, as these are important for mapping stress. The TI team will discuss how to proceed with this effort.

The next speaker was Dr. Charles Mueller (USGS), who described the approach used to develop the USGS catalog. He stated that a mix of published and well-documented, national-scale source catalogs was used, and he listed many of these catalogs. Objectives for the catalog are to have it be dominated by events from the well-researched NCEER-91 catalog as well as to have the catalog be appropriate for use for PSHA. He described the procedure followed to compile the catalog, including selecting a single record for each earthquake, selecting a preferred magnitude if more than one is reported, and declustering and removing man-made events if they pose no hazard (e.g., mining-related seismicity in Colorado and Utah). Next he displayed various aspects of the data for the portion of the catalog in the CEUS. In his concluding statements he mentioned that improvements were being made in the USGS catalog as a result of better source catalogs, a more reliable update process, and incorporation of uncertainty estimates for magnitude and location of some events. He stated that the catalog prepared as part of the CEUS SSC study will be incorporated into the USGS catalog. Mr. Mueller commented that with additional resources he would like to focus efforts on the incorporation of uncertainty in the catalog.

The next talk, titled "Revising the Earthquake History of the CEUS: Identification of New Events and New Sources of Information," was given by Mr. Jeff Munsey (Tennessee Valley Authority). In his first slide, Mr. Munsey listed impacts and benefits of updating an earthquake catalog, including providing additional information to define seismic source boundaries; refining activity rates, especially at local scales; increasing temporal and spatial completeness; and improving location and magnitude estimates. He reviewed sources of catalog information for the region surrounding the Tennessee Valley that had become available since the EPRI-SOG catalog was completed, including his own work that resulted in identification of more than 400 events from 1724 to 1927, primarily using historical newspapers available online. He listed the primary online data sources he uses and then briefly described some of the newly identified earthquakes. He also described how he has tracked down felt information and made estimates about earthquake magnitude. He concluded his talk by listing challenges and tasks ahead. These include establishing and recording the basis for existing events, reconciling multiple accounts of dramatic events, and evaluating clues to assess event depths and distances.

The final talk of the session, titled "Earthquake Data for Seismic Hazard Determinations in the Northeastern U.S.," was given by Professor John E. Ebel (Boston College). He began by listing seismic issues and items to be addressed to update a catalog. He has studied early historic earthquake events (1600s) based on journal entries and accounts of city funds appropriated to repair earthquake-induced damage. He described updates of the Northeastern United States (NEUS) catalog over the past decades, noting that when the NRC eliminated regional seismic network funding in the early 1990s, most seismic stations in the NEUS were lost. Only in the past few years have significant improvements been made, in part due to equipment changes that have improved both detection capabilities and magnitude determinations. Dr. Ebel discussed the problems of overlap between U.S. and Canadian seismicity catalogs, which result in multiple reports as well as possibly different decisions about whether a particular event has a seismic or nonseismic origin. Epicenter accuracy is better with a denser network, so the NEUS catalog reflects data of varying quality.

Next Dr. Ebel described regional earthquakes in the EUS in the recent past, as this pattern is expected to continue in the future. On average, about six small earthquakes (magnitude $\leq$ 3.5) are felt in New England each year and this regular, persistent earthquake activity has been observed for more than 25 years. Temporally clustered earthquake activity can also be observed. Dr. Ebel showed a plot of the variations of earthquake activity with time in New England since 1979. He described the 2006-2007 Bar Harbor earthquake sequence that resulted in M 3.4 and M 4.2 events.

Turning to the historical catalog, Dr. Ebel described issues concerning historical NEUS earthquake data, including the need to identify additional events and adequately assess event sizes from detailed historical research. He noted that small aftershocks can help pinpoint the location of a stronger earthquake in the historical record. Following a 1727 earthquake, over 150 aftershocks were felt in two different areas (17 were magnitude $\geq$ 4) and this information could be used to more accurately locate the epicenter of the main shock. Clusters of small earthquakes may be aftershocks from strong events that occurred hundreds or even thousands of years ago. Unlike the situation in California, there is no baseline level of earthquakes in the NEUS, so it is easier to identify earthquake clusters as aftershocks. Dr. Ebel has developed estimated ages and magnitudes for many events extending back more than 1,000 yrs.

Dr. Ebel concluded his talk with several recommendations. These include extending the catalog to the northeast by acquiring additional available databases and cross-checking duplicate event data; conducting a research program to study magnitudes of instrumental earthquakes in the NEUS; and targeting selected historical events for additional research to better constrain event size and location. In response to discussions with the group, Dr. Ebel noted that the focal mechanisms for most events are consistent with a tectonic origin, although glacial unloading is a possible cause for some. He also stated he believes a Charleston-type earthquake is possible anywhere in the NEUS region, although others question whether the crust could support an event of this magnitude.

Dr. Coppersmith asked for comments and questions from the workshop participants, including the international observers. Participants discussed different areas of seismicity and earthquake events in the CEUS and their relevance in defining source zones.

Dr. Coppersmith then made final remarks about the path forward for the CEUS SSC project. He mentioned the SSHAC implementation project that is under way and how lessons learned from that effort will be implemented in the current project (several participants in the CEUS SSC project are also participants in the SSHAC workshops). He noted the point of contact for the CEUS SSC project: lawrence.salomone@srs.gov, and he showed the task schedule for the project, noting the February 2009 timing for Workshop 2 on Alternative Interpretations. In the months before Workshop 2, many of the activities discussed in Workshop 1 will be under way, including database development and seismicity catalog development. A preliminary SSC model will be developed and used to identify the key alternatives for discussion at Workshop 2. Hazard and sensitivity analyses will be used to evaluate the preliminary SSC model.

Mr. Salomone thanked the international observers for taking the time to attend the workshop, and then he offered his parting comments. He noted that the high level of expertise of the presenters was clearly indicated by the content of their presentations. He expressed his appreciation to all who have made the project and first workshop a success, and who will continue to do so as the project continues. He believes that the CEUS SSC project will ultimately be viewed as a landmark study. He then adjourned the workshop.

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WORKSHOP 2: ALTERNATIVE INTERPRETATIONS
February 18–20, 2009

Electric Power Research Institute
3420 Hillview Ave.
Palo Alto, California 94304

The Workshop on Alternative Interpretations was the second in a series of workshops jointly sponsored by the Electric Power Research Institute (EPRI) Advanced Nuclear Technology (ANT) Program, U.S. Nuclear Regulatory Commission, and the U.S. Department of Energy (DOE) in support of the Central and Eastern U.S. Seismic Source Characterization (CEUS SSC) for Nuclear Facilities Project. The objective of the CEUS SSC is to develop a comprehensive and up-to-date SSC for a probabilistic seismic hazard analysis (PSHA) that is appropriate for use at any site in the CEUS. The Technical Integration (TI) team and TI Staff are charged with developing a seismic source model that captures the knowledge and uncertainties within the larger informed technical community. The goals of this workshop were to (1) review the project Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 methodology, ground rules, expert roles, and peer review processes; (2) provide an opportunity for the TI team and TI Staff to understand proponent views regarding important technical issues; (3) discuss the range of alternative views and uncertainties within the larger technical community; and (4) discuss the path forward for the CEUS SSC project. The goals were accomplished by a series of presentations and discussions designed to provide the TI team and TI Staff with the information it needs to develop a preliminary seismic source characterization model.

DAY 1–WEDNESDAY, FEBRUARY 18

Workshop participants were welcomed by Mr. Jeffrey Hamel, the EPRI ANT Project Manager for the CEUS SSC project, who also reviewed some workshop logistics. Mr. Lawrence Salomone, Project Manager for the CEUS SSC project, then welcomed workshop participants and thanked them for attending. He reviewed some of the project logistics. Next Mr. Salomone reviewed the project goals: (1) replace the previous EPRI Seismicity Owners Group (EPRI-SOG, 1988) and Lawrence Livermore National Laboratory (LLNL; Bernreuter et al., 1989) seismic hazard studies that were conducted in the 1980s; (2) capture the knowledge and uncertainties of the informed scientific community using the SSHAC process, and (3) present a new CEUS SSC model to the Nuclear Regulatory Commission, DOE, and others for review. Transparency of the project process is a key goal. He reviewed the management chart for the project and showed samples of the data sets available for the study region. Mr. Salomone summarized the project milestones, including the preliminary SSC model feedback to be reviewed at Workshop 3, which is scheduled to be held August 25–26, 2009. In his concluding remarks he noted that the project is on track to meet the target completion date in 2010.

Dr. Kevin Coppersmith, the lead of the TI team, then welcomed the workshop participants. His talk focused on the goals of the workshop and the ground rules. Dr. Coppersmith began by reviewing aspects of the SSHAC project, which is documented in NUREG/CR-6372 (Budnitz et al., 1997) and will be implemented in the CEUS project. He reviewed the SSHAC basic principles for a PSHA, key attributes of the process, and expert roles, with their application to the current workshop. He indicated that the focus of the workshop would be on providing information that the TI team can use in developing the preliminary SSC model, which will be completed prior to the third workshop. As such, the workshop would be structured to allow the TI team maximum opportunity to have their questions answered by the resource experts making the presentation. He reviewed the CEUS SSC task schedule and the process to be followed for Workshop 2. Prior to the workshop, key questions and issues were posed to the presenters to address in their talks (see Table 1); the knowledge and uncertainties of these members of the larger informed technical community are what the TI team is charged with capturing.

The first of the talks was given by Dr. Stephane Mazzotti of the Geological Survey of Canada. His talk was titled "Strain (and Stress) Constraints on Seismicity in the St. Lawrence Valley." Dr. Mazzotti began by discussing the distribution of earthquakes and the definition of seismic zones based on concentrations of earthquakes in regional "hot spots," in this case, the Charlevoix and lower St. Lawrence Seaway regions. He noted that earthquakes are concentrated along Iapetus rifted margins and grabens that formed about 600 million years ago (Ma). He also noted that seismic moment and deformation rates for eastern Canada can be based on two alternative models for earthquake distribution: (1) earthquake statistics in historical source zones, which indicate a few high-strain zones and relative motion of 0.0 to 2.5 millimeters per year (mm/yr); and (2) geological source zones, which have no high-strain zone and motion of only 0.0 to 0.5 mm/yr. Dr. Mazzotti reviewed GPS (global positioning systems) observations from regional networks and showed the vertical and horizontal velocities obtained from this data, noting that there is very good agreement between continuous data (3 to 6 years) and campaign data (7 to 12 years). Next he discussed preliminary results of GPS measurements in the Charlevoix and lower St. Lawrence seismic zones. This data shows very low strain rates overall, as expected, but east-west horizontal strain rates appear to be higher in high-seismicity zones. Within these zones, the recurrence rates derived from the observed seismicity are in good agreement with rates derived from geodetic data translated into seismic moment rates. Current strain rates and seismicity are not steady-state on a million-year time scale, inasmuch as the rates imply cumulative deformation over million-year time scales that are not observed. Within a resolution of approximately 1 mm/yr at 95 percent, it is not possible to discriminate between alternative models.

Next Dr. Mazzotti described the potential role of glacial isostatic adjustment (GIA) processes and models. GIA is very small and it is debatable as to whether or not it is associated with earthquakes. Dr. Mazzotti's work shows there may be a significant role of GIA and local weak rheology in seismicity for some seismic zones, as indicated in the Charlevoix and lower St. Lawrence regions. In his conclusions, Dr. Mazzotti mentioned that the observed seismic strain signal (<1 mm/yr) is at the limit of GPS precision and that GPS data cannot yet represent earthquake hazard over the next 500 to 5,000 years. He believes GPS strain rates should be used in combination with other data sets, including rheology, geology, and historical seismicity, to define seismic source zones and rates, but only once a robust integrative geodynamic model has been developed.

The following talk was given by Dr. John Ebel of Boston College, who addressed "M_{max} for Eastern North America: An Examination of the 1663 Charlevoix Earthquake." Dr. Ebel began by stating that many of the small earthquakes in the northeastern part of North America may be aftershocks of strong earthquakes that took place hundreds or even thousands of years ago. To provide a frame of reference, he first showed examples of seismicity in California, which indicate that aftershock zones can be active for decades after a main shock. Next he described the methods he used to estimate the magnitude of the 1663 Charlevoix earthquake. This event was felt strongly in Canada, with major ground deformations in what is today recognized as the Charlevoix seismic zone. Dr. Ebel obtained data from damage reports in Boston and Roxbury in Massachusetts that were possibly associated with this earthquake, and he used the data to estimate the intensity and magnitude of the 1663 event. (The Charlevoix seismic zone is between 560 and 640 kilometers [km] from Boston.) He also compared the reported earthquake effects with isoseismal maps from the 1811–1812 New Madrid earthquakes and estimated the earthquake magnitude from the length of the "aftershock" zone that is currently active in the Charlevoix region. The best estimate of the moment magnitude (M_w) of the 1663 Charlevoix earthquake from his study is M_w ~7.3–7.5.

Next, Dr. Ebel began speculation on the characteristics of large earthquake events in stable continental regions. He believes that larger aftershocks concentrate at the edges of an earlier earthquake rupture due to stress concentration at the crack tip. This appears to be the pattern at Charlevoix, where recently occurring M 4 events have been located at the edges of the 1663 event. Dr. Ebel also speculated on recurrence rates of M > ~7 for the CEUS and eastern North America. The observed rate of M > ~7 earthquakes is greater than expected from extrapolations from the smaller earthquakes recorded in these regions. If small events reflect aftershocks of larger events, then the rate of M > ~7 earthquakes during the past few thousand years may be approximately two to three times greater than predicted by recurrence relationships that extrapolate the number of large events from small events.

The next presenter was Dr. Alan Kafka of Boston College, who spoke on "Use of Seismicity to Define Seismic Sources: Application to Eastern North America." Dr. Kafka discussed how "cellular seismology" can be used to delineate future seismicity based on what is known about past seismicity. Empirical analysis of earthquakes is based on historical and instrumental earthquake history, but this information does not address causes of earthquakes and whether analysis of what is currently observed will show persistence over long time scales. Is the "tendency for future earthquakes to occur near past earthquakes" a real, measurable, physical phenomenon? Dr. Kafka has investigated this question and uses a simple method of analysis based on separating observed seismicity data into two parts before and after some point in time. He then looks at the percentage of events after that time (future events) that fall within zones defined by various radii from earthquakes prior to that time (past events). As the radii increase, of course, the probability that a future event will fall within the zone for past events increases even for a random process. However, Dr. Kafka has found that the probability increases more rapidly than a random process, suggesting that future events are more likely to occur near past events. He has looked at many regions in the United States and worldwide for these patterns. He has found that future large earthquakes in the CEUS have about 86 percent probability of occurring within 36 km of past earthquakes. He has compared the accuracy of cellular seismicity to other methods, including rate-based forecasts (percentage of hits vs. percentage of defined mapped areas). In general, he finds that for his method, greater than 60 percent hits are obtained (whereas a random process would be about 30 percent). In his conclusions, Dr. Kafka noted that he has not found any other method of forecasting locations of future earthquakes that performs better than cellular seismology.

Following a lunch break, Dr. John Adams of Natural Resources Canada discussed the Canadian seismic hazard models in a talk titled "Eastern Canadian Experience with Geological Source Zones and M_{max}." He briefly reviewed aspects of the third- and fourth-generation seismic hazard models developed for Canada. He believes that smoothed seismicity is interesting but not sufficient for assessing future hazard levels. As an example, he cited the 1988 M 5.9 Saguenay earthquake in an area that had no prior earthquake activity of $M_N > 3$ for more than 50 years prior. He believes geological sources provide essential information, and noted that geological sources were proposed in Canada as early as 1983 for the passive continental margin. For the United States, he noted that Russell Wheeler did good work on geological sources in the early 1990s, but these were not explicitly incorporated in USGS hazard maps. Dr. Adams described the association of large earthquakes ($M \geq 7$) with rifted margins, noting the 1933 Baffin Bay and 1929 Grand Banks events, which occurred on large through-going faults that were reactivated in the Mesozoic. He then showed a map of seismic source zones in eastern Canada and into the eastern United States and described how various zones were modeled, based on both geologic history (ancient rifted margins and failed rift arms) and seismicity. He noted geological structures/source zones form a way of "filling in" between historical earthquake clusters.

The eastern Canadian experience with maximum magnitude (M_{max}) was described in the next part of Dr. Adams's talk. He described how the M_{max} estimates in previous generations of seismic hazard maps had been exceeded by significant earthquakes that occurred in Canada between 1982 and 2001. Accordingly, M_{max} estimates chosen for the fourth-generation studies were larger and based on continent-scale and global analogs, using methods similar to the EPRI Stable Continental Region (Johnston et al., 1994) study. A study of M_{max} in Australia was described as an analog for the CEUS and Canada. M_{max} choices for eastern Canada were also described, including weights assigned to a range of observed M_{max} for different tectonic environments; these included Mesozoic rifted margins, Paleozoic rifted margins, and plate interiors. In his concluding remarks, Dr. Adams stated that earthquakes of M_{max} ~M_w 7.0 could not be ruled out anywhere, although probabilities will be very low in many stable continental regions. Phanerozoic rifted crust typically contains enough long and deep faults (or fault systems) that M_{max} ~8.0 M_w seems plausible. In his final slides, Dr. Adams showed how Canadian seismic source zones can be extended into the CEUS. Extensions of Canadian source zones could be postulated to extend into the US, such as the Atlantic Rifted Zone extended to Charleston, South Carolina; the Iapetan Rifted Margin extending to Giles County Virginia and the Eastern Tennessee seismic zone.

Dr. Coppersmith announced that the next scheduled speaker, Dr. Leonardo (Nano) Seeber (Lamont-Doherty Earth Observatory) was unable to attend the workshop. A talk originally scheduled for Day 3 of the workshop was substituted.

Dr. Frank Pazzaglia of Lehigh University presented a talk titled "Approaches Used to Identify and Evaluate Neotectonic Features in Appalachian Piedmont/Coastal Plain Setting." The focus of the talk was the geology and geomorphology of the passive margin in the Atlantic states. Dr. Pazzaglia addressed the influence of broad regional flexure of the Atlantic margin on current patterns of seismicity, noting that there is spatial overlap in topography, active river incision, and seismicity. He described how topography and rivers respond to rock uplift, rock hardness, and erosion. He showed maps of many of the rivers along the Atlantic coast and described different geographic areas and their association with seismic activity. He discussed the Fall Zone and its location on the classic passive margin, emphasizing that the Coastal Plain is narrow and no waterways are navigable, which doesn't make logical sense for that type of setting. Coastal margin topography suggest that this area has been undergoing uplift, thus leading to convex upward longitudinal profiles for the rivers. He suggested that the Appalachians might be more tectonically active than previously thought. For example, New England has been uplifted since the Miocene, and over time, the Hudson River has moved the sediments of the former Coastal Plain to the south. Dr. Pazzaglia described the stratigraphy along the edges of Chesapeake Bay. He provided evidence for faults up and down the coastal margin that are concentrated around the Fall Zone.

Dr. Pazzaglia believes that future earthquakes could occur in areas with low seismicity that also have apparent fault structures. He showed nick points along the Fall Zone, noting that it is clear that a base-level fall has occurred since the Miocene, although within this 10-million-year (m.y.) period we cannot tell if this occurred early or late. It is now known that the Miocene sea level was about the same as at present, so the Piedmont is clearly rising. Faults located coincident with the Fall Zone would be useful targets for detailed studies to see if river anomalies are related to tectonics. Dr. Pazzaglia continued by discussing flexural effects from glaciations and ice unloading during the Quaternary. Finally, he described the Chesapeake Bay impact structure emplaced approximately 35.4 Ma. Rivers drained into the low area created by the impact, and pulses of subsidence are apparent. Dr. Pazzaglia believes that this impact structure could be a causative structure for some of the seismicity in the eastern United States.

Dr. William Thomas of the University of Kentucky gave the next talk, titled "Ouachita Sub-Detachment Structures." He described the geology of the CEUS at 250 Ma, showing major structural features based on data from wells and seismic reflection lines. He indicated the leading edge of aulacogen (tectonic trough) locations for the Alabama-Oklahoma transform and Ouachita thrust sheets. He discussed the stratigraphy and timing of activity of faults at about 308 Ma, showing the Mississippi embayment and other major structural features in palinspastic restorations. He also noted that episodes of movement were coincident with Iapetan rifting and then thrusting. He showed several seismic reflection profiles and cross sections that indicated stratigraphy and structure. The Ouachita thrust belt was compared with the Appalachian thrust belt, and different styles of deformation were described. The Ouachita accretionary prism was emplaced about 310 to 307 Ma, and to the east, the Suwannee terrane was emplaced about 306 to 300 Ma. Reconstructions give information about the timing of faulting. Dr. Thomas next discussed the Southern Oklahoma fault system, including the Wichita uplift, which is located above a leaky transform fault. In his conclusion, he noted that major structures were formed in the CEUS about 550 to 530 Ma and 310 to 300 Ma (late Paleozoic); some structures were reactivated in 245 Ma.

After a short break, Dr. James Drahovzal of the University of Kentucky gave a talk titled "Rifts in the Midcontinent: East Continent Rift Basin, Rough Creek Graben and the Rome Trough." In his talk he discussed these structures and the associated Grenville and Hoosier thrust belts, along with the Fort Wayne rift, which is coincident with the Anna seismic zone. Dr. Drahovzal began by showing the classic CEUS "basement" bedrock geology and then noted that more complex stratigraphy and structure have been constructed from well data. Sedimentary and volcanic rocks underlie many areas of granite and other igneous rocks in the midcontinent. Dr. Drahovzal described drillhole and seismic data for portions of Ohio, Kentucky, and Indiana; seismic data indicates layered reflectors within sequences of as much as 20,000 to 25,000 feet of Mesoproterozoic rocks that are folded and faulted. He provided a preliminary Proterozoic chronology that indicates alternating episodes of extension and compression in the midcontinent. Next he described the sequence of geologic events that formed structures within the East Continent rift basin, including the aseismic Rough Creek graben and Rome trough. Both of the latter structures are likely to have experienced Mesozoic reactivation but are currently aseismic.

The Rome trough is a symmetrical Cambrian rift basin that contains three major fault zone boundaries. Several reactivations since the Paleozoic are recognized for this structure. The Rough Creek graben in western Kentucky also shows evidence of Mesozoic reactivation, with Precambrian rock offsets of up to 17,000 feet. Dr. Drahovzal described the east continent gravity high and the relationship of this structure to the Rome trough and East Tennessee seismic zone. The 1980 M 5.2 Sharpsburg earthquake was located close to the East Continent gravity high.

The next talk was by Dr. John McBride of Brigham Young University, who discussed "Geophysical Characterization of Faulting and Folding in the Illinois Basin and Relation to Seismicity." Seismic reflection data is used to understand fault deformation and seismicity in an area of the midcontinent centered on the Illinois Basin and the New Madrid seismic zone (NMSZ). Dr. McBride noted that reactivation of faults is not always clear, even in a well-constrained area like California, so fault reactivation is even more difficult to recognize in the Midwest. However, a large amount of geophysical data is available for the Illinois basin, particularly seismic profile data, because of oil production in the state that peaked in 1937. Dr. McBride showed a map displaying a CEUS earthquake catalog and questioned if an area showing little seismicity is real or an artifact of limited instrumental coverage. Next he showed a map of major structures in the southern Illinois basin and described some of these, including the La Salle deformation belt. He reviewed information for recent earthquakes in the region and showed a seismic reflection profile of the La Salle anticline. A 1987 earthquake and aftershocks associated with a frontal thrust, plus evidence of paleoliquefaction in the region, provide evidence of this anticline as a possible seismic source zone.

Next Dr. McBride described several possibly seismogenic structural features in the Illinois basin. The Fairfield subbasin (a deep part of the Illinois basin) includes a zone of locally more intense faulting, in which three fault zones can be mapped from seismic reflection profiles. Earthquakes that occurred in 1974 and 1987 were within the interpreted zone of rifting beneath the Fairfield subbasin. Dr. McBride showed the Wabash Valley fault system as imaged on a seismic profile. A 1968 earthquake event occurred in this region and may possibly have originated on a blind thrust fault. The Commerce geophysical lineament corresponds locally to disrupted geologic structures that may be seismogenic. The Du Quoin monocline complex was described. This monocline and the overlying Centralia fault zone may be an overlooked possible seismic source. Folds in this area provide some evidence for reactivation along an older reverse fault. The Cottage Grove fault system corresponds to a major crustal boundary, although the seismicity rate in the area appears to be low. The Fluorspar Area fault complex trends towards the New Madrid seismic zone; there is complexity in Fluorspar Area structures and evidence for Tertiary displacements. In his conclusions, Dr. McBride noted that the area where the La Salle anticline and Wabash Valley fault systems meet may have a high potential for fault reactivation.

After this talk, Dr. Coppersmith invited comments from observers. The participants discussed improvements in data available for smaller earthquakes, including better-constrained focal mechanisms. The group listed Paleozoic rifts that have not been reactivated. These include the Birmingham graben and the southern part of the Mississippi graben; the Ouachita graben also may not have been reactivated, but the underlying rocks are too old to indicate this history. At the conclusion of the discussions, the meeting was adjourned for the day.

DAY 2–THURSDAY, FEBRUARY 19

Dr. Coppersmith welcomed the group to the second day of the workshop. The first talk was given by Dr. Roy Van Arsdale (University of Memphis) on "Quaternary Deformation within the Reelfoot Rift, Rome Trough, and Wabash Valley Fault System." Dr. Van Arsdale began by showing the location of the Mississippi embayment and its relationship to the New Madrid seismic zone (NMSZ); earthquakes in the NMSZ define faults in the region. He showed a cross section of the Reelfoot fault with "kink bands" or back thrusts, as well as photos of trenches on the Reelfoot scarp trench. The recurrence interval for earthquakes is estimated to be approximately 500 years. He noted that the trench data is in good agreement with the regional earthquake chronology developed from paleoliquefaction features.

Dr. Van Arsdale described displacement history and slip rate on the Reelfoot fault from the late Cretaceous to the present. The slip rate increased dramatically in the Holocene, indicating an active period of fault history, but the end of this period may be near. Seismic reflection lines indicate deep basement faults with as much as 3 km displacement. Trenches opened above the seismic reflection lines show faults with transpressive right-lateral strike-slip movement. Right-lateral shear across the Reelfoot rift is responsible for the NMSZ earthquakes at the northern end of the rift. Rift margin faults are "big players" in the picture. Dr. Van Arsdale described features in the Shelby County and Memphis region, where liquefaction deposits (sand blows) and a broad fold forming an anticline are present. The anticline appears to be a tectonic feature formed about 400 a.d.

Dr. Van Arsdale then described work he did many years ago in the Rome trough near the area of the 1980 Sharpsburg earthquake, where he focused on the Kentucky River fault system. He showed the log of a trench excavated in a terrace that exhibited folding and an apparent shear zone. He estimated the timing of fault movement as within the past 5 m.y. Next he described the Hovey Lake fault in the Wabash Valley fault system and the Stull trench site in Union County, Kentucky. He concluded his talk by showing a schematic of fault scarp evolution based on the information obtained from the trench.

Mr. Robert Givler of William Lettis & Associates, Inc., gave the next talk, which was co-authored with Mr. John Baldwin. The title of the talk was "Commerce Geophysical Lineament and Northwestern Margin of the New Madrid Seismic Zone." The Commerce geophysical lineament (CGL) is a 400- to 600-km-long feature that exhibits Quaternary strike-slip and normal faulting along a 75 to 120 km portion of its length in the New Madrid region. Mr. Givler described the regional geologic setting for the CGL and the detailed studies conducted at Qulin Ridge. This locality contains Late Wisconsin glacial outwash deposits; seismic profiles show Quaternary offset along a fault, and four paleoliquefaction events have been identified. Next Mr. Givler described the Holly Ridge locality associated with the Idalia Hills fault. Seismic reflection profiles show displacement of Quaternary deposits that project upwards and correlate with surface geomorphic features. Trench data from the Bloomfield Hills locality on the Idalia Hills fault indicate two poorly constrained faulting events. Mr. Givler described trench studies for localities on the Commerce fault and the Penitentiary fault. The Benton Hills locality is on the Commerce fault, where strike-slip faulting is recognized for four late Quaternary events. The Quaternary-active Penitentiary fault is located in the Cache River valley. The Penitentiary fault is a step-over from the Commerce fault and has a prominent east-facing scarp. Seismic lines in the area were used to further test the hypothesis that the Penitentiary fault is a seismic source; these data indicate multiple faults disrupting Pleistocene and possible early Holocene deposits. A fault segment 75 to 120 km in length is recognized in southeast Missouri and southern Illinois along the Commerce fault. A weak alignment of microseismicity is associated with this fault. Based on all of this data, the CGL appears to have been active into the early Holocene. The fault has long earthquake recurrence intervals of 5 to 10 thousand years and possibly episodic activity.

Next, Dr. Randy Cox of the University of Memphis gave a talk titled "Some Mississippi Valley Holocene Faulting and Liquefaction beyond the New Madrid Seismic Zone." He began by discussing southeast Reelfoot rift margin surface faulting. He showed a map of the topographic lineament of the southeast rift margin and the locations of trenches excavated to study this feature. He described the Porter Gap trench site where a late Holocene earthquake was recognized, showing the trench logs and a shallow seismic reflection line. Structural relief and topographic relief are consistent with faulting. Evidence of faulting in the trenches indicated an event with >4 meters (m) vertical displacement and horizontal (strike-slip event) displacement of about 8 to 15 m. Earlier events of approximately equal magnitude were also observed in early Holocene deposits. Next Dr. Cox described a newly recognized sand blow field in the southern Mississippi embayment area of northeastern Louisiana, south of the New Madrid area, which was identified from an aerial photo survey. He has delineated five separate fields containing clusters of sand blows. A trench log across an area of sand blows, and photographs of sand blows were shown. The earthquakes that caused the liquefaction are estimated to be M > 6 on the basis of the minimum radii of the fields and on cone penetration tests in the region. Multiple events are indicated, and based on limited data, the earthquake recurrence rate is roughly 1,000 to 2,000 years. The earthquake events that Dr. Cox recognizes can be correlated with multiple regional events that affected more than one of his five zones, or they could be related to local earthquakes that are separate for each zone.

He concluded his talk by describing his studies of the Saline River fault system in the craton margin area of the Alabama-Oklahoma transform. Seismicity data is sparse in this region but he has examined many exposures containing features that suggest deformation. Seismic lines show Triassic grabens and flower structures that extend upward into Cenozoic deposits. The trenches that have been excavated show faulting in mid-Pleistocene deposits; overlying Holocene deposits may be warped. Paleoliquefaction features of dense sand blows have been recognized in the area, indicating multiple earthquake events in the late Pleistocene through the late Holocene. Dr. Cox believes the paleoliquefaction features were caused by local earthquakes and are not related to far-field events such as those in the New Madrid area to the north.

After a break, Dr. Russell Green of Virginia Polytechnic Institute gave a talk titled "Paleoliquefaction Interpretation of the Vincennes Earthquake, Wabash Valley Seismic Zone." Dr. Green began his talk by reviewing liquefaction phenomena. He showed photographs of classic liquefaction phenomena as well as video footage of liquefaction phenomena resulting from the 1964 Niigata, Japan, earthquake. He described a "simplified" liquefaction evaluation procedure to assess cyclic resistance or the capacity of a soil to resist liquefaction. He described combinations of conditions that can be used to assess when liquefaction will or will not occur, related to peak ground acceleration and other factors. His work has been focused on the Wabash Valley seismic zone and specifically, the effects of the Vincennes earthquake that occurred approximately 6,100 years BP. Dr. Green has estimated the probable Mmax of this earthquake by using plots of the severity of liquefaction with distance from the epicenter. The method he has developed to assess magnitude from data at various field sites incorporates an assessment of overall uncertainty.

Dr. Green discussed constraints on seismic sources, noting that the dimensions of a source can be estimated by contouring maximum dike width. Distinguishing between a small local earthquake event vs. a large distant earthquake event is difficult. Next he discussed sources of uncertainty, including ground-motion predictive relationships and field interpretations. To properly assess the uncertainties and their influence on a back-calculated Mmax, input is needed from geologists, geotechnical engineers, and seismologists, depending on the information to be evaluated. Dr. Green then reviewed ground-motion attenuation relationship information for the CEUS and described alternative presentations of site amplification data. Based on his analyses, the Vincennes earthquake may have been an M 7.3–7.5 event, with the epicenter located within an area having a defined radius of about 160 km.

In a related talk, Dr. Scott Olson of the University of Illinois at Urbana-Champagne described a geotechnical approach to evaluate the strength of shaking associated with liquefaction phenomenon. His talk was titled "Quantifying Uncertainties in Paleoliquefaction Studies." Dr. Olson began by reviewing existing methods for paleoliquefaction back-analysis, including the cyclic stress method, the magnitude bound method, and several other approaches. The cyclic stress method is suitable for evaluating a lower bound for a best estimate of an earthquake magnitude. Dr. Olson noted the variety in worldwide estimates of different magnitude bounds, which are a function of source characteristics, transmission characteristics (attenuation and site effects), and regional soil liquefaction susceptibility. To develop a magnitude bound for the CEUS, he examined historical earthquakes having M > ~5 and the liquefaction features associated with these events. He compiled the best estimates of magnitudes made by seismologists and then looked for the farthest-distance liquefaction features that could be associated with a specific earthquake. From this data he developed a CEUS magnitude bound, in which M 5.5 is the minimum magnitude for liquefaction at close-in locations; increasingly larger-magnitude events can trigger liquefaction at greater distances.

Sources of uncertainties in liquefaction susceptibility, field observations, seismicity, in situ testing techniques, and the magnitude bound approach were described. Then, Dr. Olson discussed aging, the process by which soils develop a structure that results in improved soil properties (e.g., shear strength); he noted that there may not be a need to make any correction for aging in many cases. He described characteristics of liquefaction severity (based on size of liquefaction features), and the factors of safety for different levels of liquefaction severity. A better tool than factor of safety, however, is a liquefaction potential index that incorporates stratigraphy, especially the depth and thickness of potentially liquefiable layers. Dr. Olson went on to discuss failure mechanisms and their relationship to liquefaction resistance. He listed a number of sources of uncertainty in field data, including depth of groundwater at the time of an earthquake, and variability of geologic settings. He then illustrated his approach by using data on the Vincennes earthquake. For this event he has calculated Mw 7.5 + 0.3. He noted that the Wabash Valley work was based on the availability of abundant geotechnical field data; by contrast, few sites in the New Madrid seismic zone have sufficient geotechnical data for conducting a good back-analysis of magnitude.

Following a lunch break, the first talk of the afternoon session was given by Dr. Eric Calais of Purdue University, who talked about geodetic interpretations of New Madrid rates. Dr. Calais began by describing the notion of a steady-state “elastic rebound” model, in which geodesy and paleoseismology should agree. This model works particularly well for plate boundary faults, as present-day strain has predictive power. Current GPS measurements indicate an upper-bound movement of 0.02 mm/yr at New Madrid. Dr. Calais also showed velocities measured at about 500 sites in North America with respect to a constant reference frame. Velocity analyses on deformation east of the Rocky Mountains have indicated that most measured velocities are not significant at a 95 percent confidence level. However, patterns in velocities, especially radial patterns, are apparent. Residual velocities of 0.6 mm/yr have been measured in the CEUS.

Next, Dr. Calais showed residual velocities for areas worldwide, including Europe and Australia, where these velocities are about 0.4 mm/yr. Velocity results have been stable over the past 5 years, so there can be high confidence in the measured rates. Available information indicates that velocities of 0.2 to 0.4 mm/yr are typical of stable continental areas as an upper bound. GPS detects with confidence only velocities of higher than 0.5 mm/yr and strain rates of approximately 10–9. The New Madrid region may contain the only “active” intraplate system in the world where a local, continuous GPS network is available. Dr. Calais discussed the varying levels of precision and accuracy generally obtained from the 500 GPS stations in North America, and specific results for the New Madrid region. In the past few years, velocity uncertainties have decreased by at least a factor of two at all sites; residual velocities have decreased as well. In the same region, there are no significant strain rates at 95 percent confidence level.

Dr. Calais then addressed recurrence of earthquakes indicated by paleoliquefaction. Assuming steady-state strain accumulation and release, there is a 500-year average repeat time over 12,000 years. Dr. Calais concluded that the current strain accumulation rate in the New Madrid region cannot be sustained and is not in steady state. As a counterexample, he referred to the Wasatch fault in Utah, where GPS and paleoseismology are in good agreement. His hypothesis is that some slow faults are in steady state at the 10,000-year time scale but some are not. The New Madrid region is not in steady state because the loading (equal to stressing) rate varies with time, and/or fault strength varies with time. Dr. Calais remarked that it is time to think outside the “rebound model box,” noting that the more we measure, the closer to zero we get, but the more we look, the more potential active faults we seem to find. Local strain accumulation may not be a prerequisite for large earthquakes, as perhaps earthquakes can “tap into” larger-scale reservoirs of strain.

Dr. Seth Stein of Northwestern University gave the next talk, titled “Rethinking Midcontinental Seismicity and Hazards”. He explained the evolution of his thinking about seismicity patterns. Previously he believed that focused, quasi-periodic long-term seismicity occurred in weak zones, but lately he has been moving toward the concept of episodic, clustered, and migrating patterns of seismicity. The latter suggests that the past is an extremely poor predictor of the future and that seismicity migrates between zones of rocks of similar strength. Dr. Stein noted that GPS campaigns were started in the NMSZ in 1991. Initially, fairly high rates of movement were expected but by 1999 the GPS results indicated essentially no motion. In 1999 he postulated that we could be near the end of a seismic sequence; this idea has held up over time. Maximum motion steadily converges to zero, as rate precision improves with longer observations. Dr. Stein now believes that the past 2,000 years are not representative of long-term NMSZ behavior and that the recent large earthquake cluster in this zone may be ending. He noted that geology implies NMSZ earthquakes are episodic and clustered through the Holocene; similar episodic patterns are seen in other continental plate regions. He stated that the NMSZ is not hot, weak, or special relative to surrounding regions of the CEUS. He also discussed differences between time-independent hazard and time-dependent hazard; the latter approach generally predicts lower hazard levels in the CEUS.

Dr. Stein then asked: how we can make better progress in understanding seismic hazard? He believes more and better data are needed, and that the dynamics of forces, faulting, and fault interactions in the plate interior need to be incorporated in a model and explored in detail. He noted that GPS is giving constraints on effects like postglacial rebound. In his conclusions he noted that geodetic deformation is probably required for large earthquakes, so its absence argues against large earthquakes any time soon.

Continuing on the topic of using geodetic data, Dr. Bob Smalley of the University of Memphis gave a talk titled "Geodetic Interpretations of New Madrid Rates." Dr. Smalley noted that his work was based on the same data set that was described by the previous two speakers. He began by noting that maps of worldwide strain rates indicate that plate boundaries have the highest rates, which is in good agreement with plate tectonics. Multiple occurrences of large earthquakes in a few areas, like the NMSZ, are not explained by either plate tectonic or rebound paradigms. Dr. Smalley discussed theories of how plates might deform, and the extent to which deformation can be recognized using GPS. He noted that in concentrated zones of deformation within inactive regions, it is "challenging" to see this deformation with GPS. From examination of plate tectonic dynamics, it is clear that strain rates in stable plate interiors are bound at very low rates. The challenge is to detect a small signal buried in a larger signal. Dr. Smalley believes that GPS is on the verge of not being significant for the NMSZ, thus it is difficult to see how this zone is different from the rest of North America. However, just because we see nothing there now, we cannot say this information is significant. Within the next 10 years, better data may be obtained for the New Madrid region.

Dr. Smalley went on to discuss a number of explanations for stable continental region earthquakes, including reactivation of zones of weakness, crustal weakening by fluids, and stress changes due to deglaciation or sediment loading. For the design of a continuous GPS network for the NMSZ, local, crustal, and regional scales were considered in the placement of monuments. Questions about monument stability were acknowledged and are related to factors that include water level changes in the Mississippi River, and the rise and fall of groundwater levels due to pumping. A longer time period and a larger number of stations providing higher density and redundancy are needed to collect data. Dr. Smalley then gave GPS results for other stable continental regions in the United States, Europe, and India: rates are low, but in general there are few stations in these stable areas. He believes that short-term geodetic signals should be integrated with long-term geologic deformation rates. In his conclusion he noted that GPS will continue to improve, but both denser sampling at the scale of seismic structures and longer observation times are needed.

Following a short break, Dr. Mark Zoback of Stanford University gave a talk titled" Intraplate Stress and Strain in the Central and Eastern United States and Their Relation to Intraplate Seismicity." The work he has conducted indicates relatively uniform stress orientations across complex geologic boundaries. He noted that during the past several years (since the last World Stress Map effort) there has been little progress on mapping intraplate stress in the CEUS, but for the CEUS SSC project he has gathered the new stress information available and plotted it. He showed a series of Google Earth photographs with the stress data plotted, and discussed the new data, including 38 earthquake focal mechanism data points. In the New Madrid area the new stress data indicates strong east-to-west trends, whereas the surrounding craton and eastern margin shows dominantly northeasterly stress directions. This area may have an anomalous crust and upper mantle structure in which the viscosity of the upper mantle may be lower than that of the surrounding mantle, thus leading to stress rotation.

Next, Dr. Zoback reviewed focal mechanism data for recent earthquakes, including the 2002 Mw Caborn earthquake in the Wabash area, which had slip on a west-northwest plane consistent with east-to-west stress. He noted that with uncertainties incorporated, significantly different results could be obtained, and additional well-constrained data are needed. The characteristics of New Madrid seismicity were then reviewed. Dr. Zoback. discussed the hypothesis that the retreat of the glacial ice sheets triggered Holocene earthquakes. The use of a localized weak-mantle model indicates there will be concentrated deformation locally for tens of thousands of years, as that is the amount of time needed for the mantle to recover. Dr. Zoback concluded by asserting that the New Madrid region is unique and that he believes earthquake recurrence rates are not likely to change in the near future.

Dr. Coppersmith opened the workshop to questions from all participants. After further discussion about New Madrid seismicity, the association of earthquakes with glacial unloading, stress accumulation in the crust vs. the mantle, and other topics, Dr. Coppersmith commented that these topics could be discussed again on Day 3 of the workshop. He thanked all the presenters and noted that the meeting would reconvene the following morning.

DAY 3–FRIDAY, FEBRUARY 20, 2009

Dr. Coppersmith welcomed the workshop participants to the third and final day of the workshop. The first talk of the day was by Dr. Martitia (Tish) Tuttle of USGS and was titled "Clustered Model for New Madrid Earthquakes." Dr. Tuttle began with a review of the timing, location, magnitude, and recurrence times estimated for New Madrid region paleoearthquakes. She described evidence for paleoliquefaction, noting that sand blows usually provide the best opportunities to provide minimum and maximum age estimates for paleoearthquakes because they may contain in situ materials (e.g., charcoal, sticks) that can be dated. Dating methods include radiocarbon and OSL (optically stimulated luminescence) dating, artifact analysis, and dendrochronology; age date uncertainties can range from $\pm$ 1 to 1,000 years. The New Madrid earthquake chronology based on paleoliquefaction has age estimate clusters at 1450 a.d., 900 a.d., and 2350 b.c. Independent paleoseismic studies have provided data that support these event ages. Dr. Tuttle believes the clusters formed during very large New Madrid–type events. In addition to the 1811–1812 New Madrid earthquakes, possible analog events include the 2001 **M** 7.6–7.7 Bhuj, India, earthquake. Available information suggests the New Madrid region earthquakes have an approximately 500-year repeat time. Clustered earthquakes (i.e., separated by days or months) are indicated by stratigraphic information associated with sand blows.

Dr. Tuttle reviewed all the paleoseismology information available for the Reelfoot Rift. Faults in the rift region were active at different times during the past 5,000 to 15,000 years; the most recent earthquake activity in the migration pattern is focused on the New Madrid region. She went on to discuss negative evidence for paleoearthquakes. Certain conditions need to be present (e.g., loose and sandy sediments, water-saturated conditions, and good exposures of older deposits) to conclude that liquefaction could have occurred; however, even if these conditions are met and no liquefaction features are found, the occurrence of earthquakes cannot be ruled out. Next, Dr. Tuttle discussed studies in the Charlevoix seismic zone. Three generations of liquefaction features within the past 10,000 years were identified along rivers in this region. These features were likely produced by earthquakes of $\mathbf{M} \geq 6.2$. In the Quebec City–Trois Rivieres region, which is located in a historically seismically quiet part of the St. Lawrence Valley, similar river exposures were examined but no paleoliquefaction features were found; however, the occurrence of paleoearthquakes cannot be ruled out.

The following talk by Dr. Shelley Kenner was titled "New Madrid Model for Repeated Events: Geodetic Signature along the Southeast Margin and Elsewhere." Dr. Kenner began by reviewing intraplate seismicity, noting that the majority of knowledge of earthquake physics has been developed from plate boundary regions. She then noted key differences between intraplate and plate boundary regions with respect to the (1) kinematics and temporal characteristics of seismicity; (2) reason for stress localization; and (3) source of stress that drives seismicity. She reviewed reasons for stress accumulation along faults and described the crustal stress cycle that consists of localized loading, coseismic rupture, postseismic relaxation, and associated localized loading that induces clusters of earthquakes. She also reviewed aspects of the NMSZ, emphasizing the location above a failed rift that has been reactivated repeatedly, and the increase in seismicity during the Holocene.

Dr. Kenner discussed aspects of weak zone model behavior and the question of whether such a zone could be present in regions of concentrated intraplate seismicity. Triggers for seismicity may include glaciation and sedimentation in the Mississippian embayment. Dr. Kenner then spoke about weak zone relaxation and described aspects of associated seismicity over time, including earthquake recurrence intervals. Analyses have indicated that the total duration of transient relaxation processes is very long and may last more than 20 times longer than the characteristic relaxation time of weak zone material even though surface deformation rates are low. To examine the temporal evolution of where shear zones take place, three-dimensional (3-D) weak zone models were developed and their behavior assessed. Total plastic strain plots show that with increasing time, shear zones move toward weak zone boundaries. In summary, stress loading from an underlying weak zone is a physically plausible mechanism for earthquake generation. Sequences of earthquakes due to weak zone relaxation may be triggered by temporally variable localized stress transients

Dr. Coppersmith asked Dr. Stein and Dr. Zoback for their thoughts about Dr. Kenner's model. Dr. Stein commented that if the New Madrid region is special or representative of a large number of faults everywhere, then does that indicate a weak zone is present under each of the many places where large intraplate earthquakes have occurred? Many crustal faults are known and he dislikes the concept of having to associate a weak zone with each of these faults. Dr. Zoback indicated that he agreed with Dr. Stein in terms of the global implications of Dr. Kenner's model. He noted that conceptually, Dr. Kenner's model is similar to other models proposed to explain the Holocene record of earthquakes in the New Madrid region, and it would satisfy the other criteria that are unique to New Madrid, such as the absence of a geodetic signature and the small amount of cumulative deformation. He suggested exercising caution in applying models too broadly.

Dr. Alessandro Forte of the University of Quebec at Montreal gave the next talk, titled "Physical Processes Occurring in the Mantle under the EUS and Their Implications for Surface Stress and

Deformation." He noted that plate tectonics is a 3-D process, in which deep-seated forces that drive horizontal motions also drive substantial vertical displacements that contribute to crustal stress. Vertical motions, however, are below the current level of resolution of GPS. Dr. Forte reviewed several previously proposed dynamic models of the origin of stress and seismicity in the NMSZ. He then showed his work on tomographic imaging of the shallow mantle structure below North America. In the past five years he has been working on modeling present-day mantle flow dynamics in fully global calculations of mantle flow. His tomography-based mantle convection model successfully predicts plate velocities and observations of surface gravity and topography on the North American Plate.

With viscosity structure and driving forces available, the differences in direction of subcontinental mantle flow at various depths can be evaluated. Dr. Forte showed a cross section of mantle flow below the CEUS that indicates downward movement (flow foundering) beneath the New Madrid and Mississippi region at depths below approximately 400 km. He showed a map of mantle-flow-induced horizontal tractions on the crust in the region of NMSZ. He noted that the Mississippi Valley region is being pulled down dynamically because of drag from the descending Kula-Farallon slab below. Descent of the slab into the lower mantle induces a region of maximum horizontal flow convergence and maximum compressive surface stresses directly below the CEUS oriented in a northeasterly direction. Stress directions are modeled as the same along the eastern margin of the continent, but their amplitude is lower. These stresses are generated on mantle-convection time scales, which are on the order of millions of years and can therefore support long-lived seismicity. Dr. Forte showed a video of time-dependent mantle dynamics and surface flexure (topography) over the past 30 million years. He noted that mantle-flow-induced surface depression and associated bending stress may be an important and long-lived contributor to the clustered and migrating seismic activity in the Mississippi Basin, extending from the Great Lakes to the Gulf of Mexico.

Following a short break, Dr. Martin Chapman of Virginia Polytechnic Institute spoke about seismicity in the southeastern United States in a talk about the Eastern Tennessee and Charleston fault models. The Eastern Tennessee seismic zone (ETSZ) is the most seismically active area in the Southern Appalachians. Seismicity in the zone is associated with a major potential field anomaly known as the New York–Alabama lineament. Dr. Chapman reviewed key findings of previous studies of Eastern Tennessee seismicity. He showed maps that indicated correlation of NOAA magnetic data and Bouguer gravity data with earthquake epicenters in the southern Appalachian region. From focal mechanism data, earthquake epicenters are northeast trending and many appear to be aligned along a north-dipping plane. Studies indicate that earthquakes are occurring in response to a highly uniform regional stress, with strike-slip motion predominant. The New York–Alabama lineament marks an abrupt boundary between zones of different seismicity; however, the geologic nature of this feature remains a mystery.

Dr. Chapman then talked about seismicity in the Charleston area, noting liquefaction features and the identified earthquake epicenters. Greggs Landing on the Ashley River is the focus of current seismicity and is also the location of strong shaking in the 1886 Charleston event. A seismic reflection profile in this area provides clear evidence of Cenozoic reactivation of Mesozoic extensional faulting. In the Summerville area, seismic profiles show possible faulting of Cenozoic sediments to shallow depths in close proximity to a strong magnetic gradient. Dr. Chapman also showed COCORP lines that indicate a faulted Mesozoic section underlying the Summerville and Charleston region. The imaged faulting in these areas is within the zone of modern earthquake activity. Dr. Chapman concluded his talk by saying that progress in understanding the seismicity of this area requires a long-term commitment to secure precision hypocenter locations and focal mechanism determinations.

Following a lunch break, Dr. Pradeep Talwani of the University of South Carolina gave a talk titled “The Source and Magnitude of the Charleston Earthquakes.” He began by describing the revised tectonic framework for the region that he and his colleagues have developed. He showed a map of seismicity from 1974 to 2004 and the varied focal mechanisms associated with these events. Earthquakes were relocated to develop the revised tectonic framework that shows a series of faults, which he showed projected onto a series of cross sections. Dr. Talwani described structural features in the region, including the uplifted zone of river anomalies (ZRA) and the East Coast fault system (ECFS). Results of the new seismotectonic framework indicate that seismicity is occurring primarily at the compressional left step within the southernmost segment of the ECFS. Dr. Talwani discussed paleoliquefaction studies that indicate seven separate earthquake events. Using his new work, he can link these events to faults. He described offset in the thick walls of Fort Dorchester during the 1886 earthquake event. A trench was excavated on the projection of the fault that offset the fort walls. Although the fault was not seen in the trench, a sand blow was revealed. Age dating indicated the sand blow formed in a pre-1886 event. Geotechnical data, including piezometer tests and cores, were collected in the area. Using these data, the magnitude of the earthquake was back-calculated to be ~**M** 6.2.

Next Dr. Talwani reviewed results of GPS studies in the Charleston region. Delaunay triangle modeling indicates that the strain rate in the vicinity of Charleston is high. Dr. Talwani showed magnitude estimates for the 1886 Charleston earthquake from intensity data; the latest value is **M** 6.9. He also provided a list of magnitudes of prehistoric regional earthquakes associated with liquefaction from in situ SPT (Standard Penetration Test) data. In his conclusions, Dr. Talwani noted that the 1886 Charleston earthquake and seismicity that is currently being recorded are related to the Woodstock fault and associated faults at a compressional left step in the Middleton Place–Summerville seismic zone. He believes that only this southernmost segment of the ECFS is seismically active and poses a seismic hazard.

The next talk, titled “Seismotectonic Setting and Seismic Sources of the Northern Gulf of Mexico,” was given by Mr. Michael Angell of William Lettis & Associates. Mr. Angell began by stating that although the Gulf of Mexico region has generally low seismicity, three earthquakes having $M_b > 4.5$ (M_w 5.8 was the largest) occurred in the northern Gulf in 2006. Causative mechanisms for these earthquakes were a topic of his talk, and he proceeded to describe the historical seismicity, bathymetry, and stress indicators in the Gulf region. He noted that numerous growth faults (faults driven by gravitational forces) are located above salt diapirs (mobile salt beds). Then he reviewed the information available on the 2006 earthquakes. Two of these events occurred within an area containing growth faults.

Next Mr. Angell reviewed the tectonic setting of this region. Interpretations of the tectonic history indicate that a block of oceanic crust was emplaced in the late Jurassic. Oceanic crust can be delineated on seismic lines and with gravity and magnetic data. Mr. Angell described different models that show the distribution of the oceanic crust in the Gulf of Mexico. Some of the largest recorded earthquakes occurred within this crust. Large, northwest-southeast-trending fracture zones are located to the east of the earthquakes. Turning to a discussion of seismic source models for the Gulf, Mr. Angell reviewed existing alternative models for seismic hazard. Apparent alignments of seismicity suggest a possible underlying source and association with deep structure.

Mr. Angell went on to describe growth fault settings and the associated seismicity. He discussed aspects of the February and April 2006 earthquakes, which have been modeled as gravity-driven on a shallow-dipping plane. He noted that the most appropriate model for the Gulf may be two-layered, having shallow seismic sources in growth fault areas and deeper seismotectonic sources in the basement. He discussed the possibility of a link between upper and lower faulting, mentioning that a trigger could originate from an event in either the upper or lower zone. He concluded by stating that earthquakes associated with growth faults have limited depth extent (to about 5 km), are "slow" (i.e., they do not radiate high-frequency energy), and have low magnitudes ($M < 5$); therefore they may not be significant in seismic hazard assessments.

The next talk was given in two parts by Dr. Mark Peterson and Dr. Chuck Mueller, both of the U.S. Geological Survey. Dr. Petersen spoke first in a talk titled "2008 USGS Seismic Source Model for the Central and Eastern U.S." The national hazard maps released in April 2008 were based on the 2002 and 2006 USGS models. Dr. Petersen briefly described some of the changes made for the 2008 CEUS model, including development of maximum magnitude distributions for seismicity. He reviewed New Madrid and Charleston area site-characterization details. Branches of a logic tree were used to evaluate fault rupture models (clustered and unclustered), location uncertainty, recurrence intervals, and M_{max} alternatives. To obtain alternative M_{max}, the recorded **M** 7.1 to 7.7 magnitudes of earthquakes in stable continental regions worldwide were considered.

During the second part of the talk, Dr. Mueller focused on how seismicity was used in the USGS seismic hazard model. His talk was titled "Hazard from Seismicity: the USGS Approach." He listed organizing principles for the hazard model: specific fault sources considered, historical seismicity gridded and smoothed, and large background zones defined based on geologic criteria. He described the various zones delineated on the hazard map and what earthquake catalogs were used, and he addressed regional completeness levels and *b* values. He reviewed how historical seismicity was gridded based on analyses from four different models, and he showed example results of smoothed seismicity for the different models used. He noted that gridded seismicity models are essentially a localized, variable *b*-value model. Dr. Mueller concluded his talk by describing seismic hazard studies previously conducted for the CEUS and associated hazard assessed for selected nuclear power plant sites.

With the workshop's technical talks completed, Dr. Coppersmith commented on the path forward for the project. He showed the task schedule and described the work to be completed in the next few months. The tasks include constructing the preliminary SSC model, compiling the seismicity catalog, and completing preliminary hazard calculations and sensitivity analyses that will be presented at Workshop 3. Dr. Coppersmith then thanked the presenters and complimented them on the high professional level of their interactions.

Mr. Salomone closed the meeting with several remarks. First he described the role of the Participatory Peer Review Panel (PPRP) and their review relationship with the TI team. He acknowledged the members of the PPRP, beginning with the co-chairs, Drs. Carl Stepp and Walter Arabasz. Then he acknowledged the participation at the workshop of the international observers as well as the younger professionals, who will ultimately take over the process of hazard assessment. He thanked EPRI for its support of the workshop. Finally, he observed that the original vision of what the workshop organizers had hoped would occur had, indeed, happened.

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Table 1:
Key Questions and Topics That Workshop 2 Presenters Were Asked to Address

Topic	Presenter	Questions/Topics to Address at WS2
Geodetic observations in St. Lawrence and implications to Mmax; big picture tectonic framework; limits of glacial rebound	Mazzotti, Stephane	What criteria should be used to define seismic sources? Do glacial rebound processes influence seismicity (rates-focal mechanisms) and should this be considered in defining seismic source zones? What are rates and uncertainties on geodetic observations? What is geographic area of coverage for geodetic observations? What is your confidence that observed geodetic rates reflect long-term tectonic deformation rates or short term seismicity pattern and rates? What weight would you give geodetic vs seismicity in establishing rate of EQ occurrence?
Size of 1663 Charlevoix earthquake; treating St. Lawrence seismicity zones as aftershocks	Ebel, John	What is your confidence that current patterns of seismicity represent aftershocks from large historic or prehistoric events? What maximum magnitude range and source zone geometry would you assign to sources in the St Lawrence-Charlevoix area?
Use of seismicity to define seismic sources, application in the eastern North America region.	Kafka, Alan	What approaches should be used to capture uncertainty in stationarity of seismicity with regard to defining seismic sources?
Use of geological structures and assessing Mmax for Canadian nationa hazard maps	Adams ,John	What methodology is being used to define Mmax distributions for source zones? What is the Canadian perspective on the limitations of the Johnston et al. (EPRI) approach and prior distributions? What are reasonable worldwide analogs for stable continental regions appropriate for CEUS and Canada?

Topic	Presenter	Questions/Topics to Address at WS2
Seismicity and potential faults in NYC, Pennsylvania, Ohio, New England	Seeber, Leonardo (Nano)	What are reasonable criteria for defining seismic source zones in NE US? Previous models have used hotspot tracks, onshore extensions of older transforms, evidence for reactivated structures along the Fall Zone and Mesozoic rift basins—are these still valid concepts? What is your preferred causative mechanism for seismicity in the region? What is your preferred seismic source model (geometry, Mmax) for the NY region?
Ouachita, sub-detachment structures	Thomas, Bill	What is the influence of any of older structures (e.g., Iapetan transforms) are present seismicity. What is the evidence for reactivation of these structures in the Mesozoic? What is your confidence that the Ouachita basement structure represents a seismogenic source?
Rift structures in the mid-continent (Rough Creek Graben, Rome Trough, East Continent rifts)	Drahovzal, James	Is there evidence to suggest that the Rough Creek and Rome Trough may be continuous features? Is there any evidence of Mesozoic reactivation of either structure? What is the relationship of the East Continent gravity high to the Rome Trough and to regions of elevated seismicity in Eastern Tennessee?

Topic	Presenter	Questions/Topics to Address at WS2
Integration of seismic reflection, geopotential field, and subsurface information in southern Illinois Basin	McBride, John	Previous publications suggest that moderate earthquakes (like the 1968 event may have occurred on thrust faults in the basement? What if any structural relationship is there between these structures and the Commerce Geophysical lineament? Is there sufficient evidence to model other structures such as the DuQuoin monocline as potential fault sources? What are your thoughts on the distributed paleoliquefaction 'energy centers'—is there other geologic information to suggest local sources of moderate events or are these features more likely due to more distant larger magnitude events? Should the faults in the Flurospar Area complex region be modeled as independent active faults in the current tectonic environment and if so, what are your thoughts on the timing, maximum magnitude, and recurrence of events on these structures?
Margins of Reelfoot and update on Kentucky River fault zone	Van Arsdale, Roy	What are the constraints on the continuity and length of possible fault sources along the margins of the Reelfoot rift? Are there paleoseismic data that can be used to estimate Mmax? Is there evidence of paleoliquefaction associated with events on the margin fault sources? Please comment on the southern continuation on potential continuity of the NM and Saline River source zones.
Commerce lineament and northwest boundary of New Madrid	Baldwin, John	What data is available to constrain or estimate Mmax for fault-specific sources along the northwestern margin of the Reelfoort rift? What is the extent, origin, and seismogenic potential of the Commerce Geophysical lineament?
Saline River and Reelfoot Rift	Cox, Randy	What are the uncertainties in the timing and relationships of paleoliquefaction events in the Saline River area relative to the central part of the NMSZ? Please comment on the southern continuation or potential continuity of the NM and Saline River source zones. Have you identified a tectonic feature as a potential seismic source responsible for observed liquefaction in the Saline River area?

Topic	Presenter	Questions/Topics to Address at WS2
Geotechnical evaluation of the Vincennes event in southern Illinois	Green, Russell	How can this analysis be used to constrain the dimensions of the Vincennes earthquake seismic source? Can you use similar approaches to evaluate smaller energy centers that have been identified elsewhere in southern IL and IN—i.e., what methods can be used to assess the issue of local small events versus larger more distant earthquakes? What is your uncertainty in using liquefaction to assess Mmax?
Magnitude bound relation for the Wabash Valley seismic zone; Geotechnical analysis of paleoseismic shaking using liquefaction effects	Olson, Scott	What are limitations of the magnitude bound approach? What is your uncertainty in using liquefaction to assess Mmax? What Mmax would you assign to NM, Charleston, Wabash, based on paleoliquefaction observations? Please comment on the minimum magnitude required to generate liquefaction?
Geodetic interpretations of New Madrid rates	Calais, Eric	What is your confidence that observed geodetic rates reflect long-term tectonic deformation rates or short term seismicity pattern and rates? What weight would you give geodetic vs seismicity in establishing rate of EQ occurrence? Do current data allow one to discern tectonic rates from measurement uncertainties?
Rates and recurrence in New Madrid	Stein, Seth	What is the relationship between geodetic deformation and earthquake occurrence? Have you compared the geodetic signature of other zones of seismicity in stable continental regions? Is the absence of evidence for geodetic deformation a definitive indicator of future earthquake potential?
Geodetic interpretations of New Madrid rates	Smalley, Bob	What is the relationship between geodetic deformation and earthquake occurrence? How do you relate relatively short-term geodetic deformation rates to longer-term geologic deformation rates? Have you compared the geodetic signature of other zones of seismicity in stable continental regions?

Topic	Presenter	Questions/Topics to Address at WS2
Update of stress map, strain localization, New Madrid rates	Zoback, Mark	Do available stress and strain data provide sufficient resolution to aid in defining local source zones? What is the cause of stress of intraplate stress? What are mechanisms to localize stress? Are observed rates of historic and prehistoric seismicity consistent with observed stress and strain rates?
Clustered model for New Madrid events	Tuttle, Tish	What are the resolution issues for identifying individual events and estimating the size of such events? What is your confidence that the regional absence of liquefaction in susceptible deposits reflects an absence of large magnitude (>6) earthquakes?
New Madrid model for repeated events; geodetic signature along the southeast margin and elsewhere	Kenner, Shelley	What are likely triggering events? Is the absence of a significant geodetic signal across the NMSZ consistent with this model? What are implications of the model for future large magnitude earthquakes (location, timing)?
Physical processes occurring in the mantle under the Eastern US and their implications for surface stress and deformation	Forte, Alessandro	Do mantle processes influence current seismicity? Can these patterns be used as criteria for defining seismic source zones? Do mantle processes occur at rates that should influence short term (10-1) or long-term (10-3) seismicity? What is your confidence that available heat flow data can be used to detect mantle anomalies?

Topic	Presenter	Questions/Topics to Address at WS2
Update on eastern TN and Charleston; fault model for these sources	Chapman, Martin	Please comment on your interpretation of the causative mechanism for the events in ETSZ? Do current seismicity analyses support previous models of alignments of seismicity as potential fault sources? What is the influence of the NYAL lineaments on patterns of seismicity? Are there unique conditions (fluid pressures, basement rocks, etc.) that distinguish ESTZ from other seismically active regions of the Appalachians, (i.e., Giles Co.)? Is there any current new information that can be used to assess Mmax? Please comment on your interpretation of the causative mechanism for the Charleston earthquake?
The source and magnitude of the Charleston earthquakes	Talwani, Pradeep	Please comment on your interpretation of the causative mechanism for the Charleston earthquake? Is there evidence to suggest that the tectonic features (i.e., Woodstock fault, and related thrust faults in the step over regions) that appear to be likely candidates for the source of the repeated large magnitude Charleston events extend along the full length of the postulated ECFS-S?
Approaches Used to Identify and Evaluate Neotectonic Features in Appalachian Piedmont/Coastal Plain Setting	Pazzaglia, Frank	What influence if any do the broad regional flexures have on current patterns of seismicity? Should these features be explicitly considered in defining seismic sources? Please comment on your interpretation of the causative mechanism for earthquakes in the northeastern US?
Gulf coast faulting and seismicity	Angell, Mike	Please comment on your interpretation of the causative mechanism(s) for earthquakes in the Gulf?

Topic	Presenter	Questions/Topics to Address at WS2
Seismic source model for the US National Hazard maps	Peterson, Mark	Current modeling tools (smoothed seismicity) reduce the need for using discrete seismic source zones to capture areas of elevated seismicity. Please comment on what characteristics (i.e., Mmax) would warrant defining a separate source zone?

WORKSHOP 3: FEEDBACK
August 25-26, 2009

Electric Power Research Institute
3420 Hillview Ave.
Palo Alto, California 94304

The Workshop on Feedback was the third in a series of workshops jointly sponsored by the Electric Power Research Institute (EPRI) Advanced Nuclear Technology (ANT) Program, U.S. Nuclear Regulatory Commission (NRC), and U.S. Department of Energy (DOE) in support of the Central and Eastern United States (CEUS) Seismic Source Characterization (SSC) for Nuclear Facilities Project. The objective of the CEUS SSC is to develop a comprehensive and up-to-date SSC for a probabilistic seismic hazard analysis (PSHA) that is appropriate for use at any site in the CEUS. The technical integration (TI) team and TI staff are charged with developing a seismic source model that captures the knowledge and uncertainties within the larger informed technical community.

The goals of this workshop were as follows:

- Review the progress of the project in terms of meeting key milestones, such as the database development and earthquake catalog.
- Review the processes being followed to attain the SSHAC goal of capturing the informed technical community.
- Discuss the seismicity catalog developed for the CEUS SSC project.
- Discuss the seismic source characteristics of the SSC sensitivity model.
- Present feedback to the TI team and staff in the form of SSC sensitivity analyses and hazard sensitivity analyses.
- Identify the key issues of most significance to the SSC models.
- Discuss the analyses being conducted related to hazard significance.
- Discuss the path forward for the CEUS SSC project.

These goals were accomplished by a series of presentations and discussions.

DAY 1–TUESDAY, AUGUST 25

Workshop participants were welcomed by **Mr. Frank Rahn** (EPRI), who reviewed workshop logistics. **Mr. Lawrence Salomone**, project manager for the CEUS SSC project, then welcomed workshop participants and thanked them for attending. He reviewed the project goals:

- Replace the previous EPRI Seismicity Owners Group (EPRI-SOG) and Lawrence Livermore National Laboratory (LLNL) seismic hazard studies that were conducted in the 1980s (EPRI-SOG, 1988; Bernreuter et al., 1989).
- Capture the knowledge and uncertainties of the informed scientific community using the SSHAC process (documented in NUREG/CR-6372; Budnitz et al., 1997).

- Present a new CEUS SSC model to the NRC, DOE, and others for review.

Next Mr. Salomone showed a map of the study area and the demonstration sites used for sensitivity analyses for the project. He reviewed the topics of the previous two workshops, noting the contributions of numerous resource experts, and went over the goals of Workshop 3. He also described communications with the Participatory Peer Review Panel (PPRP) and project and tracking milestones. The project appears to be on track to meet the target completion date in December 2010.

Dr. Kevin Coppersmith (Coppersmith Consulting, Inc.), the lead of the TI team, then welcomed the workshop participants. He began by reviewing aspects of the SSHAC project, including basic principles for a PSHA, key attributes of the process, and expert roles. He reviewed the purpose and goals of Workshop 3. The TI team has developed a sensitivity SSC model that is complete in that it captures the range of views in the technical community, but the TI team has not devoted a lot of effort to weighting the alternative branches of the model until they see the results of the sensitivity analyses. Sensitivity analyses to be presented in the workshop will allow understanding of the importance of key assessments of most significance to the SSC models. Dr. Coppersmith clarified that a draft data summary package—consisting of the Data Summary and Data Evaluation Tables—completed prior to the workshop and distributed to PPRP members is a "work in progress" (i.e., it is incomplete and subject to revision). Nonetheless, he noted that the data evaluation process was conducted with a focus on identifying and evaluating the data, models, and methods that have credibility. By understanding the potentially important elements of the SSC model, subsequent work for the CEUS SSC can be prioritized.

Dr. Coppersmith went on to give a talk titled "SSHAC Goal of Capturing the Informed Technical Community." He explained that the talk is based on his experience both from being a SSHAC member and from subsequently implementing SSHAC processes during the years since the 1997 SSHAC study was completed. After giving a brief historical context to probabilistic risk studies and the use of expert assessments, he noted that there has been increasing recognition of the importance of uncertainties. Probabilistic hazard is important to risk analysis, and uncertainties are important to hazard, thus quantifying uncertainties is an important aspect of the analysis. Dr. Coppersmith stated that more stable estimates of hazard are obtained by incorporating the range of views within the expert community. Based on this knowledge, there has been increased attention to concerns about expert issues, including representativeness, independence, consensus, and aggregation. Of particular importance have been strategies to deal with potential outlier judgments that may have a disproportionately large influence on results.

Dr. Coppersmith described the SSHAC concept of integration as capturing the view of the informed technical community (ITC). (Being "informed" in this case refers to being familiar with site-specific databases as well as participating in the SSHAC interactive process.) He stated that integration is not just an aggregation process for parameter values across a panel of experts, as very few parameters can be directly assessed in PSHA. Instead it is necessary to evaluate data, develop models, and quantify uncertainties. Obtaining a composite, or community, distribution is the most important objective of consensus in the SSHAC process.

Dr. Coppersmith described the steps taken in the CEUS SSC project to ensure that the views of the ITC have been captured. All participants understood their roles and agreed to abide by them within the framework of the SSHAC process. The TI team and staff, as well as members of the PPRP, have first-hand knowledge of data sets, reflecting their extensive experience in SSC for the CEUS. They have developed and are using explicit data evaluation processes to demonstrate a thorough awareness of all applicable data. Dr. Coppersmith noted that the interactive workshop processes used have proven to be a highly effective mechanism for identifying all available data and models that presently exist or are under development. In addition, he noted that the TI team and staff have expertise with the integration process. He said steps are in place that will ensure that the views of the ITC are reflected in the final results of the CEUS SSC project.

Dr. Coppersmith then gave a case history for the CEUS SSC project and traced the documentation in place to date. The case history was about the work of Drs. Eric Calais and Seth Stein, both of whom made presentations at Workshop 2, who suggested a lack of deformation in the New Madrid seismic zone and the potential that the zone will not be seismically active in the future. Dr. Coppersmith showed the questions they were asked to address in their talks, as well as a photograph of them as workshop participants, slides from their presentations, text included in the Workshop 2 summary and in a letter from the PPRP, text in a data summary table, and the logic tree used to model the hazard associated with the New Madrid fault source. He noted that the full documentation of the evaluations made by the TI team and the justification for all elements of the final SSC model will be part of the project final report. Dr. Coppersmith concluded his talk by stating that the SSHAC study will provide approaches that are instrumental in achieving the goal of capturing the views of the ITC. These approaches have been followed in the CEUS SSC project and they provide reasonable assurance that the ITC has been captured.

Workshop participants then discussed such concepts as "range of the technical opinions that the informed technical community would have," outlier judgments, and reasonable assurance. Regarding range of opinions, sensitivity studies are useful for showing when an analysis input has little or no hazard significance. There has been a gradual move away from a when-in-doubt-put-it-into-the-analysis approach and toward more careful consideration of whether or not an input is credible (e.g., tails on distributions that extend to infinity), as these approaches affect computational efforts and analysis results differently.

Workshop participants also discussed the possible subjectivity inherent in efforts to limit outlier views by promoting evaluator roles instead of proponent roles for expert inputs. A representation of the distribution of community judgments, as represented by the ITC, is the goal of the SSHAC process and underlies the importance of the evaluator role. Finally, the group addressed the concept of reasonable assurance as an accepted standard for safety decision making, based on meeting standards of practice. A member of PPRP and others at the workshop believe that the SSHAC process, if properly implemented, goes beyond the standard of preponderance of evidence in assuring that the views of the ITC have been considered and represented.

Following a short break, Dr. Robert Youngs (AMEC Geomatrix, Inc.) gave a talk on development of the CEUS SSC earthquake catalog. A preliminary earthquake catalog was completed for use in preparing the sensitivity analyses. Dr. Youngs reviewed the catalog development beginning with compilation of earthquakes from available existing catalogs, through the process of declustering, noting that the approaches used for several of these steps were initially used for the EPRI-SOG study. The primary earthquake catalogs used for the compilation were from the U.S. Geological Survey (USGS) and the Geological Survey of Canada (GSC), but several other national, regional, and historical catalogs were also used. Information on relocated events was obtained from studies described in published literature. Nontectonic events (particularly blasts) were identified. Moment magnitudes were assessed for all events, and Dr. Youngs showed plots of the alternative relationships used to convert different magnitude scales into moment magnitude. He described the process used to combine estimates from multiple magnitude measurements, when available, into a uniform magnitude scale. After conversions were completed, additional corrections were made to account for the bias in recurrence parameters due to magnitude uncertainty.

Next, Dr. Youngs explained how declustering was performed and how of the 26,426 total events in the catalog, 14,674 dependent events were identified. The final step in the catalog development process was to assess catalog completeness for events of various magnitudes. He showed the plots of catalog completeness regions within the study region for 15 different regions identified based on instrumentation and population history. He has sent the catalog to PPRP, USGS, GSC, and TVA colleagues to review selected preferential catalog entries, identify any additional data sources, evaluate conversions to moment magnitude, and garner any other suggestions. Response is needed by the end of 2009. At the conclusion of Dr. Youngs's talk, the workshop participants discussed the declustering approach and the identification of earthquakes related to blasts and located in offshore regions.

Dr. Youngs then gave a talk titled "The "EPRI" Bayesian M_{max} Approach for Stable Continental Regions (SCR)—Updated Priors." In the EPRI (1994) study, SCRs were divided into domains based on crustal type, geologic age, stress regime, and stress angle with structures. For the CEUS SSC project source zones, observed M_{max} distributions were developed based on the SCR domains identified for the 1994 study. In the project update, revised magnitude estimates were added for the New Madrid (**M**7.8) and Charleston (**M**6.9) events, and additional worldwide earthquakes were added from recent catalogs. The number of **M** ≥ 4.5 events in the SCR increased from 940 to 1,550 earthquakes. Dr. Youngs described an interesting case of a large 1917 earthquake in China and the differences in the size and location of this event as reported in various catalogs. Next he discussed bias adjustment, which is used to move from the relatively small number of observed maximum earthquakes toward what could be expected if more data were available. He described domain "pooling," in which estimates of bias adjustment can be obtained by pooling similar domains to increase sample sizes (essentially, trading space for time). He concluded the talk by describing work that needs to be completed, including the criteria used to distinguish and combine domains and to examine bias correction techniques.

Following a lunch break, Dr. Youngs briefly described the talks planned for the afternoon; these consisted of feedback on various parameters and their effects on hazard, calculated for the seven demonstration sites examined in the study. Dr. Youngs gave the first talk, titled "Logic Tree Structure for Seismic Source Sensitivity Model." He began by describing the master logic tree developed for the CEUS SSC sensitivity model. Two types of seismic sources are recognized: (1) distributed seismicity within regional source zones, characterized using historical and instrumental seismicity, and (2) repeated large-magnitude earthquake (RLME) sources characterized using the paleoearthquake record. For each of these sources, zoneless and seismotectonic structure approaches are used for characterizations and assessment of M_{max}. Distributed seismicity sources have two alternative geometries based on different extended and non-extended crust delineations.

Next, Dr. Youngs discussed the two alternative methods used to address spatially varying seismicity rates. These are the kernel model approach, based on a constant *b*-value and a cell-by-cell model approach that uses a variable *b*-value. The uncertainties and advantages and disadvantages of using each of these approaches were discussed. Dr. Youngs then described the use of a zoneless treatment of RLMEs based on use of an earthquake catalog that includes paleoearthquakes, noting that an important issue is completeness with respect to spatial and temporal earthquake coverage. What to do in areas that have not been examined in detail is problematic; hence this model is not yet ready to be used. Dr. Youngs also described the logic tree structure used for the structure-specific approach to assessing RLMEs.

Dr. Youngs moved on to a talk titled "One Approach for Spatially Varying Seismicity," in which he discussed the kernel model smoothing approach in detail. This approach assumes a constant *b*-value within a zone and a variable "a." Uncertainty in overall seismicity parameters is largely decoupled from estimation of spatial density. Dr. Youngs discussed testing for spatial non-uniformity to assess if seismicity is occurring in clusters. He showed kernel density estimation in one dimension, depicting a "classical" uniform density graph and Gaussian kernels approach. When combined, these approaches give information important for assessing the size of the kernel, which is an important parameter.

Next, Dr. Youngs described alternative kernel forms and how they affect data density. Kernel size can be adjusted as a function of data density using an adaptive kernel. Dr. Youngs showed examples of fixed kernel estimates and adaptive kernel estimates and how they affect display of data using a normalized density. He described the issue of varying completeness and how to account for this using a single catalog; possibilities include using minimum completeness for the lowest magnitude used (minimum data) and assigning a weight to each earthquake interval based on specific measures of relative completeness. He reviewed the approaches of high smoothing using uniform spatial density and low smoothing using adaptive kernel density estimation. He concluded by describing estimation of uncertainty distributions for earthquake rate and *b*-value.

The next talk, given by Dr. Gabriel Toro (Risk Engineering, Inc.), was titled "Characterization of Variable Seismicity: Penalty Approach with Variable a and b." Dr. Toro stated that the variable seismicity approach is essentially a modification of the 1988 EPRI study approach developed by Veneziano and Van Dyke (1988). He began with an overview of the 1988 EPRI study approach and described the key elements and equations. Next he discussed the new features included in the updated approach, including smaller (0.25 degree) cell size and a new solution algorithm that estimates uncertainty in certain parameters and objectively estimates penalty terms to use in the calculation (i.e., downweighting is applied if there is a large difference in value between a cell and the adjoining cells).

He then described the solution algorithm and the results that can be obtained. The approach has been used for two cases: (1) a low smoothing case using objectively determined smoothness penalty terms and a low prior of b = 1, and (2) a high smoothing case with fixed smoothness penalty terms and no prior on b. Dr. Toro displayed the results of the CEUS SSC earthquake catalog using these approaches; with low smoothing there are more local peaks depicted than with high smoothing. He compared these results with results of the approaches used by Dr. Youngs and noted that they are similar.

Dr. Toro moved on to a discussion of uncertainty characterization for the variable seismicity approach, which represents a significant improvement over the EPRI 1988 model. He described the objective and approach, which includes randomization, and showed sample results obtained for low smoothing and high smoothing examples. His conclusions included the observation that the variable b approach is particularly well suited for large source zones, and that the approach allows both objective (data-driven) and subjective specification of the smoothing parameter (i.e., penalty terms). Finally, Dr. Toro described additional work that could be conducted in the future to make improvements in the application of the updated approach.

Dr. Youngs presented maps of the historical seismicity of the CEUS that depicted the alternative spatial density models, plotted as frequency of occurrence (i.e., events per year per 0.25 degree). These maps provided feedback for the project team on the results produced by different smoothing approaches. Dr. Youngs showed three sets of maps displaying $\mathbf{M} \geq 5$, $\mathbf{M} \geq 6$, and $\mathbf{M} \geq 7$ events for each of the alternative models. He described and compared the results of different models for selected regions. The number and magnitude of earthquakes within a particular region can have a strong effect on the nature of the boundary between adjoining zones. Workshop participants discussed some of the results of the various models, as well as the basis for defining the boundary between extended and non-extended crust.

After a break, Dr. Youngs announced that talks for the remainder of the afternoon would provide a whirlwind tour of seismic hazard in the CEUS. He began by showing a map of locations of the regional sources, RMLE sources, and the seven demonstration sites that are being analyzed for the CEUS SSC project. He described the master logic tree used to assess all the seismic sources and discussed various parameter estimation approaches. He showed results of M_{max} assessments for the regional sources. Next he described in detail the analyses for the Cheraw fault and Wabash area RLME sources. He showed the logic trees used for these sources and discussed results of analyses of event frequency and magnitude distributions for each source. He then went on to describe the New Madrid RLME. The analysis is based on two groups of sources (a central zone of faults and a set of faults on the boundary of the rift) and three models of characterization (one with all structures in active mode; one with all structures turned off and a default to background seismicity; and one with only the Reelfoot thrust active). Dr. Youngs concluded his talk by showing the results of analyses of event frequency and magnitude distributions for the various structures associated with the New Madrid RLME.

Dr. Robin McGuire (Risk Engineering, Inc.) gave the next talk, titled "Seismic Hazard Sensitivity in the CEUS," noting that he would be giving his opinions of what is or is not important for hazard analyses. He began by discussing general sources of imprecision, including random and systematic errors, variability and unpredictability, expert disagreement, and approximations. Next he reviewed the hazard from the New Madrid RLME source at two demonstration sites (Central Illinois and Jackson, Mississippi). For each site he first showed PGA hazard fractiles and the mean for hard rock. He then showed the sensitivity to the ground motion model used, the cluster frequency, the characteristic magnitude, and rupture length scenarios. For the dependence on cluster frequency he noted that we are less then halfway into the recurrence interval following the 1811-1812 earthquakes; thus the renewal recurrence model gives higher hazard than the Poisson model. After showing the sensitivity results, Dr. McGuire showed the mean and fractile hazard results at 1 and 10 Hz spectral acceleration.

Next, Dr. McGuire showed PGA hazard curves from three New Madrid seismic zone models (2008 USGS, 2003 Geomatrix, and 2009 CEUS SSC) that had been computed by different analysts at Risk Engineering, and he noted that all give near-identical results. The hazard curve for additional faults (e.g., Commerce and Fluorspar) and the hazard curves for 1 and 10 Hz are also all virtually identical. Dr. McGuire also showed hazard results at the Topeka, Kansas, demonstration site. Again, at 1 and 10 Hz, the newly calculated hazard results are virtually the same as those obtained in the 2008 USGS and 2003 Geomatrix studies. Dr. McGuire emphasized that this comparison was not done using total hazard, but with the hazard contributions from the New Madrid seismic sources only. Workshop participants discussed the agreement between the different models, which is based in part on the long source-to-site distances. Also, it was noted that results from pre-2000 models would have varied, in part because these were based only on observed seismicity (i.e., no paleoearthquakes).

The next speaker was Ms. Allison Shumway (William Lettis & Associates, Inc.), who described hazard results from the Cheraw fault and Wabash Valley seismic sources at the Topeka demonstration site. The recurrence rate parameter for the Cheraw fault has the greatest effect on hazard at the Topeka site. For the Wabash Valley source, two alternative source geometry interpretations were used: narrow and wide (circular shape, consistent with the 2008 USGS source zone); the geometry has a moderate effect on hazard. The source recurrence rates used in the analysis give a factor-of-10 range, however, so this parameter is the most sensitive. The paleoseismic record appears to indicate a higher recurrence rate than the historical seismicity. To clarify the basis for the source logic trees, Ms. Kathryn Hanson (AMEC Geomatrix, Inc.) briefly described the paleoseismic record of the Cheraw fault, which includes three events in the past 20,000 years. For the Wabash source, she described the basis for rates from the paleoearthquakes near Vincennes, Indiana.

Dr. Youngs spoke next about the Oklahoma Aulacogen (OKA)/Meers fault RLME; the Meers fault is located within the OKA, so the two sources are always linked. He showed the logic tree and reviewed the branches for an in- or out-of-earthquake cluster, source geometry, earthquake model, rupture size relation, magnitude approach, and recurrence approach. A separate logic tree has been developed for OKA with broad and narrow source geometry and with the Meers fault in or out of a cluster. Additionally, given the alternative that the Meers fault is “turned off,” there is a probability that seismic activity will move to another location within the OKA but have the same source characteristics as the Meers fault. This alternative was added because numerous structures have been identified within the OKA that parallel the Meers fault.

The Alabama-Louisiana-Mississippi source (ALM; this source includes the Saline River region) located on the southern edge of the Reelfoot rift system was described next by Dr. Youngs. Four alternative source geometries were evaluated and Dr. Youngs described the data used to develop each alternative. Logic tree branches included consideration of event correlation or no correlation for paleoliquefaction interpretations, plus alternative numbers of paleoearthquakes related to these interpretations. This region does not have elevated seismicity, but paleoliquefaction evidence is present and possibly represents multiple earthquakes.

Ms. Shumway showed sensitivity results for the OKA/Meers fault RLME source. Alternative geometries may be sensitive, but this interpretation needs to be checked. The background M_{max} earthquake within the aulacogen only (i.e., without the influence of the Meers fault) is also potentially important. Next she discussed the ALM source. Four alternative geometries are considered and hazard was calculated for the highest weighted source (the Cox/Quaternary alternative) at the Jackson, Mississippi, and Houston, Texas, sites. Randomly oriented structures that are or are not allowed to extend beyond the boundary of the source zone were tested (“leaky” or “strict” source cases) and shown to have low sensitivity. Recurrence rate has a high sensitivity, and Ms. Shumway noted that with more small events, higher hazard is indicated at higher probabilities. Workshop participants discussed the paleoliquefaction data and hazard sensitivity results for the ALM source.

Dr. Coppersmith adjourned the meeting for the day.

DAY 2–WEDNESDAY, AUGUST 26

Mr. Salomone welcomed the group to the second day of the workshop. He announced that in October there would be a workshop on earthquake hazards sponsored by the USGS; this workshop is one of several synergistic projects currently under way that overlap the work being conducted as part of the CEUS SSC project. He introduced Mr. Oliver Boyd (of the USGS), who is an organizer of the upcoming earthquake hazards workshop. Mr. Boyd said that the workshop will be held October 27-28, 2009, in Memphis, Tennessee. It will provide an opportunity for researchers to present and discuss their recent investigations, discuss upcoming New Madrid bicentennial activities, and identify topics for future research priorities.

Dr. Coppersmith gave a summary of the model sensitivity information presented on Day 1 of the workshop. He noted the apparently large impact locally on predicted rate density of alternative interpretations of the position of the extended/non-extended crust boundary and seismotectonic zone boundaries. Some of the smoothing results show a distinct rate change (step function) at the boundary, which could be important for sites very near the boundary. This also highlights the potential importance of evaluating the need for source boundaries or boundaries for purposes of M_{max} assessment (i.e., the extended/non-extended boundary). For the repeated large-magnitude earthquake (RLME) sources, he noted that comparisons made the previous day showing similarity in hazard for post-2000 PSHAs near New Madrid indicate that these studies are comparable in their treatment of the New Madrid seismic zone.

Given that the RLME sources are within a cluster, there is strong sensitivity to the recurrence rate. Sensitivity analyses have not yet been conducted to demonstrate the differences between within-cluster and out-of-cluster hazard at nearby sites, but it is expected that there will be strong sensitivity to in- or out-of-earthquake-cluster recurrence rates, as well as to characteristic magnitude distributions at all RLME sources. A renewal model was developed and exercised for some of the RLME sources; the short elapsed time at New Madrid relative to the mean RLME repeat time results in somewhat lower hazard estimates than the Poisson model. The results illustrate the importance of the parameters of the renewal model, including the coefficient of variation (COV) of the mean repeat time. Sensitivity studies for the Central Illinois site (which is not immediately adjacent to the New Madrid source) indicate little sensitivity to alternative models for the rupture of the northernmost segment and to rupture length models. With increasing distances to an RLME source, the background or regional seismotectonic zones are increasingly important and contribute more than the RLME sources.

Dr. Coppersmith also reviewed the particular sensitivities associated with the RLME sources at the test sites. He listed additional feedback information that will be needed, including the hazard significance of all logic tree branches at all logic tree nodes at all seven demonstration sites. He noted that he would be adding to this list as the day progressed and would review it with the TI team at the end of the day.

Dr. Youngs continued the presentations on sensitivity models by discussing the Charleston, South Carolina, RLME source. He described the weights on various logic tree branches, including alternative interpretations for in- or out-of-earthquake-cluster recurrence rates; four source geometry configurations; various paleoliquefaction scenarios, including length of paleoliquefaction record (2,000 versus 5,000 years); the range of maximum magnitude (M_{max}) values (**M** 6.7 to 7.5); and the possible overlap in the earthquake magnitudes included within this RLME and those that are accounted for within the surrounding regional source zone.

Next, Ms. Shumway described the geometry, rate, and M_{max} sensitivity studies for the Charleston RLME and the resulting hazard at the Savannah, Georgia, and Chattanooga, Tennessee, demonstration sites. The hazard results reflect the wide range of input parameters. There is high sensitivity to earthquake recurrence models. The renewal (time-dependent) model results in lower recurrence rates for the next 50 years because the elapsed time since the large 1886 earthquake is relatively short compared to the mean repeat time for RLME events. Workshop participants discussed the relative merits of using renewal versus Poisson recurrence models. Weights on these model branches may need to reflect the maturity of the structures involved; additional feedback on sensitivity is needed.

Dr. Youngs recounted early discussions about placing an RLME source around the Charlevoix region. The project team decided this was unnecessary as the recurrence rate from the observed seismicity is comparable to or even exceeds the rates identified using paleoliquefaction data. Neither the cell-by-cell nor kernel-smoothing methods provide a close fit, in part because of uncertainty in the record of paleoliquefaction events. Checking the relative fit of the two smoothing methods using an RLME-equivalent source in the St. Lawrence and Charlevoix region may provide useful information.

Dr. Coppersmith asked PPRP members for their opinions about the use of the renewal versus Poisson smoothing approaches. Dr. Stepp remarked that if the in-cluster alternative is selected for the Charleston RLME, then a tectonic interpretation is being made and therefore the renewal model needs to be highly weighted. Dr. Coppersmith observed that the renewal model is sensitive to knowledge of COV and time since the last event; when the uncertainties in both of these factors are added, the problem is moved toward a Poissonian approach. Workshop participants discussed the use of the renewal approach for known seismic sources (e.g., structures in the New Madrid region). There was agreement that more work on COVs is needed, as there is extreme uncertainty in this parameter for many areas and thus the use of the renewal model may not be reasonable. Workshop participants also discussed how to structure a logic tree given that an in-cluster state is assumed. Dr. Coppersmith noted that the influence of the in-cluster versus out-of-cluster models on hazard still needs to be examined.

Following a break, Dr. Coppersmith announced that the next talks would address regional seismic source zones. Dr. Toro gave the first talk, titled “Sensitivity Results for CEUS Source Zones.” He began by comparing the CEUS SSC project hazard results (for the source zones only; no RLME sources) with hazard results using the zones defined by the USGS. In general, the hazard levels calculated for the CEUS project are lower than those for the USGS study, but this is likely due to not including the RLME events in the comparison. At the Savannah site the difference in hazard levels is about 50 percent; for the Chattanooga and Manchester, New Hampshire, sites the difference is closer to 20 percent. For the Central Illinois, Houston, Jackson, and Topeka sites, the hazard curves are closer together.

Dr. Toro then discussed hazard sensitivity results for seismic source zones for each of the seven demonstration sites. He noted that he would concentrate on the results from the CEUS SSC study, which incorporates SSC uncertainty but does not address ground motion uncertainty. For each demonstration site, he showed hazard results at PGA and 1 Hz and discussed the contributions to hazard for the dominant seismic sources. He also showed the mean and fractile hazard curves and described sensitivity to branches of the master logic tree, focusing on M_{max} and recurrence for the dominant sources.

Dr. Toro stated that for all sites there is moderate sensitivity to choice of smoothing approach (i.e., kernel or variable a and b) and to selection of M_{max} values. He believes that in areas having higher levels of seismicity (e.g., many low-magnitude events), the two smoothing approaches are in better agreement; however, this observation needs to be tested further. Dr. Coppersmith noted that areas having higher levels of seismicity tend to have lower uncertainty in the recurrence parameters and, hence lower sensitivity to most alternative input parameters. These observations apply to the Savannah, Manchester, Central Illinois, Topeka, and Chattanooga sites. The hazard results for the two sites in regions of lower seismicity, Houston and Jackson, have more pronounced differences in sensitivity between PGA and 1 Hz hazard curves. For both sites there is a moderately high sensitivity to the M_{max} of the Gulf of Mexico source zone and to choice of smoothing parameter. Dr. Toro noted that these differences can be at least partially attributed to the low seismicity (fewer data points) in these regions. Another potential contributor to these differences is the use of the Gulf of Mexico attenuation equations for local zones and the Midcontinent attenuation equations for distant zones.

Workshop participants discussed whether or not to keep all of the branches of the logic tree used for the initial hazard calculations, given the apparent low sensitivity of many branches. Advantages include the relative ease of making future changes to update the models; disadvantages include longer computational time. Several individuals noted that results will vary by site. The general preference of the group was to keep all of the branches as the study moves forward, since this will serve to demonstrate that all alternative hypotheses have been considered. Although the CEUS SSC project is applicable to the entire CEUS, its future applications will be for individual sites and it will be possible to simplify (e.g., by pruning the logic tree) for individual sites by showing that there is no sensitivity to more distant sources in the model.

Following a lunch break, Dr. Coppersmith showed a slide with a list of additional feedback items needed, based on the discussions at the workshop, as follows:

- the hazard significance of all logic tree branches, at all logic tree nodes, at all seven demonstration sites;
- additional evaluation of predicted versus observed seismicity for the entire CEUS and all seismotectonic zones;
- differences in earthquake recurrence related to smoothing approach and alternative zone boundaries; and
- the issue of a migrating RLME (e.g., the Meers fault versus another structure within the OKA source region).

Dr. Coppersmith indicated that these items would be addressed by the TI team during an upcoming telephone conference call. Workshop participants discussed these and related topics, including the zoneless model concept (smoothing of seismicity used in place of defined zone boundaries); separating large-magnitude events within the RLME sources from events in the surrounding host zones; offshore earthquakes in the Gulf region; and appropriate truncation of M_{max} distributions.

Dr. McGuire gave the next talk, titled "Quantifying the Precision of Seismic Hazard Results in the CEUS." The purpose of the analysis described in the talk was to derive quantitative estimates of how seismic hazard results might change if studies were repeated by different researchers using the same basic information. Dr. McGuire began by listing many general sources of imprecision, which include random error and statistical variation, overconfidence in estimating uncertainties, unpredictability, expert disagreement, and the use of approximations. Then he listed the hazard studies that provided data used to quantify levels of precision of seismic hazard results. Data on SSC was obtained from the 1989 EPRI-SOG study, the PEGASOS project that evaluated seismic hazard for nuclear power plant sites in Switzerland, and recent characterizations of the Charleston and New Madrid seismic sources.

Dr. McGuire explained the formula he used for combining sources of imprecision. He showed hazard results obtained from the PEGASOS project, including COV of mean hazard from SSC expert teams. Turning to the 1989 EPRI-SOG project, he showed COV of hazard at various levels for each of the seven demonstration sites used for the CEUS SSC project. He then provided a summary of uncertainties for the Charleston source by showing logic tree alternatives and weights. He also described the mean and variance of hazard when weights on models are variable (depending on who is making the interpretation) and how COV can be calculated for various weighted alternatives. Similar analyses were shown for the New Madrid source.

Turning to the ground motion and site response components of seismic hazard analysis, Dr. McGuire showed the relevant hazard results from the PEGASOS and 2004 EPRI Ground Motion studies. Next he used the data from the 2004 EPRI study to assess the COV of hazard versus hazard results at each of the seven demonstration sites. He noted that there is a tendency to get much lower COV from seismic source and ground motion models, relative to site response. He then listed several conclusions:

- There is less uncertainty in site response than other components of hazard.
- The source parameter contribution is smaller for area sources than RLME sources.
- For ground motion equations, area sources have a higher COV than RLME sources.

Dr. McGuire showed a plot of these results, which indicate that a minimum estimate of uncertainty in mean hazard varies between a COV of mean hazard of 0.2 to a COV of mean hazard of 0.4 for an annual frequency of exceedance of 1×10^{-4} to 1×10^{-6}, respectively. Dr. McGuire stated that an overall level of precision in mean hazard estimates would be a COV of 0.25 in annual frequency, which corresponds to a precision in ground motion of +/–8%. He said that to apply this knowledge going forward, this method of quantification would give confidence in levels of mean hazard and how much they could change with additional analyses, which reflects on how well the hazard is understood.

Dr. Coppersmith followed this presentation with the final talk of the workshop. In this talk, titled "Path Forward," he identified short-term activities to occur within the following few weeks, including meetings between the TI team and staff and preparation and distribution of documentation for Workshop 3. He then showed key dates and activities for the remainder of the calendar year, including delivery of new data sets of reprocessed gravity and magnetic field data and an updated world stress map. The preliminary SSC model will be completed by the end of February 2010, and discussed in a briefing with the PPRP in mid-March. The final SSC model is to be completed at the end of April 2010 and the draft report by the end of July 2010. The final project report will be delivered at the end of December 2010. The group discussed the schedules for the review of CEUS SSC project components by the NRC and USGS staff. Mr. Salomone will work with the NRC and the USGS to ensure the process goes smoothly.

Concluding remarks were made by Mr. Salomone, who noted that Workshop 3 was the last formal workshop for the project. For this reason he wanted to provide an engineering perspective and review the larger project context by looking at industry and government use of what will be developed for this project. He reviewed the following general guiding principles on which the project is based:

- Managing the seismic issue is critical to control cost and delays for critical mission nuclear facilities.
- Having a stable, consistent, and defensible seismic design spectrum throughout the design phase of critical mission nuclear facilities is essential.
- Accomplishing more for less with reduced risk through standardization and partnering is important to advance science and the state of practice.

Mr. Salomone showed a flow chart titled "Disciplined, Systematic Approach to Seismic Safety." Key steps in the disciplined, systematic approach to seismic safety included:

1. Define scope of work as per regulatory and owner guidance documents.
2. Analyze seismic hazards by performing PSHAs using the CEUS SSC model and available attenuation models from studies such as the EPRI 2004/2006 CEUS Ground Motion and the Next Generation of Ground Motion Attenuation Models —East (in development). .
3. Develop controls through installation of strong motion seismic monitoring instrumentation and settlement monitoring instrumentation.
4. Perform work by designing, building, and operating facilities.
5. Obtain feedback from regulatory oversight and technical exchanges using qualified consultants and expert panel members; modify surface spectrum as required.

Mr. Salomone stated that the CEUS SSC project is part of an initial step to analyze hazards and will ultimately be used for facility design. He cautioned that factors used for increased conservatism should be applied to the design spectrum used by structural engineers and not the geologically, seismologically derived spectrum used by geotechnical engineers when performing soil response analyses.

Mr. Salomone finished by thanking Mr. Rahn for the hospitality of EPRI, and the workshop participants for their contributions to the CEUS SSC project.