Attachment 3

COLA Revision 5 Highlighted Pages for Subsection 2.5.2 RAIs

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2.5.2 VIBRATORY GROUND MOTION

PTN COL 2.5-2 This subsection provides a detailed description of the vibratory ground motion assessment for the Units 6 & 7 site and demonstrates compliance with 10 CFR 100.23(c). This assessment uses the guidance from RG 1.208. RG 1.208 incorporates developments in ground motion estimation models; updated models for seismic sources; methods for determining site response; and new methods for defining a site-specific, performance-based earthquake ground motion that satisfy the requirements of 10 CFR 100.23. Identification and characterization of seismic sources lead to the determination of safe shutdown earthquake (SSE) ground motion. This subsection develops the site-specific ground motion response spectrum (GMRS) characterized by horizontal and vertical response spectra determined as free-field motions on the ground surface using performance-based procedures.

The GMRS represents the first part in development of an SSE for a site as a characterization of the regional and local seismic hazard. The GMRS is used to determine the adequacy of the certified seismic design response spectra (CSDRS) for the DCD (RG 1.208). The CSDRS is the SSE ground motion for the site, the vibratory ground motion for which certain structures, systems, and components are designed to remain functional, pursuant to Appendix S to 10 CFR Part 50.

The starting point for the GMRS assessment is the probabilistic seismic hazard analysis (PSHA) conducted by the Electric Power Research Institute (EPRI) for the seismicity owners group (SOG). The EPRI-SOG seismic hazard study is based on the evaluation of seismicity, seismic source models, and ground motion attenuation relationships (Reference 245).

Subsection 2.5.2.1 documents the review and update of the available EPRI earthquake catalog. The earthquake data are reviewed and used to update the EPRI earthquake catalog in Phase 1 of the seismicity update. A Phase 2 catalog of earthquakes is completed and used as a supplement to the EPRI earthquake catalog for the large, frequent, but distant earthquakes of the Caribbean region.

Subsections 2.5.2.2 through 2.5.2.4 address the new information on seismic source models and ground motion characterizations that relates to the 1989 EPRI seismic hazard model, the Cuba area, and the North America-Caribbean plate boundary region. The guidelines outlined in RG 1.208 are discussed in

Subsection 2.5.2.4 and are conducted to perform an updated PSHA for the Units 6 & 7 site. The results of this updated PSHA are used to develop uniform hazard response spectra (UHRS) and to identify controlling earthquakes.

Subsection 2.5.2.5 summarizes information about the seismic wave transmission characteristics of the site with to more detailed discussion of all engineering aspects of the subsurface in Subsection 2.5.4.

Subsection 2.5.2.6 describes development of the site-specific horizontal GMRS for the site following RG 1.208, which provides guidance for implementation of the risk-informed/performance-based approach. Site-specific horizontal ground motion amplification factors are developed incorporating uncertainties in site-specific estimates of subsurface soil and rock properties. These amplification factors are then used to scale the hard rock UHRS spectra to develop UHRS at the ground surface accounting for effects of the site-specific geologic/soil column on seismic wave transmission using Approach 2A of NUREG/CR-6728 (Reference 308). Note that the term "hard rock" is used throughout the remainder of this document to designate rock properties used by EPRI (Reference 242) as the basis for development of updated ground motion prediction equations for the central and eastern United States (CEUS) (Reference 242). Subsection 2.5.2.6 also describes vertical GMRS developed by scaling the horizontal GMRS by a frequency-dependent vertical-to-horizontal (V/H) factor.

2.5.2.1 Seismicity and Earthquake Catalog

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PTN COL 2.5-2

The seismic hazard analysis conducted by EPRI (Reference 245) relies, in part, on an analysis of historical seismicity in the CEUS to estimate seismicity parameters (rates of seismic activity, Gutenberg-Richter b-value, and maximum magnitude) for individual seismic sources. The historical earthquake catalog used in the EPRI seismic hazard analysis was complete through 1984.

Given the location of the Units 6 & 7 site at the southeast edge of the EPRI-SOG seismic hazard study region, the earthquake data for the site region for all time through mid-February 2008 were reviewed and used to update the EPRI earthquake catalog. These earthquakes were cataloged in Phase 1 of the seismicity update (Subsection 2.5.2.1.2). It was also recognized that there was some potential for a significant contribution to seismic hazard at the site from the large, frequent, but distant earthquakes of the Caribbean region.

The EPRI seismic hazard study did not incorporate contributions to the seismic hazard from sources in the Caribbean region and in the Gulf of Mexico except along the immediate Gulf coast. Therefore, special attention in the update of the EPRI earthquake catalog was given to earthquakes throughout the Gulf of Mexico and the Caribbean region. A Phase 2 catalog of earthquakes was completed as a supplement to the EPRI earthquake catalog for the region for moment magnitude (M_w) 3.0 and larger earthquakes occurring in the Caribbean south of the Phase 1 catalog coverage (Subsection 2.5.2.1.3).

2.5.2.1.1 1988 EPRI Regional Earthquake Catalog

Many seismic networks record earthquakes in the CEUS. An effort was made during the EPRI seismic hazard study to combine available data on historical earthquakes and to develop a homogeneous earthquake catalog that contained all recorded earthquakes for the region. “Homogeneous” means that estimates of body-wave magnitude (m_b) for all earthquakes are consistent, duplicate earthquakes have been removed, non-earthquakes (e.g., mine blasts and sonic booms) have been eliminated, and significant events in the historical record have not been missed. The EPRI earthquake catalog (Reference 246) is the basic input data source for assessing seismicity parameters such as earthquake recurrence rates and maximum magnitude.

2.5.2.1.2 Updated Seismicity Data in the Phase 1 Investigation Region

{The Phase 1 earthquake catalog used in the study region (Figure 2.5.2-201) is an updated catalog to determine whether regional earthquake patterns and seismicity parameters developed from the EPRI earthquake catalog (Reference 246) remained unchanged.} RG 1.206 specifies that earthquakes of modified Mercalli intensity (MMI) greater than or equal to IV or magnitude greater than or equal to 3.0 “that have been reported within 200 miles (320 kilometers) of the site” should be listed. The location of the Units 6 & 7 site was taken as 25.4241° N and 80.3332° W. In updating the EPRI earthquake catalog, a latitude-longitude window of 22° to 35° N, 100° to 65° W was used. This large window, called the Phase 1 seismicity investigation region, incorporates the 200-mile (320-kilometer) radius “site region” and all seismic sources north of the Caribbean contributing significantly to earthquake hazard at the site. SOF 2.5.2-1

Table 2.5.2-201 lists the earthquakes for the Phase 1 investigation region of uniform magnitude (Rmb) ≥ 3.0 or maximum intensity value (I_0) ≥ IV.

Thirty-four regional earthquake catalogs were considered in the development of the Phase 1 earthquake catalog. The earthquake catalogs used for this initial update are listed below in the order of their preference for duplicate events removal and earthquake parameter characterization:

- Electric Power Research Institute (Reference 246)
- Updated Engdahl (NENG) (Reference 249)
- Engdahl and Villasenor (EV02) (Reference 250)
- Villasenor et al. (ISSv) (Reference 333)
- Villasenor and Engdahl (VE07) (Reference 332)
- Perez (PEREZ) (Reference 298)
- Wysession et al. (Reference 338)
- Cuba Catalog (CUBA) (Reference 205)
- Southeastern U.S. Seismic Network (SEUSN) (Reference 341)
- Frohlich and Davis (FD02) (Reference 253)
- Missouri-Tennessee Regional Data, 1974-1994 (SLU) (Reference 307)
- Southeast Blacksburg Catalog (BLA) (Reference 307)
- Tennessee Earthquake Information Center (TEIC) (Reference 307)
- Decade of North America Geology (DNA) (Reference 307)
- Central U.S. Catalog (OWN) (Reference 307)
- NEIC Preliminary Determination of Epicenters (PDE, PDE-W, PDE-Q) (Reference 292)
- Panamerican Institute of Geography and History (IPGH) (Reference 307)
- National Geophysical Data Center USGS “PDE” Catalog (Reference 307)
- Advanced National Seismic System (ANSS) (Reference 204)

- International Seismological Centre (ISC) (Reference 265)
- Puerto Rico Seismic Network (PRSN) (Reference 305)
- Middle America Seismograph Consortium (MIDAS) (Reference 284)
- Regional Data from Trinidad (TRN) (Reference 307)
- Earthquake History of the U.S. (EQH) (Reference 307)
- NEIC Significant U.S. Earthquakes (USHIS) (Reference 340)
- Historical U.S., 1568-1984 (STO) (Reference 307)
- U.S. Network Catalog (USN) (Reference 307)
- Gutenberg and Richter (G-R) (Reference 307)
- NEIC Eastern, Central, and Mountain States of U.S. (SRA) (Reference 288)
- NEIC Mexico, Central America and Caribbean, 1900-1979 (MCAC) (Reference 289)
- Regional Catalog for the Caribbean Sea (CARIB) (Reference 307)
- Mexico Composite Catalog (Reference 307)
- Incorporated Research Institutions for Seismology (IRIS) (Reference 264)
- Utsu Catalog (UTS) (Reference 307)

No events were found in either the MCAC (Reference 289) or VE07 (Reference 332) catalogs. In the event of duplicate entries for a given earthquake in the remaining 32 catalogs, earthquake location and size were selected with the following order of preference: first the EPRI earthquake catalog, then special studies of regional earthquakes, then routine listings from regional catalogs, and finally routine listings from global catalogs.

For the purpose of developing earthquake recurrence statistics in the Phase 1 investigation region, it was necessary to eliminate dependent events (that is, foreshocks, aftershocks, and secondary events of an apparent seismicity cluster). The EPRI earthquake catalog distinguishes MAIN (independent) events from non-MAIN (dependent) events. The few events that were judged to be dependent

events, based on the EPRI criteria for MAIN vs. non-MAIN and on apparent spatial and temporal similarity between events, were removed from the Phase 1 update of the EPRI earthquake catalog. The remaining events in the Phase 1 investigation region were assessed to be equivalent to EPRI MAIN events.

2.5.2.1.2.1 Assessment of Best Estimate and Uniform Magnitude

For the EPRI-SOG methodology, two scales of magnitudes are required for each event in the catalog: (a) best, or expected, estimate of body-wave magnitude (E[mb], also referred to as Emb in the 1988 EPRI study; Reference 246); and (b) uniform magnitude (mb*, also referred to as Rmb in the 1988 EPRI study; Reference 246). These magnitudes were applied in the Phase 1 earthquake catalog where the EPRI earthquake catalog was considered in the development of the reevaluated earthquake catalog.

Best Estimate Magnitude Emb

Various magnitude scales may be available for a given event. Each available magnitude was considered in the evaluation of Emb for that event. If a body-wave magnitude (mb) was available, it was adopted directly. Other magnitudes were converted to the best estimate magnitude Emb using the Equation 4-1 and Table 4-1 in the 1988 EPRI study (Reference 246):

$$Emb = 0.253 + 0.907 \cdot Md \qquad \text{Equation 2.5.2-1}$$

$$Emb = 0.655 + 0.812 \cdot ML \qquad \text{Equation 2.5.2-2}$$

$$Emb = 2.302 + 0.618 \cdot MS \qquad \text{Equation 2.5.2-3}$$

where, Md is duration (or coda) magnitude, ML is "local" magnitude, and MS is surface-wave magnitude.

If no explicit magnitudes are available for an event, an available I0 was converted to Emb, using a relationship from Table 4-1 in the 1988 EPRI study (Reference 246):

$$Emb = 0.709 + 0.599 \cdot I_0 \qquad \text{Equation 2.5.2-4}$$

The EPRI PSHA study expressed maximum magnitude (Mmax) values in terms of m_b, whereas most modern seismic hazard analyses describe Mmax in terms of moment magnitude (M_w). To provide a consistent comparison between magnitude scales, m_b was related to M_w using the arithmetic average of three equations, or their inversions, presented by Atkinson and Boore (Reference 210), Frankel et al.

(Reference 252), and EPRI (Reference 244). Throughout the discussion in Subsections 2.5.2.2 and 2.5.2.3, the largest values of Mmax distributions assigned by the Earth Science Teams (ESTs) (Reference 247) to seismic sources are presented for both magnitude scales (m_b and M_w). {For example, EPRI m_b values of Mmax are followed by the equivalent M_w value. Conversion values from m_b to M_w and M_w to m_b are provided in Table 2.5.2-202.} Body-wave magnitudes converted from moment magnitudes in this fashion were considered the best estimate magnitude Emb. For each event, the final Emb was taken as the largest best estimate magnitude Emb. SOF 2.5.2-4

Uniform Magnitude Rmb

The EPRI-SOG seismic hazard methodology modifies the Emb values to develop a uniform magnitude (Rmb), m_b^*, to assess an unbiased estimate of seismicity recurrence parameters. EPRI Equation 4-2 (Reference 246) indicates that the equation from which m_b^* is estimated from $E[m_b]$ and the standard deviation of m_b, σ_{mb}, (referred to as Smb in the 1988 EPRI study; Reference 246) is:

$$m_b^* = E[m_b] + (1/2) \cdot \ln(10) \cdot b \cdot \sigma^2_{mb} \quad \text{Equation 2.5.2-5}$$

where,

$b = 1.0$

Based on an examination of the EPRI-SOG catalog, particularly σ_{mb} (Smb) values listed as related to the various size measures from which they were determined, values for σ_{mb} (Smb) were estimated for each earthquake in the updated catalog, and m_b^* (Rmb) values were calculated (Equation 2.5.2-5) for each event added to the updated earthquake catalog.

{The result of the above process was a homogeneous earthquake update of the EPRI earthquake catalog (Reference 246) for earthquakes occurring within the Phase 1 seismicity investigation region (Table 2.5.2-201).} For the purpose of earthquake recurrence analysis, all events added for the update are assumed to be independent events. SOF 2.5.2-1

2.5.2.1.3 Caribbean Seismicity Data in the Phase 2 Investigation Region

Occurrence of large earthquakes in the region south of the Phase 1 coverage suggested that additional examination of earthquakes in the Caribbean region was needed (Figure 2.5.2-201). The original EPRI-SOG analysis indicated that earthquake recurrence parameters had not been evaluated for the Caribbean

region. The occurrence of recent moderate to large earthquakes in the Caribbean region indicated the potential for a significant contribution to seismic hazard at the site from sources in this region. This required a careful evaluation of Caribbean seismicity, both before and after the development of the EPRI earthquake catalog.

In order to investigate the potential of the Caribbean region to contribute to the seismic hazard of the site, it was necessary to consider a larger area of investigation. {A latitude-longitude window of 15° to 24° N, 100° to 65° W was used to create a new catalog supplement to the EPRI earthquake catalog. This large window, called the Phase 2 seismicity investigation region, incorporates all events with $M_w \geq 3.0$ and all Caribbean seismic sources that would be expected to contribute significantly to the earthquake hazard of the site.} Table 2.5.2-203 lists the earthquakes for the Phase 2 investigation region for the larger events of moment magnitude $M_w \geq 6.0$. The Phase 2 earthquake catalog combined with the Phase 1 earthquake catalog described in Subsection 2.5.2.1.2, allows an improved characterization of the seismicity within the project seismicity investigation window. SOF 2.5.2-2

There are many earthquake catalogs covering the Phase 2 seismicity investigation region, but no single published catalog includes everything for assessing earthquake occurrence. Thus, several regional and global catalogs were combined to make a new catalog supplement. These catalogs cover different time, space, and magnitude ranges with varying accuracy.

For instance, the magnitudes of earthquakes in the Cuba catalog (Reference 205) have been estimated using various methods from historical macroseismic data (that is, based on non-instrumental felt and damage effects), instrumental data from international agencies, and instrumental data from the Cuban local network. The majority of earthquakes in the Cuba catalog have an estimate of intensity-based magnitude. In these cases, the magnitude scale, M_I, of Garcia et al. (Reference 254) is used, fitting the isoseismals (contour lines of equal intensity). For earthquakes recorded by the Cuban seismographic network, the surface-wave magnitudes (M_S), which is intended to be equivalent to the intensity-based magnitude (M_I), are obtained by the Alvarez et al. (Reference 237) regression relationships. The remaining magnitudes in the Cuba catalog are adopted from international agency compilations.

Note that most earthquakes in the Cuba catalog (Reference 205), whose magnitudes have been obtained from macroseismic data, do not have well-constrained locations and depend on inherently subjective information. Comparison of magnitude scales in the Cuba catalog with more recent

earthquakes recorded by other seismological agencies shows that the M_l for the earthquakes reported in the Cuba catalog often appear to have been overestimated.

Therefore, reliance on reports of earthquake effects in the Cuba area has apparently resulted in an overestimate of earthquake size in some cases. Nevertheless, this Cuba Catalog (Reference 205) data is the best available and, in spite of its likely conservatism, was used to prepare a dataset for Cuba characterized by only one magnitude entry for each event (Subsection 2.5.2.1.3.1).

Besides the Cuba catalog (Reference 205), 22 significant regional earthquake catalogs were considered in the development of the Phase 2 earthquake catalog within the Phase 2 investigation region. The earthquake catalogs used for this phase of the update are listed below in the order of their preference for duplicate events removal and earthquake parameter characterization:

- Updated Engdahl (NENG) (Reference 249)
- Villasenor et al., 1997 (ISSv) (Reference 333)
- Villasenor and Engdahl, 2007 (VE07) (Reference 332)
- Engdahl and Villasenor, 2002 (EV02) (Reference 250)
- Perez (PEREZ) (Reference 298)
- Puerto Rico Seismic Network (PRSN) (Reference 305)
- International Seismological Centre (ISC) (Reference 265)
- Advanced National Seismic System (ANSS) (Reference 204)
- NEIC Preliminary Determination of Epicenters (PDE, PDE-W, PDE-Q) (Reference 292)
- National Geophysical Data Center USGS “PDE” Catalog (Reference 307)
- NEIC Mexico, Central America and Caribbean, 1900-1979 (MCAC) (Reference 289)
- NEIC Significant Worldwide Earthquakes (NOAA) (Reference 307)

- Cuba Catalog (CUBA) (Reference 205)
- Regional Catalog for the Caribbean Sea (CARIB) (Reference 307)
- Panamerican Institute of Geography and History (IPGH) (Reference 307)
- Middle America Seismograph Consortium (MIDAS) (Reference 284)
- Gutenberg and Richter (G-R) (Reference 307)
- Mexico Composite Catalog (Reference 307)
- Decade of North America Geology (DNA) (Reference 307)
- Earthquake History of the U.S. (EQH) (Reference 307)
- Regional Data from Trinidad (TRN) (Reference 307)
- U.S. Network Catalog (USN) (Reference 307)
- Wysession et al., 1995 (Reference 338)

Duplicate entries from these 23 catalogs were removed under a process that included selection of preferred entries for location and size parameters based on a regionally defined preference order for Phase 2 of the seismicity update to yield an initial earthquake catalog. As implied by the above preference order, the earthquake location and size were selected based on seismicity data from local or international seismic networks with the following order of preference: first special studies of local earthquake catalogs, then routine listings from regional catalogs, and finally routine listing from global catalogs.

After an initial uniform earthquake catalog was compiled (Subsection 2.5.2.1.3.1), foreshocks and aftershocks were eliminated using the 1974 time-distance window method of Gardner and Knopoff (Reference 256). In this method dependent events (classified as those that fall within specified time and space intervals around the mainshock and that are of smaller magnitudes) are eliminated to obtain a data set of mainshocks that is assumed to show a Poisson distribution in time.

The Gardner-Knopoff (Reference 256) method is proposed as an appropriate technique for removing dependent events for an earthquake catalog such as the Phase 2 catalog, which has variable quality station coverage in different regions

and over different time periods. That is, the method does not depend upon details of small magnitude earthquake completeness to help identify mainshocks (Reference 314).

Dependent or "related" events of a mainshock are identified within time-distance windows as a function of the time, location, and magnitude of the mainshock. The first earthquake in the catalog is declared provisionally to be a mainshock event, and then all equal or smaller magnitude related events are identified and eliminated as aftershocks from the catalog using the specified time-distance window parameters. The next earthquake in the rest of the catalog is then declared to be the next provisional mainshock event, and this cluster removal procedure is repeated, this time considering related events both before and after this mainshock. Equal or smaller magnitude related events occurring before the mainshock are marked for deletion as foreshocks—possibly including a previously assumed mainshock, that may now be identified as a foreshock of the current provisional mainshock—and equal or smaller magnitude related events occurring after the mainshock are marked for deletion as aftershocks. This procedure is repeated throughout the compilation of the entire Phase 2 earthquake catalog.

A listing of values selected for the shape of the time-distance envelope is given in Table 1 of Gardner and Knopoff (Reference 256). There is an upper-bound (enveloping) linear relationship between time and magnitude, such that all aftershocks occur at times less than the envelope value. There is also an upper-bound linear relationship between distance and magnitude that is used in a similar way to the time bounds. The original table proposed by Gardner and Knopoff (Reference 256), which gives discrete time-distance envelope values, is generalized for all magnitudes by interpolating it in the form of the following smooth linear relationships:

$$\text{Distance (km)} = 10^{(0.1238M + 0.983)} \qquad \text{Equation 2.5.2-6}$$

$$\text{Time (days)} = 10^{(0.032M + 2.7389)} \text{ for } M \geq 6.5 \qquad \text{Equation 2.5.2-7}$$

$$= 10^{(0.5409M - 0.547)} \text{ for } M < 6.5$$

where, "M" is assumed to be equivalent to M_w. As an example, any earthquake within 918 days after an $M_w = 7.0$ earthquake and with an epicenter location within about 71 kilometers of the epicenter of the $M_w = 7.0$ mainshock, is identified as an aftershock. For $M_w \geq 6.5$, the slope of the time window is less than $M_w < 6.5$ to conform with improved estimates of the shape of the envelope given by Gardner and Knopoff (Reference 256).

Figure 2.5.2-201 shows the Units 6 & 7 site and its associated site region, the defined latitude-longitude windows, both the original EPRI earthquake catalog and updated seismicity data for the Phase 1 and Phase 2 investigation regions. These earthquake catalogs are used later in Subsection 2.5.2.4 to develop earthquake recurrence parameters for the Gulf of Mexico and Caribbean region for use in the PSHA of the site.

2.5.2.1.3.1 Uniform Magnitude M_w

{In this subsection, the rationale for selecting moment magnitude (M_w) as the uniform magnitude scale for the Phase 2 earthquake catalog is discussed and the magnitude conversion process adopted for all events in the Cuba and Caribbean Phase 2 earthquake catalog is described in detail. PTN RAI 02.05.02-5 SOF 2.5.2-5

Rationale for Selecting M_w as the Uniform Magnitude Scale for the Phase 2 Catalog

Seismologists performing conventional probabilistic seismic hazard analyses, as well as development of ground motion prediction equations (References 300 and 344), prefer the use of M_w over other magnitude scales, including m_b scale, because it is a more direct indication of the seismic energy associated with an earthquake, particularly for both shallow and deep focus earthquakes with large fault dimensions and/or complex rupture mechanisms that occur in the Caribbean. The m_b magnitude scale saturates, or is progressively insensitive to, energy release, beginning with magnitudes greater than approximately 5.0 due to the difference in the period and the seismic-wave type used to determine the magnitude size. While the magnitudes of earthquakes within the CEUS region have generally and traditionally been adequately represented by the m_b scale, the largest events in the Caribbean are not. This rationale for selecting moment magnitude was the basis for its use in developing the Phase 2 earthquake catalog. LDP-CS564 LDP-CS564

Also, the update of the Phase 1 earthquake catalog, as discussed in Subsection 2.5.2.1.2, was constrained to maintain the magnitude scale in m_b because both the EPRI-SOG seismicity catalog and recurrence characterization of the EPRI-SOG seismic sources use the m_b scale.

NUREG-0800 Section 2.5.2 and RG 1.206 specify that the earthquake catalog should include all earthquakes having Modified Mercalli Intensity (MMI) greater than or equal to IV, or magnitude greater than or equal to 3.0 that have been reported within 320 kilometers (200 miles) of the site. Large earthquakes outside LDP-CS564

PTN RAI 02.05.02-5

of this area that would impact the SSE (in NUREG-0800) or the GMRS (in RG 1.206) should be reported. The Phase 1 and Phase 2 catalogs were developed to meet these requirements. The magnitude scale is not explicitly specified in these requirements, although both documents later state that "magnitude designations such as m_b, M_L, M_s, M_w should be identified." There is no specification of the magnitude scale for the earthquake catalog given in RG 1.208.

The magnitude conversion relations between the moment magnitude scale and many other scales, such as m_b scale, show that the magnitudes less than about 4.5 (very short fault lengths) are assumed to be numerically equivalent to M_w and that the conversion relations are nonlinear at large magnitude values to reflect the saturation of some magnitude scales, specifically m_b scale (Reference 346). Therefore, in the development of the Phase 2 catalog, all small earthquakes of any magnitude scale less than 4.5 were assumed to be numerically equivalent to M_w. As a result of this assumption for small events, the selected threshold magnitude scale $M_w \geq 3.0$ for the Phase 2 earthquake catalog and m_b (or (E)m_b) ≥ 3.0 for the Phase 1 earthquake catalog presents no inconsistency in terms of minimum size or minimum seismic energy of a given earthquake considered in the two catalogs. Therefore, under the process used to develop moment magnitudes for the Phase 2 catalog, all earthquakes of magnitude 3.0 and larger, regardless of characterization as moment magnitude or body-wave magnitude, are included in both Phase 1 and Phase 2 earthquake catalogs, and there is no impact on the number of earthquakes in the two earthquake catalogs associated with the different magnitude scales used in the two earthquake catalogs.

Magnitude Conversion Process for Earthquakes in the Caribbean Region

The differences that exist among published seismotectonic region-specific magnitude conversion relations make the selection of appropriate relations for a given region important and, if such relations are not available, difficult. Seismic network operational histories are such that catalogs of events in a given region contain earthquakes located with different location programs. These programs use different station configurations and different crustal-velocity models with magnitudes calculated using different calibration. Therefore, conversions of diverse best estimates of magnitudes determined in different regions to a given uniform magnitude scale may show notable differences, depending on tectonic setting (Reference 240).

In contrast to the CEUS tectonic environment considered for the Phase 1 earthquake catalog, the Caribbean region with its (1) different tectonic environments (e.g., plate boundary and near plate boundary shallow crustal faults

and subduction zones), (2) different magnitude scales, and (3) different seismic network instrumentation and operational histories, required consideration of different global or regional magnitude conversion relationships for the Phase 2 earthquake catalog development. PTN RAI 02.05.02-5

To contrast the nature of earthquakes from the Caribbean region to the CEUS region, a magnitude conversion process was developed to consider the various magnitude scales used in the original source catalogs considered in the development of the Phase 2 earthquake catalog, and these various magnitude scales were converted to M_w.

Among the various earthquake source catalogs used for compiling the Phase 2 catalog, there were 19 different magnitude types that needed to be converted to moment magnitude. These different magnitude scale conversions are discussed further below based on the following simplified process. First, magnitudes of any type less than 4.5, with reference to the Heaton et al. (Reference 346) correlation plot described below, were assumed to be equivalent to M_w directly. For magnitudes of any type of 4.5 and larger, the following simplified process was followed:

- Moment magnitudes were already moment magnitudes, so no conversion was necessary. LDP-CS564
- Surface-wave magnitudes M_s were converted to M_w considering the Ekstrom and Dziewonski relations (Reference 240) and the Kanamori relation (Reference 269).
- Body-wave magnitudes m_b were converted to M_s considering the Garcia et al. relation (Reference 254) and then the above process of conversion from M_s to M_w was followed.
- Intensity-based magnitudes in the Cuba catalog were considered equivalent to M_s magnitudes (Reference 254) and then the above process of conversion from M_s to M_w was followed.
- All other magnitude types were considered equivalent to m_b and then the above process to convert from m_b to M_s to M_w was followed.

The Heaton et al. (Reference 346) magnitude correlations, following similar work by Kanamori (Reference 347), plot various magnitude scales relative to M_w for a

seismotectonic setting more similar to the Caribbean than the CEUS region (e.g., western U.S. region or other active plate boundary regions), allowing conversion of Caribbean earthquake magnitudes in other scales into moment magnitude. These magnitude-scale plots graphically show relationships between the moment magnitude scale and several other magnitude scales, applicable magnitude ranges, and how they are nonlinear to reflect the saturation of some of the magnitude scales. PTN RAI 02.05.02-5 LDP-CS564

Following is a detailed summary of the approach that was used to provide specific magnitude scale conversions to estimate M_w for the Phase 2 earthquake catalog.

Specific Magnitude Scales Used in the Phase 2 Earthquake Catalog

The Phase 2 earthquake catalog developed for the Caribbean region contains 19 different measures of size for earthquakes that have occurred in notably different tectonic regions as compared to the CEUS region.

- Moment magnitudes (M_w)

The moment magnitude scale, which provides an estimation of total energy released in an earthquake, was the preferred magnitude scale in the Caribbean Phase 2 catalog under the rationale given above. Therefore, for all earthquakes in Phase 2 earthquake catalog that were originally reported in the M_w magnitude scale, these M_w values were directly included in the catalog.

- Surface-wave magnitudes (M_s)

The surface-wave magnitude (M_s) scale is commonly used for shallow events larger than M_s 5.0 (References 347 and 350) which, by definition, are earthquakes where surface waves may have been generated. Since the surface-wave magnitude gives the poorest results for small earthquakes or those deep or at intermediate depth, there are relatively few earthquakes of this type of magnitude scale in the Phase 2 catalog. For those reported earthquakes with M_s less than 4.5, these M_s magnitude scales were considered to be numerically equivalent to M_w. For M_s values equal to or greater than 4.5, the 1988 global surface-wave magnitude to average seismic moment (M_o) conversion relations of Ekstrom and Dziewonski (Reference 240) and then the seismic moment-to-moment magnitude conversion relation of Kanamori (Reference 269) was used to convert surface-wave magnitudes to M_w in the Phase 2 earthquake catalog development.

PTN RAI 02.05.02-5

- Body-wave magnitudes (m_b)

The Heaton et al. (Reference 346) m_b-M_w magnitude correlation plot suggests that body-wave magnitude (m_b) less than about 4.5 are consistent with M_w, and thus, they were assumed to be numerically equivalent to M_w for the Caribbean region. This consideration is also consistent with USGS Open File Report 97-464 (Reference 350) for body-wave magnitudes in the western U.S. region.

As may also be seen in the Heaton et al. (Reference 346) magnitude correlation plot, there is an issue of saturation of the m_b scale beginning with magnitudes larger than approximately 5.0. The m_b scale stops increasing with increasing earthquake size at about magnitude 6.4 corresponding to a moment magnitude of approximately 7.5. Therefore, for m_b magnitudes of 4.5 and larger the magnitude conversion relation for m_b to M_s from the Garcia et al. study (Reference 254) was used, and then the M_s to M_w scaling, discussed above, was applied for these larger m_b values in the Caribbean Phase 2 catalog.

- Intensity-based magnitudes (M_I and M_k) in the Cuba catalog

The majority of earthquakes in the Cuba catalog have an estimate of intensity-based magnitude, M_I and M_k, as discussed in the Garcia et al. study (Reference 254). Both of these magnitude types are considered to be correlated to coda or duration magnitudes [see below]. For the magnitude conversion process, where there were no region-specific magnitude conversion relations for intensity-based magnitudes, as well as none for coda- or duration-magnitudes, to M_w, these M_I and M_k magnitudes were taken as equivalent to M_w for magnitudes less than 4.5, following Heaton et al. (Reference 346), and equivalent to M_s for magnitudes 4.5 and larger, following the Garcia et al. study (Reference 254). The M_s magnitude scale values were then converted to M_w as described above.

- Local, Duration, and Coda magnitudes (M_L, M_d, DR and M_c)

The local magnitude (M_L), duration magnitude (M_d), sometimes designated “DR” or “M_D” in the National Geophysical Data Center (NGDC) database, and coda magnitude (M_c) are three types of measurements for earthquakes that are used to determine the local magnitudes and are conventionally considered equivalent. The instrumental M_c and M_d are typically reported for small and moderate magnitude earthquakes less than approximately 6.0, while it is found that M_L is also reported for larger earthquakes up to about 7.0. These three magnitude scales in the Phase 2 earthquake catalog, which are provided by different seismic networks with varying operational histories and different station calibrations, are

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comparable on average to M_w for magnitudes less than 4.5 in the Phase 2 earthquake catalog (References 346 and 350). Nuttli and Herrmann (Reference 351) report that M_L and m_b values are nearly equal in the western United States. Given the common equivalence of M_L, M_d, and M_c magnitudes and the Nuttli and Herrmann observation, these magnitudes when larger than 4.5 are considered equivalent to m_b and converted to M_w as detailed above.

- Broadband body-wave magnitudes (m_B)

There are also some earthquakes larger than 6.0 in the Phase 2 catalog that are designated broadband body-wave magnitude (m_B). The main advantage of m_B magnitude scale rather than M_s is its applicability to both shallow and deep earthquakes. These m_B magnitude-scale events in the Phase 2 catalog are considered to be equivalent to M_s over the applicable magnitude range of events between about 6.0 and 8.0 (References 346 and 347), and then converted to M_w as described above.

- Intensity-based magnitudes ($M(I_o)$), not in the Cuba catalog

These magnitudes are estimated from maximum intensity (I_o) using the Gutenberg-Richter (Reference 345) relationship, which correlates to local magnitude M_L. Therefore, these earthquakes are converted from M_L to M_w as described above.

- Equivalent local and coda-duration magnitudes (m_1, m_2, fm, xm, MA, and m_t)

The PRSN earthquake catalog, which locally collects the events in the Caribbean region, has recorded earthquakes whose magnitudes are determined using different local magnitude relations (m_1 and xm), as well as different magnitude-coda duration relations (m_2 and fm) – the xm and fm magnitudes are determined using the earthquake location program Hypoellipse (Reference 348). An event less than magnitude 3.0, excluded from the Phase 2 catalog, is reported as a type MA magnitude, attributed to PRSN – it may be expected that this small magnitude is one of or an average of the other PRSN magnitudes. Also reported in the PRSN catalog are earthquakes from the Jamaica Seismic Network (JSN), which determines average coda magnitudes (m_t) based on the regression between standard m_b and log of the signal duration (Reference 352).
As for local, duration, and coda magnitudes described above when greater than 4.5 these magnitudes are considered equivalent to m_b and are converted to M_w.

- Unspecified magnitudes (nk and MG)

Finally, there are some earthquakes in the Phase 2 catalog with unknown magnitude scale labeled "nk" or " " (e.g., the computational method was unknown and could not be determined from published sources) as well as an unspecified magnitude scale labeled "MG" (e.g., magnitudes either have been reported by the contributor without listing the type [e.g., "MG 3.5"] or have been computed using procedures which are not defined by the magnitude types routinely reported). These types of earthquakes were considered to be equivalent to m_b for small ($3 \leq M_w < 4.5$) and moderate ($4.5 \leq M_w < 6$) earthquake magnitudes in the Phase 2 catalog. Lamarre and Shah (Reference 349) have plotted the unspecified magnitude scales versus M_L for the NGDC database used in the Phase 2 earthquake catalog, and have indicated that it is very closely approximated by the M_L and m_b for earthquakes in magnitude range less than about 5.0. Taken as equivalent to m_b, these magnitudes were converted to M_w as described above. PTN RAI 02.05.02-5

Since the types of data used in determination of these magnitude scales are very different from region to region (e.g., observational errors and intrinsic variations in source properties), it is important to establish tectonically-similar regional magnitude scale correlations (Reference 347). Therefore, it should be emphasized that this magnitude conversion process was not incorporated into Phase 1 earthquake catalog that includes all events in the CEUS region with a notably different tectonic environment as compared to the Caribbean region (Reference 2.5.1).}

2.5.2.1.4 Final Earthquake Catalogs

The objective of compiling earthquake catalogs for the Units 6 & 7 site was to develop an improved characterization of seismicity for all time within the seismicity investigation region (15° to 35° N, 100° to 65° W), which is used to not only compare to the EPRI-SOG earthquake catalog, as it had been used in the development of the seismic source characterization for the EPRI-SOG seismic hazard study, but also to suggest and facilitate characterization of possible additional seismic sources to the south of the original EPRI-SOG CEUS study region.

The final earthquake catalog consists of two separate catalogs. The earthquake catalog for the Phase 1 seismicity investigation region (22° to 35° N, 100° to 65° W) is primarily the earthquakes in the EPRI-SOG catalog supplemented by earthquakes from several additional earthquake catalogs. Table 2.5.2-201 lists the earthquakes for the Phase 1 investigation region for which the events are Rmb ≥ 3.0 or intensity $I_0 \geq$ IV through mid-February 2008. The earthquake catalog for the Phase 2 seismicity investigation region (15° to 24° N, 100° to 65° W) is a

composite of several earthquake catalogs appropriate for Cuba and the Caribbean for events that have moment magnitude $M_w \geq 3.0$ for all years through mid-March 2008. Table 2.5.2-203 lists the earthquakes for the Phase 2 investigation region for the larger events of moment magnitude $M_w \geq 6.0$.

It should be noted that there is a 2-degree overlap in the Phase 1 and Phase 2 regions of the Units 6 & 7 seismicity investigation—the region between 22° N and 24° N. As elaborated later in discussions about the seismic sources, different magnitude scales were required for characterization of the EPRI-SOG sources in the northern portion of the investigation region, as compared to the Caribbean sources in the southern portion. The 2-degree overlap of the coverage of the two phases of seismicity update allowed for completeness and consistency of seismicity characterization of each subregion. In the plot of seismicity for the investigation region in Figure 2.5.2-201, the seismicity of Phase 2 is presented in the 2-degree overlay area to fully encompass Cuba seismicity.

The distribution of epicenters indicated that the largest density of earthquakes was located along the Caribbean transform fault zones. Within the updated earthquake catalog there are two moderate seismic events in the Gulf of Mexico that are significant for an updated characterization of the regional seismicity. These are (1) a possible M_w 5.1 (m_b 5.6) earthquake or a possible landslide event that occurred on February 10, 2006, offshore of the Louisiana coast within the Gulf of Mexico (Subsection 2.5.2.4.3.1.2), and (2) a M_w 5.8 (m_b 5.9) earthquake that occurred on September 10, 2006, off the Florida coast within the Gulf of Mexico (Subsection 2.5.2.4.3.1.1).

A moment-tensor source can be used to model the surface waves generated by the possible February 10, 2006, earthquake if the earthquake centroid is placed within a few miles of the earth's surface in a medium with a very low shear modulus. The explanation for the February 10 earthquake that is currently in best agreement with the observed seismic data is a gravity-driven displacement surface within a thick shallow sedimentary wedge (Reference 293).

The focal mechanism for the September 10, 2006, earthquake indicates a reverse sense of motion, and the earthquake depth is reported as 14 to 19 miles (22 to 31 kilometers) (Reference 290). This mechanism is that of an earthquake caused by tectonically driven stresses within the earth's crust.

2.5.2.1.5 Periods of Completeness for the Offshore Florida Earthquakes

The EPRI seismic hazard methodology (Reference 246) uses estimates of periods of completeness for the reporting of earthquakes as a function of magnitude. This methodology employs a matrix of probability of detection of earthquakes for an area for selected ranges of time-before-present and magnitude. The purpose of this subsection is to develop detection probability matrices for the areas in the Gulf of Mexico and off the coast of Florida where such information is not available in the original EPRI parameterization (Reference 243), but is necessary for the complete characterization of updated EPRI-SOG seismic sources (Figure 2.5.2-202). Matrices for three regions—referred to as "Gulf of Mexico," "Near Florida," and "Near Atlantic"—are used later in Subsection 2.5.2.4 to develop EPRI-consistent earthquake recurrence parameters for use in the PSHA of the site.

Gulf of Mexico

{Table 2.5.2-204 lists the 26 earthquakes within the Gulf of Mexico seismicity recurrence region, considered EPRI MAIN or independent events that were used to develop the matrix of detection probability for this area.} This matrix was prepared to be consistent with the 1988 EPRI seismic hazard methodology. Generation of the matrix of detection probability used, as a conservative guideline, the adjacent EPRI matrices of detection probability available onshore. The 1988 EPRI seismic hazard study used a detailed analysis of United States demographics and history, number, quality, and distribution of seismographic instruments to develop matrices of probability of completeness as a function of time period, gridded area, and magnitude interval. Given uneven population distributions over time and uneven deployment of seismographic networks these completeness probability matrices also vary by location. EPRI "Incompleteness Regions" 2 and 3 are closest to the Gulf of Mexico seismicity recurrence region (Reference 243, Table 5-1) — Figure 2.5.2-202. SOF 2.5.2-3

It was assumed that the probabilities of earthquake detection for the Gulf of Mexico are less than those given for onshore coastal locations for comparable time periods. The procedure followed for estimating detection probabilities for the Gulf of Mexico was, therefore, to start with an available EPRI matrix, suggesting the lowest probabilities along the shoreline—that is, EPRI Incompleteness Region 2, as it has lower detection probabilities than Incompleteness Region 3—and to assume lower probabilities of detection within the Gulf of Mexico.

{The first matrix shown in Table 2.5.2-205 is a version of the EPRI Incompleteness Region 2 matrix, modified to add additional years since 1984 (the last complete year in the 1988 EPRI earthquake catalog).} The latest bin time period of the Incompleteness Region 2 matrix (1975–1983) has detection probabilities of 1.00 for all magnitude bins. Therefore, given that detection probability would not be expected to decrease with time, additional time bins with detection probabilities of 1.00 for all magnitudes were appended to the Incompleteness Region 2. SOF 2.5.2-3

The first matrix of detection probability shown in Table 2.5.2-205 is appropriate for much of the on, or very near onshore sites of seismic activity of the Gulf of Mexico. This matrix may be used for seismicity occurring through the year 2007.

In developing the detection probability of matrix appropriate for the Gulf of Mexico region, the modified Incompleteness Region 2 matrix in Table 2.5.2-205 was qualitatively modified in consideration of the following constraints:

- For a given magnitude bin, detection probability for a given time bin would be expected to be the same or more than the detection probability of an adjacent earlier time bin. That is, the overall trend is for detection probabilities for a given magnitude interval to increase with time.
- For a given time bin, the probability of earthquake detection for a given magnitude bin would be the same or more than the detection probability for an adjacent smaller magnitude bin. That is, the overall trend is for detection probabilities for a given time interval to increase with magnitude.
- Given the lack of regional seismographic stations in the Gulf of Mexico, as well as the obvious lack of felt or damage reports in the Gulf, detection probabilities for the Gulf of Mexico are expected to be no higher for any magnitude and time bin than that corresponding to the nearest onshore location of lowest detection probabilities.
- It was assumed that after the advent of the World-Wide Standardized Seismograph Network in the mid-1960s most earthquakes of magnitude 5.5 and greater would be detectable and recorded (Reference 250).
- In general, global b-values tend to average about 0.8 to 1.2 (Table 2 of the 2002 Engdahl and Villasenor study [Reference 250] and Table 4-7 of the 1994 Johnston et al. study [Reference 268] for stable continental regions). It was assumed that a value within this range is reasonable for the Gulf of Mexico.

The time intervals of the matrix of detection probabilities for Incompleteness Region 2 were subdivided to allow for refinement of the probabilities of detection for the Gulf of Mexico region—the second matrix shown in Table 2.5.2-205. Following the elements of expert judgment noted above, the EPRI Incompleteness Region 2 matrix of detection probability was modified for the Gulf of Mexico region, as given in Table 2.5.2-206. Using the detection probability matrix with the seismicity of the Gulf of Mexico region results in a reasonable test b-value of 0.84.

Near Atlantic

The Near Atlantic region may be considered to have reduced probabilities of detection for reasons similar to those for the Gulf of Mexico region, however, the Near Atlantic region is most proximal to the Incompleteness Region 13 (Figure 2.5.2-202).

To estimate the probability of detection matrix for the Near Atlantic region, the reduction in probabilities developed for the Gulf of Mexico region as a fraction of the probabilities for Incompleteness Region 2 may be applied as a scaling factor to the probabilities of detection for Incompleteness Region 13, shown as the third matrix in Table 2.5.2-205. The results of this scaling gives the same probability of detection matrix for the Near Atlantic region, as was developed for the Gulf of Mexico region, and considered for the Near Atlantic region because of the distribution of the unity [1.00] and zero [0.00] values in both of the probabilities of detection matrices for Incompleteness Regions 2 and 13.

Seismicity is actually too sparse within the Near Atlantic region to determine a test calculation of b-value to assess the probability of detection matrix for the Near Atlantic region.

Near Florida

For the Near Florida region, the appropriate probability of detection matrix would be transitional between those values in Florida, given by the matrix for the Incompleteness Region 13, and those developed for Near Atlantic region. Therefore, the probability of detection matrix for Near Florida region was developed as simply the average of the detection probabilities for Incompleteness Region 13 (Table 2.5.2-205, third matrix) and Near Atlantic region (Table 2.5.2-206). These average values are listed in Table 2.5.2-206.

Again, seismicity is too sparse within the Near Florida region to determine a test calculation of b-value to assess the probability of detection matrix for the Near Florida region.

2.5.2.2 Updating the EPRI Seismic Source Model for the Site Region

PTN COL 2.5-2 RG 1.208 provides guidance on methods acceptable to the NRC to satisfy the requirements of 10 CFR 100.23 for assessing the appropriate SSE ground motion levels for new nuclear power plants. RG 1.208 states that an acceptable starting point for this assessment at sites in the CEUS is the PSHA conducted by the EPRI in the 1980s (References 243 and 247). RG 1.208 further specifies that the adequacy of the EPRI source model must be evaluated in light of more recent data and evolving knowledge pertaining to seismic hazard evaluation in the CEUS. As described in Subsection 2.5.1, a comprehensive review of available geological, seismological, and geophysical data has been performed for the site region and adjoining areas.

Subsection 2.5.2.2 summarizes seismic source interpretations from the original EPRI PSHA study (References 243 and 247). Modifications and updates to the original EPRI model are required for the following reasons:

- Recent earthquakes in the Gulf of Mexico and U.S. Gulf Coast region require updates to Mmax distributions and weights for the original EPRI model. Subsection 2.5.2.4.3 describes these Mmax updates.
- The original EPRI model (Reference 243) does not cover the entire 200-mile radius site region. As such, supplemental source zones are defined to cover the entire site region. Subsection 2.5.2.4.4.1 describes these supplemental source zones.
- New seismic source characterizations of seismic sources beyond the site region, including the Cuba area, the North America-Caribbean plate boundary region, and the Charleston seismic source, should be included. Subsections 2.5.2.4.4.2 and 2.5.2.4.4.3 describe the Charleston source characterization and the Cuba and northern Caribbean source characterization, respectively.

2.5.2.2.1 Summary of EPRI Seismic Sources

This subsection summarizes the seismic sources and parameters used in the original EPRI project (References 243 and 247). The description of seismic

sources includes those sources located at least partially within 200 miles of the Units 6 & 7 site (i.e., the site region).

In the original EPRI project, six independent ESTs evaluated geological, geophysical, and seismological data to develop a model of seismic sources in the CEUS. These sources were used to model the occurrence of future earthquakes and evaluate earthquake hazards at nuclear power plant sites across the CEUS. The six ESTs involved in the original EPRI project were Bechtel Group, Dames & Moore, Law Engineering, Rondout Associates, Weston Geophysical, and Woodward-Clyde Consultants. Each team produced a report (volumes 5 through 10 of Reference 247) providing detailed descriptions of how they identified and defined seismic sources. The results were implemented into a PSHA study (Reference 243).

For the computation of hazard in the 1989 study, a few seismic source parameters were modified or simplified from the original parameters determined by the six ESTs. EPRI (Reference 243) summarizes the parameters used in the final PSHA calculations, and this reference is the primary source for the seismicity parameters. Each EST provides more detailed descriptions of the rationale and methodology used in evaluating tectonic features and establishing the seismic sources (volumes 5 through 10 of Reference 247).

Figures 2.5.2-203 through 2.5.2-209 show the EPRI source zones located at least partially within the site region. These figures also show earthquakes from the Phase 1 seismicity update (Subsection 2.5.2.1.2) to show the spatial relationships between seismicity and seismic sources.

The Mmax, interdependencies, and probability of activity for each EST's seismic sources are presented in Table 2.5.2-207. This table presents the parameters assigned to each source. Table 2.5.2-207 also indicates whether new information has been identified that would lead to a revision of the source's geometry, Mmax, or recurrence parameters.

The EPRI PSHA study expressed Mmax values in terms of m_b, whereas most modern seismic hazard analyses describe Mmax in terms of moment magnitude M_w. To provide a consistent comparison between magnitude scales, Subsection 2.5.2.1.2.1 relates body-wave magnitude to moment magnitude using the arithmetic average of three equations, or their inversions, presented in Atkinson and Boore (Reference 210), Frankel et al. (Reference 252), and EPRI TR-102293 (Reference 244). The conversion relations are consistent for magnitudes ≥4.5, but begin to show divergence at lower magnitudes.

Table 2.5.2-202 lists m_b and M_w equivalences developed from these relations over the range of interest for this study. Throughout this subsection, the values of Mmax distributions assigned by the ESTs to seismic sources are presented for both magnitude scales (m_b and M_w) to give perspective on the maximum earthquakes that were considered possible in each seismic source. For example, EPRI m_b values of Mmax are followed by the equivalent M_w value.

The following subsections describe the most significant EPRI sources for each EST with respect to the site. For all EPRI sources located within the site region, recent, post-EPRI-catalog earthquakes exceed the minimum Mmax bound assigned by the ESTs, thereby requiring Mmax updates for all EPRI sources within the site region. Subsection 2.5.2.4.3 describes these Mmax updates.

2.5.2.2.2 Sources Used for EPRI PSHA — Bechtel Group

Bechtel Group characterized only one seismic source within the site region, the Gulf Coast (BZ1) source zone. Table 2.5.2-207 summarizes the source parameters for this and other EPRI-ESTs' source zones within the site region. Figures 2.5.2-203 and 2.5.2-204 show the location and geometry of Bechtel Group's Gulf Coast (BZ1) seismic source zone.

The Units 6 & 7 site is located within Bechtel Group's Gulf Coast (BZ1) source zone. This background source extends from east Texas to the continental shelf east of Florida, including all of Louisiana and the southern portions of Mississippi, Alabama, and Georgia. The Bechtel Group assigned a maximum Mmax value of m_b 6.6 (M_w 6.5) to this zone.

2.5.2.2.3 Sources Used for EPRI PSHA — Dames & Moore

Dames & Moore characterized only one seismic source within the site region, the Southern Coastal Margin (20) source zone. Table 2.5.2-207 summarizes the source parameters for this and other EPRI-ESTs' source zones within the site region. Figures 2.5.2-203 and 2.5.2-205 show the location and geometry of Dames & Moore's Southern Coastal Margin (20) seismic source zone.

The Units 6 & 7 site is located within Dames & Moore's Southern Coastal Margin (20) source zone. This source roughly parallels the Paleozoic rifted continental margin from Texas to Alabama and also includes most of Florida. This source represents the down-warping wedge of continental margin sediments that has been accumulating since the Cretaceous Period and is characterized by diffuse seismicity (Reference 247). The Dames & Moore team assigned a maximum

Mmax value of m_b 7.2 (M_w 7.5) to this zone, reflecting its assumption of the possibility for moderate to large earthquakes within this area.

2.5.2.2.4 Sources Used for EPRI PSHA — Law Engineering

Law Engineering characterized only one seismic source within the site region, the South Coastal block (126) source zone. Table 2.5.2-207 summarizes the source parameters for this and other EPRI-ESTs' source zones within the site region. Figures 2.5.2-203 and 2.5.2-206 show the location and geometry of Law Engineering's South Coastal block (126) seismic source zone.

The Units 6 & 7 site is located within Law Engineering's South Coastal block (126) source zone. This source represents an area of low amplitude, broad wavelength magnetic anomalies extending from the Texas/Mexico border to the continental shelf east of Florida. Law Engineering interprets the northern portion of the zone from Texas to Alabama as the Paleozoic edge of the North American craton (Reference 247). The Law Engineering team assigned a maximum Mmax value of m_b 4.9 (M_w 4.5) to this zone.

2.5.2.2.5 Sources Used for EPRI PSHA — Rondout Associates

Rondout Associates characterized two seismic sources within the site region. These two sources are:

- Appalachian Basement (49-05)
- Gulf Coast to Bahamas Fracture Zone (51)

Table 2.5.2-207 summarizes the source parameters for these two Rondout Associates source zones, as well as other EPRI-ESTs' source zones within the site region. Figures 2.5.2-203 and 2.5.2-207 show the locations and geometries of the Rondout seismic sources 49-05.

The Units 6 & 7 site is located within the Gulf Coast to Bahamas Fracture Zone (51) source zone. This roughly coast-parallel background source extends from the Texas/Mexico border to southern Florida. Source zone 51 comprises Paleozoic crust that is separated from Appalachian crust of roughly the same age based on differing stress regimes (Reference 247). The Rondout Associates team assigned a maximum Mmax value of m_b 5.8 (M_w 5.4) to this zone.

At its nearest point, the Appalachian Basement (49-05) source zone is located about 115 kilometers (70 miles) northeast of the Units 6 & 7 site. This source zone

incorporates crust located east of the Precambrian cratonic edge and represents a complex accretionary terrane that may not have uniform seismic potential (Reference 247). The Rondout Associates team assigned a maximum Mmax value of m_b 5.8 (M_w 5.4) to this zone.

2.5.2.2.6 Sources Used for EPRI PSHA — Weston Geophysical

Weston Geophysical characterized only one seismic source within the site region, the Gulf Coast (107) source zone. Table 2.5.2-207 summarizes the source parameters for this and other EPRI-ESTs' source zones within the site region. Figures 2.5.2-203 and 2.5.2-208 show the location and geometry of Weston Geophysical's Gulf Coast (107) seismic source zone.

The Units 6 & 7 site is located within Weston Geophysical's Gulf Coast (107) source zone. This background source extends from eastern Texas to Florida, including all of Louisiana and the southern portions of Mississippi, Alabama, and Georgia. The Weston Geophysical team assigned a maximum Mmax value of m_b 6.0 (M_w 5.7) to this zone.

2.5.2.2.7 Sources Used for EPRI PSHA — Woodward-Clyde Consultants

The Woodward-Clyde Consultants team characterized only one seismic source within the site region, the Turkey Point Background (BG-35) source zone. Table 2.5.2-207 summarizes the source parameters for this and other EPRI-ESTs' source zones within the site region. Figures 2.5.2-203 and 2.5.2-209 show the location and geometry of Woodward-Clyde's Turkey Point Background (BG-35) seismic source zone.

The Turkey Point Background (BG-35) source is a large rectangle containing the Units 6 & 7 site and covering most of southern Florida and extending offshore to include parts of the Atlantic continental shelf, the Gulf Coast, and northern Cuba. This source is a background zone defined as a rectangular area centered on the Units 6 & 7 site, and its geometry is not based on any geological, geophysical, or seismological features. The largest Mmax assigned by the Woodward-Clyde Consultants team to this zone is m_b 6.6 (M_w 6.5).

2.5.2.3 Correlation of Seismicity with Geologic Structures and Seismic Sources

Seismic sources used in the Turkey Point Units 6 & 7 PSHA include updated EPRI seismic sources (Subsection 2.5.2.4.3.2), supplemental seismic sources (Subsection 2.5.2.4.4.1), Charleston, South Carolina seismic sources

(Subsection 2.5.2.4.4.2), and Cuba and northern Caribbean seismic sources (Subsection 2.5.2.4.4.3). The EPRI earthquake catalog covers earthquakes in the CEUS through 1984, as described in Subsection 2.5.2.1. Figures 2.5.2-203 through 2.5.2-209 show the distribution of earthquake epicenters from both the EPRI (pre-1985) and Phase 1 update (through mid-February 2008) earthquake catalogs in comparison to the seismic sources identified by each of the EPRI ESTs. Seismicity is sparse and appears evenly distributed throughout each EPRI source zone that is located within the site region. There is no clear association of seismicity with any known geologic structure in these sources.

Comparison of the additional events of the updated Phase 1 earthquake catalogs to the EPRI earthquake catalog shows:

- There are no new earthquakes within the site region that can be associated with a known geologic structure.
- There are no unique clusters of seismicity that suggest a new seismic source not captured by the EPRI seismic source model.
- The updated earthquake catalog does not show a pattern of seismicity that requires revision to the geometry of any of the EPRI seismic sources.
- The Phase 1 earthquake catalog does not imply a significant change in seismicity parameters (rate of activity, b-value) for any of the EPRI seismic sources.

The Phase 1 earthquake catalog does indicate that Mmax updates are required for most of EPRI seismic sources located within the site region. Subsection 2.5.2.4.3 describes these Mmax updates.

The correlation of seismicity from the Phase 1 earthquake catalog with supplemental seismic sources is described in Subsection 2.5.2.4.4.1. The correlation of seismicity from the Phase 1 earthquake catalog with the Charleston, South Carolina seismic source is described in Subsection 2.5.2.4.4.2. The correlation of seismicity from the Phase 2 earthquake catalog with Cuba and northern Caribbean seismic sources is described in Subsection 2.5.2.4.4.3.

2.5.2.4 Probabilistic Seismic Hazard Analysis and Controlling Earthquakes

This subsection describes the PSHA conducted for the Units 6 & 7 site following the guidelines outlined in RG 1.208. Subsections 2.5.2.4.1 through 2.5.2.4.4 address the potential significance of new information on seismic source

characterization, as that new information relates to the 1989 EPRI seismic hazard model (Reference 245), the Cuba area, and the North America-Caribbean plate boundary region. Subsection 2.5.2.4.5 summarizes the methods used to characterize ground motions within the original EPRI-SOG seismic sources in the CEUS region, and develops new attenuation models for the Caribbean seismic sources.

Subsection 2.5.2.4.6 describes the results of PSHA sensitivity analyses used to test the impact of the new information on the seismic hazard and the procedure conducted to perform an updated PSHA for the site. The results of this updated PSHA are used to develop UHRS and to identify controlling earthquakes. Development of GMRS for the Units 6 & 7 site in terms of the site-specific UHRS is described in Subsections 2.5.2.5 and 2.5.2.6.

2.5.2.4.1 1989 EPRI Seismic Hazard Study

The starting point of the PSHA calculations for the site was the 1989 EPRI study (Reference 245). The 1989 EPRI study used expert opinion on alternative, competing models of earthquake occurrences (size, location, and rates of occurrence) and ground motion amplitude and its variability to weight alternative hypotheses. PSHA calculations are conducted for these alternative hypotheses. The result is a family of weighted seismic hazard curves from which mean and fractile seismic hazard can be derived.

There were no PSHA results published in the 1989 EPRI study (Reference 245) for the Units 6 & 7 site. Therefore, as a starting point for calculations, the seismic hazard for the Crystal River site was replicated, because those hazard results were available from the 1989 EPRI study. The Crystal River site is on the west coast of Florida, near the northern end of the Florida Peninsula, and is the closest site for which 1989 EPRI study results are available. The purpose of this replication was to use the same assumptions on seismic sources and ground motion attenuation relationships, to calculate seismic hazard, and to compare results to the 1989 EPRI study.

{Table 2.5.2-208 compares individual team and total annual frequencies of exceedance calculated in the 1989 EPRI study for the Crystal River site (labeled "EPRI-SOG") to annual frequencies of exceedance calculated in the Units 6 & 7 study for peak ground acceleration (PGA) amplitudes of 100, 250, and 500 centimeters/second^2.} All results are for hard rock. The "% diff" columns show the percent difference between the 1989 calculations and the current hazard calculations at the Crystal River site. Comparisons are shown for mean PGA SOF 2.5.2-5 SOF 2.5.2-5

hazard and for the 15th fractile, median, and 85th fractile hazard curves. Note that the minimum magnitude (Mmin) for these hazard calculations was m_b = 5.0, which was the assumption made in the 1989 EPRI study (Reference 245). Observations for these comparisons are as follows:

- Bechtel team: comparison showed similar results, with current results slightly higher than for 1989 EPRI study (Reference 245).
- Dames & Moore team: comparison showed similar results except for 85th fractile hazard values, with current PGA results being +43 percent to -30 percent different from 1989 EPRI study (Reference 245). The 85th fractile hazard values show a larger difference, but the overall comparison is considered acceptable because the main concern is with replication of mean hazard. For mean hazard at three amplitudes 100, 250, and 500 centimeters/second^2, the current PGA results are within 2 percent of the 1989 EPRI results.
- Law Engineering: current results are well below 1989 EPRI study results (Reference 245). The host source (LAW-126) has Mmax values that are all below the value of Mmin = 5.0 used in the 1989 EPRI study, so it is reasonable that the current calculation shows very low hazard for the Law team (the host source contributes zero hazard in the current calculation).
- Rondout: comparison showed similar results except for the 15 percent fractile, where the current results are much lower than the 1989 EPRI results (Reference 245). Rondout sources RND-51 and RND-C01 (the host sources) have a Mmax distribution that includes a value of 4.8 (weight 0.2), which is below Mmin = 5.0, so it is reasonable that the 15 percent fractile hazard would be very low for the Rondout team, as the current calculations show.
- Weston: comparison showed similar results, with current results slightly higher than for the 1989 EPRI study (Reference 245).
- Woodward-Clyde: comparison showed similar results except for the 15 percent fractile, where the current results are much lower than the 1989 EPRI results (Reference 245). Woodward-Clyde source WGC-B36 (the background host source) has a Mmax distribution that includes a value of 4.9 (weight 0.17), which is below Mmin = 5.0, so it is logical that the 15 percent fractile hazard would be very low for the Woodward-Clyde team, as the current calculations show.

- Total: comparison of mean hazard showed similar results, with agreement being between 0 percent and 4 percent for PGA amplitudes of 100, 250, and 500 centimeter/second^2. The agreement for specific fractiles is not as good, for reasons discussed above, but this is less of a concern because (a) mean hazards are used to derive recommendations for design spectra, and (b) differences related to Mmax distributions are resolved since Mmax distributions for the EPRI team sources are updated as described below.

The conclusion from this comparison is that the overall mean seismic hazard from the 1989 EPRI study (Reference 245) can be replicated accurately, but unstated assumptions and different treatment of Mmax distributions below a value of 5.0 lead to somewhat different fractile hazards for individual team results. Given that mean hazards are used to derive recommendations for design spectra, the comparison is considered acceptable.

At the Units 6 & 7 site, updates to the inputs to PSHA lead to changes in the level of seismic hazard compared to what would have been calculated based on the 1989 EPRI model (Reference 245). Seismic source characterization data and ground motion assessments that could affect the calculated level of seismic hazard include:

- Updates in the characterization of the rate of earthquake occurrence as a function of magnitude for one or more seismic sources.
- Updates in the characterization of the maximum magnitude for seismic sources.
- Extension of seismic sources to additional regions not covered in the EPRI 1989 study.
- Modeling of new seismic sources to the south, outside the original 1989 EPRI study region.
- Updates to models used for estimating strong ground shaking and its variability in the CEUS.

Possible changes to seismic hazard caused by changes in these areas are addressed in the following subsections.

2.5.2.4.2 Effect of Updated Earthquake Catalog

Subsection 2.5.2.1.2 describes the development of an updated earthquake catalog. This updated catalog involves the addition of earthquakes that have occurred after completion of the EPRI evaluation development (post-1984). The impact of the new catalog information was assessed by evaluating the effect of the new data on earthquake recurrence estimates for the Florida Peninsula, as described below.

The 1989 EPRI study (Reference 245) defined completeness regions for the entire CEUS, within the boundaries of a study region that approximately followed the Atlantic and Gulf of Mexico coasts. In the Florida region only the Florida Peninsula was defined to be within the boundaries of the EPRI study region because the earthquake catalog was thought to be incomplete in the Gulf of Mexico and in the Atlantic region east of Florida. {Figure 2.5.2-210 shows the boundary of the EPRI region and also shows the "Florida test region" used here to examine the effects of an updated earthquake catalog.} Earthquake locations are shown for both the original EPRI earthquake catalog and for the updated catalog (south of latitude 35° N), as given in Table 2.5.2-201. SOF 2.5.2-6

The effect of the updated earthquake catalog on earthquake occurrence rates was assessed by computing earthquake recurrence parameters for the Florida test region shown in Figure 2.5.2-210. The truncated exponential recurrence model was fit to the seismicity data using the EPRI EQPARAM program, which uses the maximum likelihood technique. Earthquake recurrence parameters were computed first using the original EPRI earthquake catalog and periods of completeness, and then using the updated earthquake catalog and extending the periods of completeness to 2007, assuming that the probability of detection for all magnitudes is unity for the time period 1985 to 2007.

{The resulting earthquake recurrence rates for the Florida test region are compared in Figure 2.5.2-211. This comparison shows that the updated earthquake catalog results in lower estimated earthquake recurrence rates.} On the basis of the comparison shown in Figure 2.5.2-211, it is concluded that the earthquake occurrence rate parameters developed in the 1989 EPRI evaluation (Reference 245) have not increased in the period 1985-2007. SOF 2.5.2-6

Therefore, on the basis of earthquake occurrences alone, the seismicity rates of all EPRI team sources were not updated. Note that the EPRI analysis assumed that the EPRI earthquake catalog was complete for all magnitudes during the

period 1975–1984 (probability of detection is 1.0, Table 2.5.2-205), so this was an extension of that assumption to cover the updated catalog period.

2.5.2.4.3 New Maximum Magnitude Information

The updated earthquake catalog described in Subsection 2.5.2.1 indicates that increases in Mmax values are required for all source zones within the site region except for Woodward-Clyde source BG-35. Post-EPRI earthquakes in the updated earthquake catalog require Mmax increases because recent earthquakes have occurred in each site region source zone with magnitudes exceeding the original EPRI lower bound Mmax values (Table 2.5.2-207). Subsection 2.5.2.4.3.1 describes these earthquakes, and Subsection 2.5.2.4.3.2 and Table 2.5.2-207 present rationale for, and updates of, the original EPRI source parameters.

With the exception of earthquakes in the Cuba area and the North America-Caribbean plate boundary region, the updated earthquake catalog does not indicate any post-EPRI seismicity patterns indicative of new seismic sources. Assessment of seismicity in the Cuba area and the North America-Caribbean plate boundary region was not included in the original EPRI study. Subsection 2.5.2.4.4.3 presents details of the Cuba and northern Caribbean seismic source model.

2.5.2.4.3.1 Earthquakes Significant to EPRI Mmax Values

{A total of four post-EPRI earthquakes from the updated earthquake catalog (Table 2.5.2-201) have magnitudes greater than the lower bound Mmax value for the source zone within which they occurred.} These new data require revision to the Mmax distributions for all seven EPRI seismic source zones within the site region except for Woodward-Clyde source BG-35. The following subsections describe these four earthquakes. In the following discussion, magnitude estimates are presented in units of either body-wave magnitude, m_b, or the "best estimate" of body-wave magnitude, Emb. For the purposes of this subsection, m_b and Emb are considered equivalent. SOF 2.5.2-1 SOF 2.5.2-20

2.5.2.4.3.1.1 September 10, 2006, Emb 5.90 Gulf of Mexico Earthquake

The September 10, 2006, earthquake occurred in the Gulf of Mexico, roughly equidistant from the Florida and Alabama coasts. The event was felt throughout the southeastern U.S., including Louisiana, Arkansas, Missouri, Alabama, Georgia, South Carolina, and Florida. Maximum felt intensities were MMI IV (Reference 330). Focal mechanisms indicate reverse faulting and hypocentral

depth estimates indicate a source located beneath the Gulf of Mexico sedimentary section (Reference 330).

The updated earthquake catalog compiled for the Units 6 & 7 site assigns Emb 5.90 to the September 10, 2006, Gulf of Mexico earthquake (Figures 2.5.2-204 through 2.5.2-209). Based on preliminary data, however, previous studies assigned Emb 6.11 to this same earthquake. The Emb 6.11 estimate is adopted for the purpose of updating EPRI Mmax ranges. The difference in magnitude estimates for this event reflects the uncertainty in magnitude determination and the older and slightly larger estimate is used.

The magnitude of the September 10, 2006, earthquake exceeds the original EPRI Mmax lower bound magnitudes, and thereby requires upward revision of the Mmax distributions for the following sources (Table 2.5.2-207):

- Bechtel source BZ1 (Gulf Coast)
- Rondout Associates source 51 (Gulf Coast to Bahamas Fracture Zone)
- Weston Geophysical source 107 (Gulf Coast)

2.5.2.4.3.1.2 February 10, 2006, Emb 5.58 Gulf of Mexico Earthquake

The February 10, 2006, earthquake occurred in the Gulf of Mexico south of Louisiana. This Emb 5.58 event was felt in coastal Louisiana, Texas, and Florida with a maximum intensity of MMI III (Reference 291). The event occurred along the Sigsbee Escarpment offshore of Louisiana. Nettles (Reference 293) and Dellinger et al. (Reference 228) suggest that this event may be the result of a gravity-driven landslide. This interpretation is based on the lack of high-frequency energy in the waveforms, slow rise time, preliminary focal mechanism determinations, and the location of the event on the Sigsbee Escarpment.

Dewey and Dellinger (Reference 239) suggest that this event represents either: (a) faulting within crystalline basement at a depth beneath approximately 13 kilometers; (b) faulting within the sedimentary section above approximately 13 kilometers; or (c) a landslide within the sedimentary section. Based on seismic waveform characteristics, Dewey and Dellinger (Reference 239) consider a source within the crystalline basement unlikely for this event, and therefore favor either a shallow earthquake or landslide mechanism. Regardless of mechanism, Dewey and Dellinger (Reference 239) suggest a focal depth of 5 kilometers for this event, but they indicate that the depth could not be calculated reliably and

most likely is between 1 and 15 kilometers. If the event occurred near the deep end of this range, then a landslide origin is precluded.

Based on available data, there is the possibility that the February 10, 2006, event was nontectonic in origin. Because this is not a consensus conclusion within the seismological community and to capture uncertainty associated with this event, it is assumed to be of tectonic origin and Mmax values are updated for source zones containing the event.

The magnitude of the February 10, 2006, event exceeds the original EPRI Mmax lower bound magnitudes, and thereby requires upward revision of the Mmax distributions for the following sources (Table 2.5.2-207):

- Dames & Moore source 20 (Southern Coastal Margin)
- Law Engineering source 126 (South Coastal block)

While this event also is located within Rondout Associates source 51 (Gulf Coast to Bahamas Fracture Zone) and Weston Geophysical source 107 (Gulf Coast) and has a larger magnitude than the lower bound Mmax value for both zones, updates to Rondout Associates source 51 and Weston Geophysical source 107 are based on the larger September 10, 2006, earthquake described above. The February 10, 2006, event is located about 22 miles south of Law Engineering source 126 (Figure 2.5.2-206). This event was poorly located by traditional land-based seismograph networks, and the epicentral location is uncertain.

Therefore, it is assumed that the February 10, 2006, Emb 5.58 event occurred within Law Engineering source 126 based on positional uncertainty and the lack of any known seismotectonic boundaries that would suggest a change in seismotectonic behavior across the southern source boundary.

2.5.2.4.3.1.3 October 24, 1997, Emb 4.96 Southwestern Alabama Earthquake

The October 24, 1997, Escambia County, Alabama earthquake occurred in southwestern Alabama. This Emb 4.96 event was felt throughout southwestern Alabama and westernmost Florida with a maximum intensity of MMI VI to VII (Reference 259). This earthquake occurred within or at the perimeter of an active oil and gas extraction field, suggesting the possibility of a causal relationship between hydrocarbon recovery and the October 24, 1997, earthquake (Reference 259). Therefore, it is possible that this earthquake is non-tectonic in origin. Regardless, this event is assumed to be tectonic in origin, and Mmax values are updated for source zones containing the event as appropriate.

The magnitude of the October 24, 1997, earthquake exceeds the original EPRI Mmax lower bound magnitude, and thereby requires upward revision of the Mmax distributions for the following sources (Table 2.5.2-207):

- Rondout Associates source 49-05 (Appalachian Basement)
- Law Engineering source 126 (South Coastal block)

However, as described in the preceding subsection, it is assumed that the poorly located and larger February 10, 2006, Emb 5.58 earthquake also occurred within Law Engineering source 126. Therefore, the Mmax distribution for Law Engineering source 126 is updated based on the February 10, 2006, earthquake.

2.5.2.4.3.1.4 January 23, 1880, Emb 6.09 West Cuba Earthquake

The largest earthquake in Woodward-Clyde seismic source BG-35 is the January 23, 1880, Emb 6.09 San Cristobal-Candelaria, Cuba earthquake in west Cuba (Figures 2.5.2-203 and 2.5.2-214). The magnitude of this earthquake exceeds the minimum Mmax value (m_b 5.8) defined by Woodward-Clyde for its source BG-35 (Table 2.5.2-207). However, as described in Subsection 2.5.2.4.4.3, the southern margin of Woodward-Clyde source BG-35 is truncated by the northern boundary of the new Cuba and northern Caribbean seismic source model to avoid double-counting of earthquakes.

As such, the January 23, 1880 west Cuba earthquake is located outside of the truncated Woodward-Clyde source and within the area modeled by the new Cuba and northern Caribbean seismic source model. Therefore, the January 23, 1880, earthquake does not provide rationale for updating the original EPRI Mmax distribution for Woodward-Clyde source BG-35.

The largest earthquake in the truncated Woodward-Clyde source is the June 2, 1990, Emb 4.09 earthquake, north of Cuba (Figure 2.5.2-209). Subsection 2.5.2.4.4.3 describes the geometry of the truncated Woodward-Clyde source zone. Because this earthquake is smaller than the minimum value of the original EPRI Mmax distribution (m_b 5.8), no change to the original Mmax distribution is required for the truncated Woodward-Clyde seismic source.

2.5.2.4.3.2 EPRI Site Region Source Zone Mmax Revisions

The following subsections describe Mmax modifications to the original EPRI source zones within 200 miles of the Units 6 & 7 site. Review of published literature does not indicate any new information that requires revision to the

existing EPRI source zone geometries. Post-EPRI earthquakes in the updated earthquake catalog, however, require Mmax increases for five of the six ESTs because recent earthquakes have occurred in each site region source zone with magnitudes larger than the original EPRI lower bound Mmax values (Table 2.5.2-207).

Modifications to the original EPRI seismic source zones in the site region are limited to:

- Revising Mmax distributions based on updated seismicity data.
- Truncating the southern extent of Woodward-Clyde source BG-35 to prevent overlap with the Cuba and northern Caribbean seismic source model. Subsection 2.5.2.4.4.3 describes the Cuba and northern Caribbean source model.

Mmax distribution revisions follow the individual EST methodologies as described in the original EPRI team reports (Reference 247). These recommended changes are described in the subsections below.

2.5.2.4.3.2.1 Mmax Update — Bechtel Group

Source BZ1 (Gulf Coast) is the only Bechtel source within 200 miles of the Units 6 & 7 site (Figure 2.5.2-204) (Table 2.5.2-207). The only post-EPRI information that requires revision to this source zone is the September 10, 2006, Emb 5.90 earthquake that occurred within the Gulf Coast source zone. As described in Subsection 2.5.2.4.3.1.1, Emb 6.11 is adopted for this earthquake.

The original EPRI Mmax distribution for Bechtel source BZ1 (with weights in brackets) is: m_b 5.4 [0.1], 5.7 [0.4], 6.0 [0.4], and 6.6 [0.1] (Table 2.5.2-207) (Reference 243). Because the September 10, 2006, earthquake has a larger magnitude than the lower bound Mmax magnitude, the original EPRI Mmax distribution is updated.

{The following summarizes the Bechtel Group's methodology for defining Mmax distributions, as described within their EST volume (Reference 247), and its application to update Source BZ1. SOF 2.5.2-20

- The lower-bound magnitude of the distribution is defined as the greater of either the largest observed earthquake magnitude within the zone, or m_b 5.4 with a weight of 0.1. For Source BZ1 this lower-bound Mmax value is m_b 6.1 with a weight of 0.1. SOF 2.5.2-20

- The next higher magnitude is 0.3 magnitude units greater then the lower-bound Mmax value and is given a weight of 0.4. For Source BZ1 this results in a Mmax value of m_b 6.4 with a weight of 0.4.

- A third magnitude is 0.6 magnitude units above the lower-bound Mmax value and is given a weight of 0.4. For Source BZ1 this results in a Mmax value of m_b 6.7 with a weight of 0.4.

- A fourth magnitude is m_b 6.6 interpreted by the Bechtel EST as the largest intraplate earthquake in the CEUS with specific exceptions, and is given a weight of 0.1.

Applying this methodology to account for the Emb 6.11 earthquake results in updated Mmax values, listed in increasing magnitude order, of 6.1, 6.4, 6.6, and 6.7 with weights of 0.1, 0.4, 0.1, and 0.4, respectively, for Source BZ1 (Table 2.5.2-207).}

{It is noted, however, that a different initial interpretation of the Bechtel methodology was used in the development of the rock UHRS shown in Tables 2.5.2-210 and 2.5.2-227. The resultant Mmax distribution and weights for BZ1 based on this initial distribution was 6.1, 6.4, and 6.6 with weights of 0.1, 0.4, and 0.5, respectively. A sensitivity study has been performed showing that the effect of adopting the updated BZ1 Mmax distribution shown in Table 2.5.2-207 would, over the entire frequency range of interest (0.5 to 100 Hz) and in the 10^{-4} to 10^{-5} mean annual frequency of exceedance range used to determine ground motion design response spectrum values, result in an increase of 0.18 percent or less.} Based on these results, it is concluded that this increase is insignificant, and that the design ground motions derived from the response spectra in Tables 2.5.2-210 and 2.5.2-227 remain appropriate for the Units 6 & 7 site. SOF 2.5.2-22

2.5.2.4.3.2.2 Mmax Update — Dames & Moore

Source 20 (Southern Coastal Margin) is the only Dames & Moore source within 200 miles of the Units 6 & 7 site (Figure 2.5.2-205) (Table 2.5.2-207). The only post-EPRI information that requires revision to this source zone is the February 10, 2006, Emb 5.58 earthquake that occurred within the southern boundary of the Southern Coastal Margin source zone.

The original EPRI Mmax distribution for Dames & Moore source 20 (with weights in brackets) is: m_b 5.3 [0.8] and 7.2 [0.2] (Reference 243) (Table 2.5.2-207). The February 10, 2006, earthquake was poorly recorded by traditional land-based

seismograph networks. Despite the potential uncertainty in location, it is assumed that this event is correctly positioned within the source zone. Because the earthquake's Emb 5.58 magnitude is larger than the lower bound Mmax value, the original EPRI Mmax distribution is updated.

The Mmax distribution for Dames & Moore source 20 presented here results from increasing the lower-bound Mmax to match the magnitude of the observed Emb 5.58 earthquake (and rounding to the nearest tenth of a magnitude unit), while maintaining the same upper bound and weightings as the original EPRI Mmax distribution for the source zone. The updated Mmax values are (with weights in brackets) m_b 5.6 [0.8] and 7.2 [0.2] (Table 2.5.2-207).

Moreover, Dames & Moore did not prescribe any smoothing in determining seismicity parameters for their source 20 (Reference 243). The revised smoothing options shown in Table 2.5.2-207 are based on the range of smoothing options provided to the EPRI ESTs. The smoothing options vary between moderate to strong smoothing on a- and b-values, and all the options have a strong prior of 1.04 on b-value based on the Dames & Moore preference of that option (Reference 243).

2.5.2.4.3.2.3 Mmax Update — Law Engineering

Source 126 (South Coastal block) is the only Law Engineering source within 200 miles of the Units 6 & 7 site (Figure 2.5.2-206) (Table 2.5.2-207). The only post-EPRI information that requires revisions to this source zone is the February 10, 2006, Emb 5.58 earthquake that occurred about 22 miles south of the South Coastal block source zone. The February 10, 2006, earthquake was poorly recorded by traditional land-based seismograph networks and is assumed to have occurred within Law Engineering source 126.

The original EPRI Mmax distribution for Law Engineering source 126 (with weights in brackets) is: m_b 4.6 [0.9] and 4.9 [0.1] (Table 2.5.2-207) (Reference 243). Based on the inclusion of the earthquake within the source zone and the observation that the earthquake's Emb 5.58 magnitude is larger than the lower bound Mmax value, the original EPRI Mmax distribution for this source zone is revised.

The updated Mmax distribution of m_b 5.6 [0.90] and 5.7 [0.10] (Table 2.5.2-207) is determined using Law Engineering's methodology for developing Mmax distributions, as follows (Reference 247):

- The lower bound Mmax is the magnitude of the maximum observed earthquake in the zone.
- The upper bound Mmax magnitude defined by Law Engineering for regions with earthquakes occurring within 6.2 miles (10 kilometers) of the surface is m_b 5.7.

Weights for the original Mmax distribution (0.9 on the lower bound Mmax and 0.1 on the upper bound Mmax) (References 243 and 247) are retained in the updated Mmax distribution.

2.5.2.4.3.2.4 Mmax Update — Rondout Associates

Source 51 (Gulf Coast to Bahamas Fracture Zone) and source 49-05 (Appalachian Basement) are the only Rondout Associates source zones within 200 miles of the Units 6 & 7 site (Figure 2.5.2-207) (Table 2.5.2-207). Two sources of post-EPRI information require revisions to the Mmax distributions of these source zones: (1) the October 24, 1997, Emb 4.96 earthquake that occurred within source 49-05, and (2) the September 10, 2006, Emb 5.90 earthquake that occurred within source 51. As described in Subsection 2.5.2.4.3.1.1, Emb 6.11 is adopted for the September 10, 2006, earthquake.

The original EPRI Mmax distribution for sources 51 and 49-05 (with weights in brackets) is: m_b 4.8 [0.2], 5.5 [0.6], and 5.8 [0.2] (Reference 243) (Table 2.5.2-207). Because the October 24, 1997, and September 10, 2006, earthquakes have larger magnitudes than the lower bound Mmax magnitude, the original EPRI Mmax distributions for sources 51 and 49-05 are updated.

For Rondout Associates source 51, the updated Mmax values of m_b 6.1 [0.3], 6.3 [0.55], and 6.5 [0.15] (Table 2.5.2-207) follow from reclassifying the source zone as one capable of producing moderate earthquakes instead of the original classification of the source zone as one only capable of producing smaller than moderate earthquakes (Reference 247). The original Rondout Associates Mmax distribution for moderate earthquake source zones is m_b 5.2 [0.3], 6.3 [0.55], and 6.5 [0.15]. The updated Mmax distribution follows this distribution with the exception of an increase in the lower bound of the distribution to m_b 6.1 to account for the observed September 10, 2006, earthquake within this zone.

For Rondout Associates source 49-05, the updated Mmax values of m_b 5.0 [0.2], 5.5 [0.6], and 5.8 [0.2] (Table 2.5.2-207) result from increasing the lower Mmax bound to match the magnitude of the observed October 24, 1997, Emb 4.96

earthquake while maintaining the same upper bound and weightings of the original Mmax distribution for the source zone.

2.5.2.4.3.2.5 Mmax Update — Weston Geophysical Corporation

Source 107 (Gulf Coast Background) is the only Weston Geophysical source within 200 miles of the Units 6 & 7 site (Figure 2.5.2-208 and Table 2.5.2-207). The only post-EPRI information requiring revisions to any of these source zones is the September 10, 2006, Emb 5.90 earthquake that occurred within the Gulf Coast source zone. As described in Subsection 2.5.2.4.3.1.1, Emb 6.11 is adopted for this earthquake to be consistent with earlier studies.

The original EPRI Mmax distribution for Weston Geophysical source 107 (with weights in brackets) is: m_b 5.4 [0.71] and 6.0 [0.29] (Table 2.5.2-207) (Reference 243). Because the September 10, 2006, earthquake has a larger magnitude than the lower bound Mmax magnitude, the original EPRI Mmax distribution is updated.

Weston Geophysical's methodology for defining Mmax is based on developing discrete distributions for the probability of Mmax being a particular value (Reference 247). For source 107, these Mmax values and probabilities determined by the Weston Geophysical EST are: m_b 3.6 [0.04628], 4.2 [0.11982], 4.8 [0.27542], 5.4 [0.34415], 6.0 [0.16169], 6.6 [0.04461], and 7.2 [0.00553] (Reference 247). Following a conservative interpretation of Weston Geophysical's methodology, this discrete probability distribution is truncated at the magnitude that is closest to, yet greater than, the maximum observed earthquake within the source zone.

For this study the distribution is truncated at 6.6 because the September 10, 2006, Emb 5.90 earthquake (for which Emb 6.11 is adopted) occurred within the source zone, and the next highest discrete magnitude in the distribution is 6.6. The truncated distribution is then renormalized so that the sum of all the probabilities is 1.0. The final Mmax values are the truncated distribution, and the weightings are the renormalized probabilities. {For source 107, the updated Mmax distribution is: SOF 2.5.2-7
m_b 6.6 [0.89], 7.2 [0.11] (Table 2.5.2-207).}

2.5.2.4.3.2.6 Mmax Update — Woodward-Clyde Consultants

Woodward-Clyde Consultants originally defined large background zones that cover the majority of the CEUS and a small set of source zones to represent tectonic features (Reference 247). These large background zones were simplified in later stages of the EPRI project to individual, rectangular background zones

centered on plant sites. Source BG-35 (Turkey Point Background) is a roughly 400 x 400 miles rectangle centered on the Turkey Point site that extends southward into northern Cuba (Figure 2.5.2-203). The original EPRI Mmax distribution for source BG-35 is the same as those for the other Woodward-Clyde East Coast backgrounds: m_b 5.8 [0.33], 6.2 [0.34], 6.6 [0.33] (Table 2.5.2-207) (Reference 243).

To update Woodward-Clyde source BG-35, this source is truncated at the northern margin of the new Cuba and northern Caribbean seismic source model. Subsection 2.5.2.4.4.3 describes the new Cuba and northern Caribbean source model. Southward truncation of Woodward-Clyde source BG-35 is required to avoid double-counting of earthquakes in the northern portion of the new Cuba and northern Caribbean seismic source model.

The largest earthquake in the truncated Woodward-Clyde BG-35 source zone is the June 2, 1990, Emb 4.09 earthquake located off the north coast of Cuba (Figure 2.5.2-209 and Table 2.5.2-207). Because this earthquake is smaller than the minimum value of the original EPRI Mmax distribution (m_b 5.8), no change to the original Mmax distribution is required for the truncated Woodward-Clyde source.

2.5.2.4.4 New Seismic Source Characterizations

To complement the updated EPRI seismic source model described above, three new seismic source characterizations are included for analysis. These three new source characterizations are:

- Supplemental seismic source zones that fill the area of the site region beyond the area covered by the original EPRI source model (Subsection 2.5.2.4.4.1).
- New, post-EPRI characterization of the Charleston seismic source (Subsection 2.5.2.4.4.2).
- New, post-EPRI characterization of seismic sources located in the Cuba area and the North America-Caribbean plate boundary region (Subsection 2.5.2.4.4.3).

An additional post-EPRI model is the USGS National Seismic Hazard Mapping Project (NSHMP) (Reference 300), which characterizes seismic sources throughout the continental United States using multiple classes of earthquake source models. While the NSHMP source model is described below, source parameters from this model are not included in the updated PSHA for the Turkey

PTN RAI 02.05.02-13

Point Units 6 & 7 site. The general approach used by the USGS for modeling distributed seismicity in the CEUS is based on gridded, spatially smoothed seismicity in large background zones. Seismic sources within the CEUS most relevant to the Turkey Point Units 6 &7 site are modeled with: (1) a regional uniform background source model dividing the Extended Margin of the CEUS from the Craton; (2) special zones accounting for variability in catalog completeness, seismicity, maximum magnitude, and b-value, such as the uniform source zones for the Eastern Tennessee and New Madrid seismic zones; and (3) finite fault sources, such as those included for the New Madrid and Charleston seismic sources. LDP-CS564 PTN RAI 02.05.02-13 LDP-CS564

The 2008 NSHMP earthquake sources are depicted in Figure 2.5.2-276. Significant changes from the 2002 NSHMP model of seismic hazard in the CEUS (Reference 251) include: (1) uncertainty in the maximum magnitude (Mmax) assigned to Mmax zones (e.g., extended margin); (2) revised geometry of the Charleston seismic source zones; and (3) revised magnitudes, rates, and geometry for the New Madrid seismic source. As a result of these updates, the 2008 NSHMP characterizes Mmax for the Extended Margin and Craton as weighted distributions ranging between M7.1-7.7 and M6.6-7.2, respectively. The two areal zones defining the Charleston source are both assigned Mmax distributions of M6.8-7.5 with a recurrence interval of 550 years, unchanged from the 2002 NSHMP. The USGS NSHMP Charleston seismic source update is discussed in Subsections 2.5.2.4.4.2.2 and 2.5.2.4.4.2.3.

2.5.2.4.4.1 Supplemental Source Zones

In all but one case, the Woodward-Clyde Consultants team, the EPRI ESTs' source zones do not cover the entire 200-mile radius site region (Figure 2.5.2-203). In general, the EPRI Gulf Coast seismic source zones do not extend much beyond the site to either the south or east, thus leaving large portions of the site region without any seismic source zones. This subsection provides the rationale for adding supplemental source zones to account for potential seismic sources within the remainder of the site region north of the northern border of the new Cuba and northern Caribbean seismic source model (Subsection 2.5.2.4.4.3), consistent with current knowledge of the geologic, geophysical, and seismic characteristics of the crust in this region.

The areas of the site region not covered by the original EPRI model are largely devoid of seismicity (Figures 2.5.2-203 through 2.5.2-209). Based on this observation, new supplemental sources within the site region are added to represent the extension of Gulf Coast seismic sources, instead of expanding the

existing EPRI source zones to cover the site region. By simply expanding existing EPRI Gulf Coast source zones to offshore areas devoid of historical earthquake activity, the site hazard may be unduly decreased due to seismicity smoothing options detailed for these zones. Adding new source zones (with similar parameters to the updated EPRI Gulf Coast zones) instead is an appropriate approach, the details of which are described below. The combination of a Gulf Coast zone and a new supplemental source zone with similar parameters provides source zones covering the entire site region to account for future earthquakes.

In general, the EPRI ESTs provide minimal documentation describing the data and interpretations that define the southern and eastern boundaries of their Gulf Coast source zones (Reference 247). The eastern and southern boundaries of the Gulf Coast source zones are largely arbitrary and are often not tied to any specific geologic, seismologic, or geophysical features. The southern boundary of five of the six original EPRI ESTs' Gulf Coast source zones appear to have been arbitrarily truncated at about 25° N latitude (Figure 2.5.2-203). The sixth team, Woodward-Clyde Consultants, defines its Turkey Point Background (BG-35) source as a rectangular area centered on the Turkey Point site and is not based on any geological, geophysical, or seismological features.

The new supplemental source zones are based on an assessment after evaluating the existing data that the entire site region is potentially seismogenic. The geometries of these supplemental zones, which were created by using the original EPRI Gulf Coast source zone geometries and filling in the remainder of the site region north of the northern boundary of the new Cuba and northern Caribbean seismic source model, are shown in Figures 2.5.2-204 through 2.5.2-208. As shown in Table 2.5.2-211, this process results in five new source zones (one for each EPRI EST except Woodward-Clyde). A sixth, modified source, shown in Figure 2.5.2-209, is the result of truncating existing Woodward-Clyde source BG-35 by the northern boundary of the new Cuba and northern Caribbean seismic source model. This truncated source is intended to replace the original EPRI Woodward-Clyde source BG-35. Table 2.5.2-212 provides geographic coordinates of the corner points of the five supplemental source zones and the truncated Woodward-Clyde source.

The new supplemental source zones also are based on the evaluation that the crust within the site region between southern Florida and the northern boundary of the newly assessed Cuba and northern Caribbean seismic source model is similar and has similar earthquake potential. The EPRI Gulf Coast sources are broad, regional seismic source zones that include predominantly extended continental

crust characterized by low rates of seismicity. While individual seismic source zones characterizing this crust from each EST differ, they generally extend from Texas to Florida (Figures 2.5.2-203 through 2.5.2-209). Basement rock within the Gulf of Mexico region has been divided by Sawyer et al. (Reference 315) into four major types: oceanic, thin transitional, thick, transitional, and continental crust (Figure 2.5.1-238). These gross characteristics and boundaries between various types of crust in the Gulf of Mexico region are based on reflection and refraction seismic profiles, gravity, magnetic, and subsidence data and reflect the manner in which crust was created or modified by Mesozoic rifting. Based on mapping of crust in this region (e.g., References 258 and 315), the majority of these regional Gulf seismic source zones comprise thick transitional crust, however the northeast area of northern Florida, Georgia, and Alabama is considered continental crust by Sawyer et al. (Reference 315). These zones also include significant amounts of thin transitional crust as well as minor amounts of oceanic crust near their southern boundary (Figure 2.5.1-238). Additional discussion is provided in Subsection 2.5.1.1.1.2.2.

Implementation of this method involves the following:

- No changes to the geometries of the original EPRI Gulf Coast source zones (except Woodward-Clyde seismic source BG-35, which is truncated at the northern boundary of new Cuba and northern Caribbean seismic source model).

- Add five additional source zones (one for each EST except Woodward-Clyde) to fill in the site region, truncated at the northern boundary of new Cuba and northern Caribbean seismic source model (Figures 2.5.2-204 through 2.5.2-209) (Tables 2.5.2-211 and 2.5.2-212).

- Reassess Mmax distributions and weights for original EPRI source zones within the site region based on the updated earthquake catalog, as described in Subsection 2.5.2.4.3.2.

- Assess Mmax distributions and weights for five new source zones based on the updated earthquake catalog. These five new source zones are largely devoid of historical seismicity (Table 2.5.2-211), thus Mmax distributions are based on Mmax estimates for their respective updated EPRI EST Gulf Coast zones (Table 2.5.2-207). Due to the similarity of the crust between the supplemental source zones and the original EPRI Gulf Coast source zones, the new zones reflect the same Mmax distributions as their updated Gulf Coast source zone counterpart for each EST.

Figures 2.5.2-204 through 2.5.2-208 show the supplemental seismic source zones and epicenters from the Phase 1 earthquake catalog. Seismicity within each of the supplemental sources is very sparse, with a total of just one or two earthquakes in each (Figures 2.5.2-204 through 2.5.2-208). The largest magnitude earthquake from the Phase 1 earthquake catalog in each supplemental source zone is Emb 4.09.

Given the paucity of earthquakes in 1 x 1 degree cells offshore of Florida, the following steps were used to assign a- and b-values to the updated EPRI sources and new supplemental source zones:

- {Average a- and b-values were calculated for peninsular Florida using the updated earthquake catalog and original completeness matrices (extended to 2007) and full smoothing. The average values for the 15-degree cells are a = -2.28 and b = 1.03.} SOF 2.5.2-6 LDP-CS536

- These average a- and b-values were used to represent seismicity in 1 x 1 degree cells for the five new supplemental source zones.

- These average a- and b-values also were used to represent seismicity in 1 x 1 degree cells in the updated EPRI team sources representing Gulf Coast seismicity outside of the original EPRI completeness regions. One x one degree cells more than 200 miles from the Units 6 & 7 site were not modeled.

- The original a- and b-values were used for the updated EPRI team sources, where they are defined.

2.5.2.4.4.2 Updated Charleston Seismic Source (UCSS) Model

The Units 6 & 7 site is located roughly 500 miles from Charleston, South Carolina (Figure 2.5.2-203). The original EPRI seismic source model (References 243 and 247) includes assessments of the Charleston seismic source. However, several studies that post-date the EPRI EST assessments demonstrate that the source parameters for geometry, Mmax, and recurrence of Mmax in the Charleston seismic source need to be updated to capture a more current understanding of both the 1886 Charleston earthquake and the seismic source that produced this earthquake. Therefore, this subsection presents an update of the Charleston seismic source.

The Updated Charleston Seismic Source (UCSS) model presented in this subsection was developed through use of a Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 process (Reference 318) for the Vogtle site in

Georgia. Subsections 2.5.2.4.4.2.1 through 2.5.2.4.4.2.3 describe the UCSS model.

2.5.2.4.4.2.1 UCSS Model Geometry

The UCSS model includes four mutually exclusive source zone geometries (A, B, B', and C; Figure 2.5.2-212). Table 2.5.2-213 presents the latitude and longitude coordinates that define these four source zones. The four geometries of the UCSS model are defined based on current understanding of geologic and tectonic features in the 1886 Charleston earthquake epicentral region: the 1886 Charleston earthquake shaking intensity; distribution of seismicity; and geographic distribution, age, and density of liquefaction features associated with both the 1886 and prehistoric earthquakes. These features strongly suggest that the majority of evidence for the Charleston source is concentrated in the Charleston area and is not widely distributed throughout South Carolina.

Geometry A - Charleston

Geometry A is an about 100 x 50 kilometers, northeast-oriented area centered on the 1886 Charleston meizoseismal area (Figure 2.5.2-212). Geometry A is intended to represent a localized source area that generally confines the Charleston source to the 1886 meizoseismal area (i.e., a stationary source in time and space). Geometry A completely envelops the 1886 earthquake MMI X isoseismal (Reference 216), the majority of identified Charleston-area tectonic features and inferred fault intersections, and the majority of reported 1886 liquefaction features. Geometry A excludes the northern extension of the southern segment of the postulated East Coast fault system because this system extends well north of the meizoseismal zone and is included in its own source geometry (Geometry C).

Geometry A also excludes outlying liquefaction features because liquefaction occurs as a result of strong ground shaking that may extend well beyond the areal extent of the tectonic source. Geometry A also envelops instrumentally located earthquakes spatially associated with the Middleton Place-Summerville Seismic Zone (MPSSZ), which is located in the meizoseismal zone of the 1886 Charleston earthquake (References 272, 324, and 325). The preponderance of these moderately abundant earthquakes is thought to be aftershocks of the historical 1886 Emb 6.75 event (References 272, 324, and 325). The largest magnitude earthquake from the Phase 1 earthquake catalog in Geometry A is the historical 1886 Emb 6.75 event.

The preponderance of evidence strongly supports the conclusion that the seismic source for the 1886 Charleston earthquake is located in a relatively restricted area defined by Geometry A. These observations show that future earthquakes having magnitudes comparable to the Charleston earthquake of 1886 most likely would occur within the area defined by Geometry A. The UCSS model assigns a weight of 0.70 to Geometry A (Figure 2.5.2-213). To confine the rupture dimension to within the source area and to maintain a preferred northeast fault orientation, Geometry A is represented in the model by a series of closely spaced, northeast-striking faults parallel to the long axis of the zone.

Geometries B, B', and C

Whereas the preponderance of evidence supports the assessment that the 1886 Charleston meizoseismal area and Geometry A defines the area where future events would most likely be centered, it is possible that the tectonic feature responsible for the 1886 earthquake either extends beyond or lies outside of Geometry A. Therefore, the remaining three geometries (B, B', and C) are assessed to capture the uncertainty that future events may not be restricted to Geometry A.

The distribution of liquefaction features along the entire coast of South Carolina and observations from the paleoliquefaction record that a few events were localized (moderate earthquakes to the northeast and southwest of Charleston) suggest that the Charleston source could extend well beyond Charleston proper. Geometries B and B' represent a larger source zone, while Geometry C represents the southern segment of the postulated East Coast fault system as a possible source zone.

The UCSS model assigns a weight of 0.20 to the combined geometries of B and B', and a weight of 0.10 to Geometry C. Geometry B' is a subset of B, and formally defines the onshore coastal area as a source that restricts earthquakes to the onshore region. Geometry B, which includes the onshore and offshore regions, and Geometry B' are mutually exclusive. The UCSS model assigns equal weights of 0.10 to Geometries B and B'.

Geometry B — Coastal and Offshore Zone

Geometry B is a coast-parallel, approximately 260 x 100 kilometers source area that (a) incorporates all of Geometry A, (b) is elongated to the northeast and southwest to capture other, more distant liquefaction features in coastal South Carolina (References 207, 208, and 323), and (c) extends to the southeast to

include the offshore Helena Banks fault zone (Reference 213) (Figure 2.5.2-212). Seismicity within Geometry B, outside of the area of overlap with Geometry A, is sparse. The largest magnitude earthquake from the Phase 1 earthquake catalog in Geometry B is the historical 1886 Emb 6.75 event (Figure 2.5.2-212). The elongation and orientation of Geometry B is roughly parallel to the regional structural grain as well as roughly parallel to the elongation of 1886 isoseismals. The mapped extent of paleoliquefaction features (References 207, 208, and 323) defines the northeastern and southwestern extents of Geometry B.

The location and timing of paleoliquefaction features in the Georgetown and Bluffton areas to the northeast and southwest of Charleston suggest to some researchers that the earthquake source may not be restricted to the Charleston area (References 207, 295, 296, and 323). Geometry B accounts for the possibility that there may be an elongated source or multiple sources along the South Carolina coast. Paleoliquefaction features in the Georgetown and Bluffton areas may be explained by an earthquake source both northeast and southwest of Charleston, as well as possibly offshore.

Geometry B extends southeast to include an offshore area and the Helena Banks fault zone. The Helena Banks fault zone is clearly shown by multiple seismic reflection profiles and has demonstrable late Miocene offset (Reference 213). Offshore earthquakes in 2002 (m_b 3.5 and 4.4) suggest a possible spatial association of seismicity with the mapped trace of the Helena Banks fault system. Whereas these two events in the vicinity of the Helena Banks fault system do not provide a positive correlation with seismicity or demonstrate recent fault activity, these small earthquakes are new data that post-date the EPRI studies.

The UCSS model assigns a low weight of 0.10 to Geometry B (Figure 2.5.2-213) because the preponderance of evidence indicates that the seismic source that produced the 1886 earthquake lies onshore in the Charleston meizoseismal area and not in the offshore region. To confine the rupture dimension to within the source area and to maintain a preferred northeast fault orientation, the UCSS model represents Geometry B as a series of closely spaced, northeast-striking faults parallel to the long axis of the zone.

Geometry B' — Coastal Zone

Geometry B' is a coast-parallel, approximately 260 x 50 kilometers source area that incorporates all of Geometry A, as well as the majority of reported paleoliquefaction features (References 207, 208, and 323). Unlike Geometry B, however, Geometry B' does not include the offshore Helena Banks fault zone

(Figure 2.5.2-212). Seismicity within Geometry B', outside of the area of overlap with Geometry A, is sparse. The largest magnitude earthquake from the Phase 1 earthquake catalog in Geometry B' is the historical 1886 Emb 6.75 event.

The Helena Banks fault system is excluded from Geometry B' because the preponderance of data and evaluations support the assessment that the fault system is not active and because evidence strongly suggests that the 1886 Charleston earthquake occurred onshore in the 1886 meizoseismal area and not on an offshore fault. Whereas there is little uncertainty regarding the existence of the Helena Banks fault, there is a lack of evidence that this feature is still active. Isoseismal maps documenting shaking intensity in 1886 indicate an onshore meizoseismal area (Figure 2.5.2-212). An onshore source for the 1886 earthquake and prehistoric events is supported by the instrumentally recorded seismicity in the MPSSZ and the corresponding high-density cluster of 1886 and prehistoric liquefaction features.

Similar to Geometry B above, the UCSS model assigns a weight of 0.10 to Geometry B', reflecting the assessment that Geometry B' has a much lower probability of being the source zone for Charleston-type earthquakes than Geometry A (Figure 2.5.2-213). To confine the rupture dimension to within the source area and to maintain a preferred northeast fault orientation, the UCSS model represents Geometry B' as a series of closely spaced, northeast-striking faults parallel to the long axis of the zone.

Geometry C — East Coast Fault System-South

Geometry C is about 200 x 30 kilometers, north-northeast-oriented source area (Figure 2.5.2-212) enveloping the southern segment of the proposed East Coast fault system shown in Figure 3 of Reference 278. The area of Geometry C is defined to envelop the original depiction of the postulated East Coast fault System-South by Marple and Talwani in Reference 278. The largest magnitude earthquake from the Phase 1 earthquake catalog in Geometry C is Emb 4.31. The location of the 1886 Emb 6.75 earthquake from the Phase 1 earthquake catalog plots just outside of Geometry C, but, given the uncertainty in the location of this earthquake, it is considered to have possibly occurred within Geometry C. There is partial overlap between Geometries A and C. Within the area of overlap, seismicity in Geometry C is moderately abundant. To the north, outside the area of overlap, seismicity in Geometry C is very sparse.

The UCSS model assigns a low weight of 0.10 to Geometry C to reflect the assessment that Geometries B, B', and C all have equal, but relatively low,

likelihoods of producing large-magnitude earthquakes (Figure 2.5.2-213). As with the other UCSS alternative geometries, the UCSS model represents Geometry C as a series of parallel, vertical faults oriented northeast-southwest and parallel to the long axis of the narrow rectangular zone. The faults and extent of earthquake ruptures are confined within the rectangle depicting Geometry C.

UCSS Model Parameters

Based on studies by Bollinger et al. (References 214 and 215) and Bollinger (Reference 217), the UCSS model assumes a 20-kilometer thick seismogenic crust. To model the occurrence of earthquakes in the characteristic part of the Charleston distribution ($M_w \geq 6.7$), the model uses a series of closely-spaced, vertical faults parallel to the long axis of each of the four source zones (A, B, B', and C). Faults and earthquake ruptures are limited to within each respective source zone and are not allowed to extend beyond the zone boundaries, and ruptures are constrained to occur within the depth range of 0 to 20 kilometers.

The UCSS model assumes fault rupture areas have a width-to-length aspect ratio of 0.5, conditional on the assumed maximum fault width of 20 kilometers. To obtain Mmax earthquake rupture lengths from magnitude, the UCSS model uses the Wells and Coppersmith (Reference 334) empirical relationship between surface rupture length and magnitude for earthquakes of all slip types.

To maintain as much similarity as possible with the original EPRI model, the UCSS model treats earthquakes in the exponential part of the distribution (M_w < 6.7) as point sources uniformly distributed within the source area (full smoothing), with a constant depth fixed at 10 kilometers.

2.5.2.4.4.2.2 UCSS Model Mmax

Mmax estimates for the Charleston seismic source are based on published literature and previous source characterizations. Given the large uncertainties in working with the paleoliquefaction record and methods for estimating magnitudes from these data, the best representation of the Mmax for the Charleston seismic source should be based on estimates of the size of the 1886 earthquake.

Based on assessment of the currently available data and interpretations regarding the range of modern Mmax estimates, the UCSS model modifies the 2008 U.S. Geological Survey (USGS) hazard model magnitude distribution (Reference 300) to include a total of five discrete magnitude values, each separated by 0.2 M_w units (Figure 2.5.2-213). The UCSS Mmax distribution is based on recent studies, as summarized in Table 2.5.2-214.

The UCSS Mmax distribution includes a discrete value of M_W 6.9 to represent the Bakun and Hopper (Reference 211) best estimate of the 1886 Charleston earthquake magnitude, as well as a lower value of M_W 6.7 to capture a low probability that the 1886 earthquake was smaller than the Bakun and Hopper (Reference 211) mean estimate of M_W 6.9. Bakun and Hopper (Reference 211) do not explicitly report a 1-sigma range in magnitude estimate of the 1886 earthquake, but do provide a 2-sigma range of M_W 6.4 to 7.2.

The UCSS magnitudes and weights are as follows:

M_W	Weight	
6.7	0.10	
6.9	0.25	Bakun and Hopper (Reference 211) mean
7.1	0.30	
7.3	0.25	Johnston (Reference 267) mean
7.5	0.10	

This results in a weighted Mmax mean magnitude of M_W 7.1 for the UCSS, slightly lower than the mean magnitude of M_W 7.2 in the 2008 USGS model (Reference 300).

2.5.2.4.4.2.3 UCSS Model Recurrence of Mmax

In the 1989 EPRI study (Reference 243), the six EPRI ESTs use an exponential magnitude distribution to represent earthquake sizes for their Charleston sources. Parameters of the exponential magnitude distribution are estimated from historical seismicity in the respective source areas. This results in recurrence intervals for Mmax earthquakes (at the upper end of the exponential distribution) of several thousand years.

The UCSS model for earthquake recurrence is a composite model consisting of two distributions. The first is an exponential magnitude distribution used to estimate recurrence between the lower-bound magnitude used for hazard calculations and M_W 6.7. The parameters of this distribution are estimated from the earthquake catalog, as they were for the 1989 EPRI study. This is the standard procedure for smaller magnitudes and is the model used, for example, by the USGS 2002 national hazard maps (Reference 251).

The second distribution treats Mmax earthquakes ($M_W \geq 6.7$) according to a characteristic model, with discrete magnitudes and mean recurrence intervals

estimated through analysis of geologic data, including paleoliquefaction studies. The term Mmax is used to describe the range of largest earthquakes in both the characteristic portion of the UCSS recurrence model and the EPRI exponential recurrence model.

This composite model achieves consistency between the occurrence of earthquakes with $M_w < 6.7$ and the earthquake catalog and between the occurrence of large earthquakes ($M_w \geq 6.7$) with paleoliquefaction evidence. It is a type of "characteristic earthquake" model, in which the recurrence rate of large events is higher than what would be estimated from an exponential distribution inferred from the historical seismic record.

Mmax Recurrence

This subsection describes how the UCSS model determines mean recurrence intervals for Mmax earthquakes. The UCSS model incorporates geologic data to characterize the recurrence intervals for Mmax earthquakes. As described earlier, identifying and dating paleoliquefaction features provides a basis for estimating the recurrence of large Charleston area earthquakes. Most of the available geologic data pertaining to the recurrence of large earthquakes in the Charleston area were published after 1990 and therefore were not available to the six EPRI ESTs. In the absence of geologic data, the six EPRI EST estimates of recurrence for large, Charleston-type earthquakes are based on a truncated exponential model using historical seismicity (References 243 and 247).

The truncated exponential model also provides the relative frequency of all earthquakes greater than m_b 5.0 up to Mmax in the EPRI PSHA. The recurrence of Mmax earthquakes in the EPRI models is on the order of several thousand years, which is significantly greater than more recently published estimates of about 500 to 600 years, based on paleoliquefaction data (Reference 323).

Paleoliquefaction Data

Strong ground shaking during the 1886 Charleston earthquake produced extensive liquefaction, and liquefaction features from the 1886 event are preserved in geologic deposits at numerous locations in the South Carolina coastal region. Documentation of older liquefaction-related features in geologic deposits provides evidence for prior strong ground motions during prehistoric large earthquakes. Estimates of the recurrence of large earthquakes in the UCSS are based on dating paleoliquefaction features.

Many potential sources of ambiguity and/or error are associated with dating and interpreting paleoliquefaction features. This assessment does not reevaluate field interpretations and data; rather, it reevaluates criteria used to define individual paleoearthquakes in the published literature. In particular, the UCSS model reevaluates the paleoearthquake record interpreted by Talwani and Schaeffer (Reference 323) based on that study's compilation of sites with paleoliquefaction features.

Talwani and Schaeffer (Reference 323) compile radiocarbon ages from paleoliquefaction features along the coast of South Carolina. These data include ages that provide contemporary, minimum, and maximum limiting ages for liquefaction events. Radiocarbon ages are corrected for past variability in atmospheric ^{14}C using well-established calibration curves and converted to "calibrated" (approximately calendar) ages. From their compilation of calibrated radiocarbon ages from various geographic locations, Talwani and Schaeffer (Reference 323) correlate individual earthquake episodes.

Talwani and Schaeffer (Reference 323) identify individual earthquake episodes based on samples with "contemporary" age constraints that have overlapping calibrated radiocarbon ages at approximately 1-sigma confidence interval. The estimated age of each earthquake is calculated from the "weighted averages of overlapping contemporary ages" (Reference 323, p. 6632). They define as many as eight events (named 1886, A, B, C, D, E, F, and G, in order of increasing age) from the paleoliquefaction record, and offer two scenarios to explain the distribution and timing of paleoliquefaction features (Table 2.5.2-215). The two scenario paleoearthquake records proposed by Talwani and Schaeffer (Reference 323) have different interpretations for the size and location of prehistoric events (Table 2.5.2-215).

In their Scenario 1, the four prehistoric events, A, B, E, and G, that produced widespread liquefaction features similar to the large 1886 Charleston earthquake are interpreted to be large, 1886 Charleston-type events. Three events, C, D, and F, are defined by paleoliquefaction features that are more limited in geographic extent than other events and are interpreted to be smaller, moderate-magnitude events (approximately M_w 6). Events C and F are defined by features found north of Charleston in the Georgetown region, and Event D is defined by sites south of Charleston in the Bluffton area.

In their Scenario 2, all events are interpreted as large, 1886 Charleston-type events. Furthermore, Events C and D are combined into a large Event C'. Talwani and Schaeffer (Reference 323) justify the grouping of the two events based on the

observation that the calibrated radiocarbon ages that constrain the timing of Events C and D are indistinguishable at the 95 percent (2-sigma) confidence interval.

The length and completeness of the paleoearthquake record based on paleoliquefaction features is a source of epistemic uncertainty in the UCSS model (epistemic uncertainty is the result of inaccurate or incomplete information and can be reduced or eliminated given better models or additional observations, as opposed to aleatory uncertainty that results from randomness and cannot be reduced with more or better observations). The paleoliquefaction record along the South Carolina coast extends from 1886 to the mid-Holocene (Reference 323).

There is uncertainty regarding the length of completeness of the paleoliquefaction record in the Charleston region. There is general agreement that the paleoliquefaction record is complete for the past approximately 2000 years and that liquefaction events may be missing from the older portions of the geologic record (Reference 323). The suggested incompleteness of the older portions of the record is based on the argument that past fluctuations in sea level have produced time intervals of low water table conditions (and thus low liquefaction susceptibility), during which large earthquake events may not have been recorded in the paleoliquefaction record (Reference 323). While this assertion may be true, it is possible that the paleoliquefaction record may be complete back to the mid-Holocene.

2-Sigma Analysis of Event Ages

The Talwani and Schaeffer (Reference 323) data compilation of liquefaction is the basis for analysis of the coastal South Carolina paleoliquefaction record performed in support of Subsection 2.5.2. As described previously, Talwani and Schaeffer (Reference 323) use calibrated radiocarbon ages with 1-sigma error bands to define the timing of past liquefaction episodes in coastal South Carolina. The standard in paleoseismology, however, is to use calibrated ages with 2-sigma (95.4 percent confidence interval) error bands (Reference 261). Likewise, in paleoliquefaction studies, to more accurately reflect the uncertainties in radiocarbon dating, Tuttle (Reference 328) advises the use of calibrated radiocarbon dates with 2-sigma error bands (as opposed to narrower 1-sigma error bands).

Talwani and Schaeffer's (Reference 323) use of 1-sigma error bands may lead to over-interpretation of the paleoliquefaction record such that more episodes are interpreted than actually occurred. In recognition of this possibility, the

conventional radiocarbon ages presented in Talwani and Schaeffer (Reference 323) are recalibrated and reported with 2-sigma error bands. The recalibration of individual radiocarbon samples and estimation of age ranges for paleoliquefaction events show broader age ranges with 2-sigma error bands that are used to obtain broader age ranges for paleoliquefaction events in the Charleston area.

Event ages based on overlapping 2-sigma ages of paleoliquefaction features are presented in Table 2.5.2-215. Paleoearthquakes are distinguished based on grouping paleoliquefaction features that have contemporary radiocarbon samples with overlapping calibrated ages. Event ages are defined by selecting the age range common to each of the samples. For example, an event defined by overlapping 2-sigma sample ages of 100 to 200 calendar years before present and 50 to 150 calendar years before present has an event age of 100 to 150 calendar years before present. The UCSS model considers these "trimmed" ages to represent the approximately 95 percent confidence interval, with a "best estimate" event age as the midpoint of the approximately 95 percent age range.

The UCSS model 2-sigma analysis identifies six distinct paleoearthquakes in the data presented by Talwani and Schaeffer (Reference 323). As noted by that study, Events C and D are indistinguishable at the 95 percent confidence interval, and in the UCSS, those samples define Event C' (Table 2.5.2-215). Additionally, the UCSS 2-sigma analysis suggests that Talwani and Schaeffer Events F and G (Reference 323) are a single, large event, defined in the UCSS as F'.

One important difference between the UCSS result and that of Talwani and Schaeffer (Reference 323) is that the three Events C, D, and F in their Scenario 1, which are inferred to be smaller, moderate-magnitude events, are grouped into more regionally extensive Events C' and F' (Table 2.5.2-215). Therefore, in the UCSS, all earthquakes in the 2-sigma analysis are interpreted to represent large, Charleston-type events.

The incorporation of large Events C' and F' into the UCSS model is, in effect, a conservative approach. In the effort to estimate the recurrence of Mmax events (M_w 6.7 to 7.5), moderate-magnitude (about M_w 6) earthquakes C and D would be eliminated from the record of large (Mmax) earthquakes in the UCSS model, thereby increasing the calculated Mmax recurrence interval and lowering the hazard without sufficient justification.

For these reasons the UCSS model uses a single, large Event C' (instead of separate, smaller Events C and D) and a single, large Event F' (instead of

separate, smaller Events F and G). Analysis suggests that there have been four large earthquakes in the most-recent, about 2000-year portion of the record (1886 and Events A, B, and C'). In the entire 5000-year paleoliquefaction record, there is evidence for six large, Charleston-type earthquakes (1886, A, B, C', E, F'; Table 2.5.2-215). Figure 2.5.2-212 shows the geographic distribution of liquefaction features. The distributions of paleoliquefaction sites for Events A, B, C', E, and F' are all very similar to the coastal extent of the liquefaction features from the 1886 earthquake.

Recurrence intervals developed from the earthquakes recorded by paleoliquefaction features assume that these features were produced by large Mmax events and that both the 2000-year and 5000-year records are complete. However, the UCSS model highlights at least two concerns regarding the use of the paleoliquefaction record to characterize the recurrence of past Mmax events.

First, it is possible that multiple, moderate-sized earthquakes closely spaced in time produced the paleoliquefaction features associated with one or more of the pre-1886 events. If this is the case, then the calculated recurrence interval would yield artificially short recurrence for Mmax, because it is calculated using repeat times of both large (Mmax) events and smaller earthquakes. Limitations of radiocarbon dating and limitations in the stratigraphic record often preclude identifying individual events in the paleoseismologic record that are closely spaced in time (i.e., separated by only a few years to a few decades). Several seismic sources have demonstrated tightly clustered earthquake activity in space and time that are indistinguishable in the radiocarbon and paleoseismic record:

- New Madrid (December 1811, January 1812, and February 1812)
- North Anatolian fault (August 1999 and November 1999)
- San Andreas fault (December 1812 and January 1857)

Therefore, the UCSS acknowledges the distinct possibility that Mmax occurs less frequently than what is calculated from the paleoliquefaction record.

A second concern is that the recurrence behavior of the Mmax event may be highly variable through time. For example, the UCSS considers it unlikely that M_w 6.7 to 7.5 events have occurred on a Charleston source at an average repeat time of about 500 to 600 years (Reference 323) throughout the Holocene Epoch. Such a moment release rate would likely produce tectonic landforms with clear geomorphic expression, such as are present in regions of the world with

comparably high rates of moderate to large earthquakes (for example, faults in the Eastern California shear zone with sub-millimeter per year slip rates and recurrence intervals on the order of about 5000 years have clear geomorphic expression [Reference 309]).

Perhaps it is more likely that the Charleston source has a recurrence behavior that is highly variable through time, such that a sequence of events spaced about 500 years apart is followed by quiescent intervals of thousands of years or longer. This sort of variability in inter-event time may be represented by the entire mid-Holocene record, in which both short interevent times (e.g., about 400 years between Events A and B) are included in a record with long inter-event times (e.g., about 1900 years between Events C' and E).

Recurrence of Mmax

The UCSS model calculates two average recurrence intervals covering two different time intervals. The UCSS model represents these two recurrence intervals as separate branches on the logic tree (Figure 2.5.2-213). The first average recurrence interval is based on the four events that occurred within the past about 2000 years. This time period is considered to represent a complete portion of the paleoseismic record (Reference 323). These events include 1886, A, B, and C' (Table 2.5.2-215). The average recurrence interval calculated for the most recent portion of the paleoliquefaction record (four events over the past about 2000 years) is given 0.80 weight on the logic tree (Figure 2.5.2-213).

The second average recurrence interval is based on events that occurred within the past about 5000 years. This time period represents the entire paleoseismic record based on paleoliquefaction data (Reference 323). These events include 1886, A, B, C', E, and F' as listed in Table 2.5.2-215. Published literature and questioned researchers suggest that the older part of the record (older than about 2000 years ago) may be incomplete. Whereas this assertion may be true, it is also possible that the older record, which exhibits longer inter-event times, is complete.

The UCSS model assigns a weight of 0.20 to the average recurrence interval calculated for the 5000-year record (six events) (Figure 2.5.2-213). The 0.80 and 0.20 weighting of the 2000-year and 5000-year paleoliquefaction records, respectively, reflects incomplete knowledge of both the short- and long-term recurrence behavior of the Charleston source.

The mean recurrence intervals for the most recent 2000-year and 5000-year records represent the average time interval between earthquakes attributed to the

Charleston seismic source. The mean recurrence intervals and their parametric uncertainties are calculated according to the methods outlined by Savage (Reference 313) and Cramer (Reference 227). The methods provide a description of mean recurrence interval, with a best estimate mean and an uncertainty described as a lognormal distribution with a median and parametric lognormal shape factor.

The lognormal distribution is one of several distributions, including the Weibull, Double Exponential, and Gaussian, among others, used to characterize earthquake recurrence (Reference 248). Ellsworth et al. (Reference 248) and Matthews et al. (Reference 280) propose a Brownian-passage time model to represent earthquake recurrence, arguing that it more closely simulates the physical process of strain build-up and release. This Brownian-passage time model is currently used to calculate earthquake probabilities in the greater San Francisco Bay region (Reference 337).

Analyses show that the lognormal distribution is very similar to the Brownian-passage time model of earthquake recurrence for cases where the time elapsed since the most recent earthquake is less than the mean recurrence interval (References 225 and 248). This is the case for Charleston, where 120 years have elapsed since the 1886 earthquake and the mean recurrence interval determined over the past 2000 years is about 548 years. The UCSS model calculates average recurrence intervals using a lognormal distribution because its statistics are well known (Reference 294) and numerous other studies use this method (References 227, 313, and 336).

The average interval between earthquakes is expressed as two continuous lognormal distributions. The average recurrence interval for the 2000-year record, based on the three most recent inter-event times (1886—A, A-B, and B-C'), has a best estimate mean value of 548 years, an uncertainty distribution described by a median value of 531 years, and a lognormal shape factor of 0.25. The average recurrence interval for the 5000-year record, based on five inter-event times (1886—A, A-B, B-C', C'-E, and E-F'), has a best estimate mean value of 958 years, an uncertainty distribution described by a median value of 841 years, and a lognormal shape factor of 0.51.

At one standard deviation, the average recurrence interval for the 2000-year record is between 409 and 690 years; for the 5000-year record, it is between 452 and 1564 years. Combining these mean values of 548 and 958 years with their respective logic tree weights of 0.8 and 0.2 results in a weighted mean of 630 years for Charleston Mmax recurrence.

The UCSS model uses mean recurrence values that are similar to those determined by earlier studies. Talwani and Schaeffer (Reference 323) consider two possible scenarios to explain the distribution in time and space of paleoliquefaction features. In their Scenario 1, large earthquakes have occurred with an average recurrence of 454 ±21 years over about the past 2000 years; in their Scenario 2, large earthquakes have occurred with an average recurrence of 523 ±100 years over the past 2000 years.

Talwani and Schaeffer (Reference 323) state that, "In anticipation of additional data we suggest a recurrence rate [sic] between 500 and 600 years for M 7+ earthquakes at Charleston." For the 2000-year record, the 1-standard-deviation range of 409 to 690 years completely encompasses the range of average recurrence interval reported by Talwani and Schaeffer (Reference 323). The best-estimate mean recurrence interval value of 548 years is comparable to the midpoint of the Talwani and Schaeffer (Reference 323) best-estimate range of 500 to 600 years.

The best estimate mean recurrence interval value from the 5000-year paleoseismic record of 958 years is outside the age ranges reported by Talwani and Schaeffer (Reference 323), although they did not determine an average recurrence interval based on the longer record.

The 2008 USGS updated seismic hazard maps for the conterminous United States use a mean recurrence value of 550 years for characteristic earthquakes in the Charleston region (Reference 300). This value is based on the above-quoted 500 to 600 year estimate from Talwani and Schaeffer (Reference 323). The updated USGS seismic hazard maps for the conterminous United States do not incorporate uncertainty in mean recurrence interval in their calculations.

For computation of seismic hazard, discrete values of activity rate (inverse of recurrence interval) are required as input to the PSHA code (Reference 224). To evaluate PSHA based on mean hazard, the mean recurrence interval and its uncertainty distribution should be converted to mean activity rate with associated uncertainty. The final discretized activity rates used to model the UCSS in the PSHA reflect a mean recurrence of 548 years and 958 years for the 2000-year and 5000-year branches of the logic tree, respectively. Lognormal uncertainty distributions in activity rate are obtained by the following steps:

1. Invert the mean recurrence intervals to get mean activity rates.

2. Calculate median activity rates using the mean rates and lognormal shape factors of 0.25 and 0.51 established for the 2000-year and 5000-year records, respectively.

3. Determine the lognormal distributions based on the calculated median rate and shape factors.

The lognormal distributions of activity rate can then be discretized to obtain individual activity rates with corresponding weights.

2.5.2.4.4.3 Cuba and Northern Caribbean Source Model

This subsection describes the seismic source characterization developed for Units 6 & 7 of the Cuba area and the North America-Caribbean plate boundary region. Subsections 2.5.1.1.2 and 2.5.1.1.1.3.2.4 describe the geologic and seismic information assessed in support of the development of this seismic source characterization. The original EPRI study did not model this region, despite the presence of major active earthquake sources (Figures 2.5.2-214 and 2.5.2-215).

In order to evaluate contributions to seismic hazards from all portions of the 200-mile radius site region, and contributions from more distant but potentially significant seismic sources, additional seismic sources in the Cuba area and the North America-Caribbean plate boundary region are required to supplement the updated EPRI source model.

The seismic source characterization of Cuba and the North America-Caribbean plate boundary region was performed through the use of a Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 process. This process involves input from recognized experts and a Technical Integrator (TI) team to characterize specific seismic source parameters and associated parametric uncertainty and to assess an overall regional seismic source model that captures the hazard contributed from each seismic source (Reference 318).

A SSHAC Level 2 study is required to develop a seismic source model because there is no seismic source model approved by the NRC (e.g., EPRI) that covers the Cuba area and the North America-Caribbean plate boundary region. The SSHAC process has been approved by the NRC in RG 1.208 as an acceptable approach for developing a seismic source model outside the CEUS and the SSHAC Level 2 assessment is considered acceptable for a site-specific application. A detailed discussion of the SSHAC Level 2 process is provided in Subsection 2.5.2.4.4.3.1.

The northern boundary of the new Cuba and northern Caribbean seismic source model lies north of, and roughly parallel to, northern Cuba, partially within the Units 6 &7 site region. To avoid double-counting earthquakes between the new supplemental sources described in Subsection 2.5.2.4.4.1 and the new Caribbean seismic sources, the supplemental sources have all been truncated southward by the northern boundary of the new Cuba and northern Caribbean seismic source model (Figures 2.5.2-204 through 2.5.2-209).

There are many earthquake catalogs that list historical and instrumental earthquakes within portions of the Cuba area and the North America-Caribbean plate boundary region, but no single earthquake catalog includes sufficient coverage for assessing earthquake occurrence within this region. Data were compiled from regional and global catalogs into the Phase 2 earthquake catalog that covers the region 15° and 24° N, and 100° to 65° W for all time through mid-March 2008 (Figure 2.5.2-216). Subsection 2.5.2.1.3 describes in detail the development of the Phase 2 earthquake catalog. The Phase 2 earthquake catalog, along with earthquake descriptions from the published literature, was used to constrain maximum magnitude estimates for seismic sources within the Cuba area and the North America-Caribbean plate boundary region.

2.5.2.4.4.3.1 Implementation of the SSHAC Level 2 Process

A SSHAC Level 2 study was performed to incorporate current literature, data, and the understanding of experts into a new Cuba and northern Caribbean seismic source model. SSHAC (Reference 318) outlines this methodology and provides guidance on incorporating uncertainty and the use of experts in PSHA studies. The goal of the SSHAC process is to represent the range of current understanding of seismic source parameters by the informed technical community.

SSHAC (Reference 318) describes four levels of study (Levels 1 through 4), in increasing order of sophistication and effort. The choice of the level of a PSHA is driven by two factors: (1) the degree of uncertainty and contention associated with the particular project, and (2) the amount of resources available for the study (Reference 318). SSHAC (Reference 318, Table 3-1) suggests that a Level 2 study is appropriate for issues with "significant uncertainty and diversity," and for issues that are "controversial" and "complex."

The SSHAC Level 2 process utilizes an individual, team, or company to act as the TI. In a SSHAC Level 2 study, the TI is responsible for reviewing data and literature and contacting experts who have developed interpretations or who have specific knowledge of the seismic sources. The TI interacts with experts to identify

issues and interpretations, and to assess the body and range of informed expert opinion.

This TI team: (1) compiled and reviewed literature pertaining to the geology, tectonics, and seismicity of Cuba and the Northern Caribbean; (2) contacted scientists familiar with recent and ongoing research in the study region; and (3) integrated this information to develop a seismic source characterization of the Cuba area and the North America-Caribbean plate boundary region that captures the body and range of views of the informed technical community. Table 2.5.2-216 provides a tabulation of the experts contacted as part of the SSHAC Level 2 process.

The experts listed in Table 2.5.2-216 were provided with a standard questionnaire pertaining to key issues regarding seismic sources in Cuba and the northern Caribbean. This survey was not a formal process of interrogation to obtain from each expert all of the specific parameters and weights to be used in the model. Instead, the experts were asked to speak to their own areas of expertise. It was then the TI's responsibility to combine these responses with data from the published literature to capture the body and range of expert opinion and judgment regarding parameters and weights to be used in the seismic source model.

The seismic source model presented herein represents the TI's assessment of the body and range of informed expert opinion regarding seismic sources in Cuba and the northern Caribbean. The seismic source model parameters for geometry, Mmax, and recurrence of Mmax are the TI's assessment of the body and range of expert interpretations.

2.5.2.4.4.3.2 Seismic Source Characterization

The seismic source characterization of the Cuba and North America-Caribbean plate boundary region comprises ten seismic sources, including one areal source for Cuba and nine fault sources that represent tectonic elements of the North America-Caribbean plate boundary region to a distance of approximately 900 miles from the Units 6 & 7 site. Taken together, these seismic sources represent an appropriate model of earthquake recurrence on and near the North America-Caribbean plate boundary. Given that these sources are all located at significant distances from the Units 6 & 7 site (approximately 140 to 760 miles), some generalization of the source model geometry is justified to compute contributions to ground motion at the Units 6 & 7 site. The seismic sources, identified in Figure 2.5.2-217, are as follows:

- Cuba areal source zone
- Oriente fault – western
- Oriente fault – eastern
- Septentrional fault
- Northern Hispaniola fault – western
- Northern Hispaniola fault – eastern
- Swan Islands fault – western
- Swan Islands fault – eastern
- Walton-Duanvale fault
- Enriquillo-Plantain Garden fault

These ten seismic sources are based on geologic, geophysical, and seismic data described in Subsections 2.5.1.1.1.3.2.4 (Cuba) and 2.5.1.1.2.3 (Active Tectonic Structures of the Northern Caribbean Plate). Subsection 2.5.1.1.2.3 also describes tectonic features that are too distant from the Units 6 & 7 site to contribute to the ground motion hazard, even from the largest earthquakes that could occur in them. These distant tectonic features are not included in the seismic source characterization, and include the Muertos Trough, Mona Passage extensional zone, eastern portion of the Puerto Rico Trench, and the Beata Ridge (Figure 2.5.1-202). The decision to exclude these tectonic features from this seismic source characterization is based on the assessment that these tectonic features would not significantly contribute to ground motion hazard at the Units 6 & 7 site. Specifically, this assessment is based on the great site-to-source distances for these tectonic features.

Table 2.5.2-217 presents a summary of source parameters for the ten seismic sources in the seismic source characterization. Geographic coordinates of the Cuba areal source zone and the nine fault sources are presented in Tables 2.5.2-218 and 2.5.2-219, respectively.

The seismic source characterization presented in this subsection appropriately generalizes source geometries. Earthquake occurrence, derived from slip rates and Mmax earthquakes, sufficiently captures the hazard contribution of these

sources at the Units 6 & 7 site. This reflects the intention of the source characterization to capture the contribution to ground motions at the Units 6 & 7 site due to large-magnitude earthquakes on distant sources.

Cuba Areal Source Zone

The Cuba areal source zone is characterized with a maximum magnitude (Mmax) earthquake distribution determined by historical seismicity, published values, fault lengths, and the TI team's assessment of the body and range of informed technical knowledge. {An exponential recurrence model describes Mmax earthquake behavior for the areal source zone, with calculated recurrence parameters (a- and b-values) based on observed seismicity.} For Cuba, which is partially inside the 200-mile radius site region, an areal source model is adopted because of the lack of knowledge about fault behavior and slip rates for Cuban faults with which to support assessment of fault-specific sources. SOF 2.5.2-8

North America-Caribbean Fault Sources

Major faults along the North America-Caribbean plate boundary are represented in the source model by fault sources. For the North America-Caribbean plate boundary faults, generalized source geometry is acceptable because of the distances (about 420 miles or more) from the Units 6 & 7 site to the sources. Thus, generalized source models and recurrence models that capture the hazard contributions of the largest earthquakes are sufficient for evaluating sensitivity of these sources to the ground-motion hazards at the site.

Earthquake activity is modeled based on assessments of fault slip rate (based on geodetic and paleoseismic data, as well as plate boundary reconstruction data), effective seismic coupling (the fraction or ratio of slip rate accommodated during large, main-shock earthquakes), and Mmax. {Mmax, in turn, is determined based on estimates of fault source geometry (fault length, fault width, and fault area) and published empirical relations between earthquake magnitude and fault area or earthquake magnitude and fault length.} SOF 2.5.2-21

The fault sources are characterized by fault slip rate, effective seismic coupling (the fraction or ratio of slip rate accommodated during large, main-shock earthquakes), and Mmax, with logic trees containing values and weights that integrate the knowledge base described in published literature and the informed opinions of scientists familiar with recent and ongoing research in the study region (Table 2.5.2-216). The rupture model assumes pure characteristic behavior. Because the attenuation model developed for the region does not require inputs

of fault depth, dip direction, and slip type, those parameters are not reviewed here. In most cases, fault slip rate is determined from published geodetic rates using network Global Positioning System (GPS) geodetic data, with additional information provided by geologic and paleoseismic studies.

Seismic coupling ratios are estimated based on historical seismicity rates, published modeling experiments, analogs with similar tectonic environments, and judgment. For the two modeled thrust fault sources with non-vertical dips (the western and eastern portions of the Northern Hispaniola fault), earthquakes are assumed to occur on the fault's surface trace. This is a conservative modeling decision because the two thrust fault sources dip to the south. By constraining earthquake locations to the surface traces of these two thrust faults, source-to-site distances are minimized. Mmax is determined based on consideration of historical seismicity and empirical moment-area and moment-length scaling relationships. Fault length and fault area are defined either by the total source length or, where a single source can arguably be divided into several rupture segments, the length of the longest rupture segment.

For all fault sources in the model regardless of slip type, consideration is given to:

- The empirical rupture area-magnitude relation of Wells and Coppersmith (Reference 334) for all slip types.
- The empirical rupture area-magnitude relation of Wyss (Reference 339).
- The rupture length-magnitude relation of Wells and Coppersmith (Reference 334) for all slip types.

For strike-slip fault sources in the model, additional consideration is given to the empirical rupture area-magnitude relations of:

- Hanks and Bakun (Reference 262).
- Working Group on California Earthquake Predictions (WGCEP) (Reference 337).

For subduction zone fault sources in the model (i.e., western and eastern portions of the Northern Hispaniola fault), additional consideration is given to:

- The empirical rupture area-magnitude relation of Abe (References 201 and 202).

- The empirical rupture area-magnitude relation of Geomatrix (Reference 257).
- The empirical rupture length-magnitude relation of Geomatrix (Reference 257).

Table 2.5.2-220 presents a summary of these empirical relations. The range of results from the various empirical relations guided assessment of the final magnitudes and weights on the logic trees.

2.5.2.4.4.3.2.1 Cuba Areal Source Zone

The single areal source zone representing Cuba (Figure 2.5.2-217) encompasses the major tectonic elements on the island and the majority of the historical seismicity. Subsection 2.5.1.1.1.3.2.4 provides discussion of geologic, geophysical, and seismic data for Cuba. The northern and eastern boundary of the source zone is drawn near the base of the submarine escarpment that marks the location of the Nortecubana fault suture and the geologic boundary between the relatively undeformed North American crust of the Bahama Platform and the highly attenuated crust of the former leading edge of the plate boundary zone (Figures 2.5.1-210 and 2.5.1-202). To account for uncertainty in the position of the boundary, a buffer of 12.5 miles from the base of the escarpment toward the north and east was added to the Cuba areal source zone. This buffer was added to account for poorly located earthquakes that probably occurred within the Cuba island arc region and/or a zone of fractured and faulted crust beyond the suture zone that formed during early Cenozoic subduction. The western boundary of the Cuba areal source zone is based on bathymetry and the locations and density of historical seismicity. This boundary approximately follows the boundary between the Yucatan Basin and the continental shelf surrounding Cuba. The southern boundary of the Cuba source zone coincides with the southern boundary of Cuba and the steep submarine escarpment that borders the Oriente fault. At closest approach, the Cuba areal source zone is located about 140 miles from the Units 6 & 7 site. The Cuba areal source is associated with moderately abundant seismicity that is distributed throughout the source (Figure 2.5.2-217). There appears to be higher concentration of epicenters in the southeastern portion of the Cuba areal source, near the active plate boundary and the eastern and western Oriente fault sources. Also, there appears to be a higher concentration of epicenters distributed along the northern coast and near-shore portions of Cuba within the Cuba areal source. The largest earthquakes from the Phase 2 catalog associated with this source are the 1551 M_w 5.98 event in southeastern Cuba, the 1880 M_w 6.13 event in western Cuba, and 1914 M_w 6.29 event offshore northeastern Cuba.

For Cuba, which is partially inside the 200-mile radius site region, an areal source model is adopted because of the lack of knowledge about specific fault behavior and slip rates for Cuban faults. As described in Subsection 2.5.1.1.1.3.2.4 there are several major crustal faults mapped in Cuba. However, these faults and the earthquake activity in Cuba are insufficiently described in the literature to warrant fault sources in the seismic source characterization. Specifically:

- No fault is characterized with a late Quaternary slip-rate.
- No fault has unambiguous data to constrain the recurrence of large earthquakes.
- Poorly located earthquakes and the limited number of focal mechanisms preclude the association of earthquakes with mapped faults in Cuba.
- Subsection 2.5.1.1.1.3.2.4 describes the most detailed available geologic maps of Cuba, including the 1:500,000-scale Mapa Geológico de Republica de Cuba (Reference 231), the 1:250,000-scale Mapa Geológico de Cuba (Reference 233), and the 1:500,000-scale Mapa Tectonico de Cuba (Reference 234). The scale and quality of these geologic and tectonic maps of Cuba are inadequate to support an assessment of potential activity, geometry, and segmentation of faults.

Recent peer-reviewed literature provides support for the assessment of the lack of knowledge regarding the state of fault mapping in Cuba. For example, Cotilla-Rodríguez et al. (Reference 321) states, "...the detailed association between destructive earthquakes and active tectonic features is extremely complex and not known in depth [...] there is not a close correlation of seismic events with individual faults in Cuba." Furthermore, Cotilla-Rodríguez et al. (Reference 321) states, "...most [historical, pre-instrumental earthquakes] have scarce data and do not permit a clear association to a seismic zone. There is no uniform knowledge about the historical seismicity of Cuba..."

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Garcia et al. (Reference 254) present seismic hazard maps for Cuba that are based on seismogenic zone (SZ) source zones. Their SZs are narrow, elongated, areal seismic sources intended to represent potentially active faults. Seismicity rates for these "fault-like" SZs are not based on geologic- or geodetic-based fault slip rates because these data do not appear to exist. Instead, Garcia et al.'s (Reference 254) SZs are large enough to envelop sufficient numbers of earthquakes to estimate separate rates of seismicity for each source from the earthquakes observed within that source. In a subsequent publication, Garcia et

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al. (Reference 255) compare the results of their earlier SZ approach with those obtained by their implementation of a smoothed seismicity approach to hazard. Relative to the results obtained from their smoothed seismicity approach, Reference 255 concludes that the seismotectonic zone approach tends to result in slightly higher PGA values in northwestern Cuba. They indicate that "an improvement of the seismicity data collection would be welcome for a better knowledge of the seismicity in northwestern Cuba" (Reference 255). Moreover, they indicate that "although the definition of SZs is positive because it focuses on understanding the regional tectonics, this exercise could be misleading when not supported by data. Consequently, a mixture of the two approaches would probably be the best solution: a seismotectonic approach for the more seismic areas and only seismicity elsewhere" (Reference 255). According to Garcia et al. (Reference 255), "the northern intraplate region [of Cuba] is related to a moderate to low seismicity." This observation of low to moderate rates of seismicity in northern Cuba is consistent with observations made from the Phase 2 earthquake catalog, which indicates a higher concentration of earthquakes and higher magnitudes in southernmost Cuba at and near the modern plate boundary relative to the rest of the island. Therefore, Garcia et al.'s (Reference 254) seismotectonic zone approach may not be applicable to the moderate to low seismicity areas of northern Cuba.

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As described in Subsection 2.5.1.1.1.3.2.4, the available GPS geodetic data are from Cuba (from only one station, which is located at Guantanamo Bay, near the plate boundary) and from nearby stations in Florida and the Caribbean. These data indicate deformation rates across Cuba relative to North America of <3 millimeters/year, and likely much less. However, data are insufficient to determine which faults or tectonic structures in Cuba accommodate this low deformation budget.

Hence, the island of Cuba is represented in the model as an areal source zone modeled with catalog seismicity representing earthquake activity. Earthquake rates within the Cuba areal source zone are determined from an analysis of completeness and an evaluation of earthquake magnitude-frequency for the source zone, and a Gutenberg-Richter relation is tested and represented by the parameters a- and b-values. Maximum magnitude values for Cuba are based on previous Cuba source models, historical seismicity, published literature, and estimates of fault capability based on assessments of possible fault dimensions and empirical moment-area and moment-length scaling relationships.

Table 2.5.2-217 summarizes source parameters for the Cuba areal source zone. The distribution of Mmax shows equal weight to branches with M_w = 7.0 and M_w =

7.25. This magnitude distribution is larger than the maximum instrumented earthquake in the catalog (February 1914 M_w ~6.3) and larger than the maximum historical earthquake (January 1880 M_w ~6.1) (Table 2.5.2-221). Our Mmax distribution is consistent with a recently published source model for Cuba, the Garcia et al. study (Reference 254), that shows a Mmax upper limit of M_S 7.0 for intraplate Cuba sources. The Garcia et al. study (Reference 254) is based on previous source characterizations of Cuba's historical seismicity, and assessment of fault capability. Garcia et al.'s study (Reference 255) assigns M_S 6.5 to their intraplate Cuba zone. The M_w 7 to 7.25 range of Mmax for Cuba presented herein is consistent with rupture lengths of about 50 to 80 kilometers and rupture thicknesses of about 12 to 18 kilometers. These rupture dimensions are reasonable given the lengths of major crustal faults in Cuba such as the Pinar, Nortecubana, and Cauto-Nipe faults (Reference 226) and estimates of Cuban crustal thickness (Reference 327).

2.5.2.4.4.3.2.2 {Oriente Fault — Western SOF 2.5.2-21

At closest approach, the western Oriente fault source is located about 420 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.1.1.2 provides discussion of the geologic, geodetic, and seismic characteristics of the Oriente fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The western Oriente fault source is associated with abundant seismicity along its length, with an apparent concentration of epicenters at its western end near the Cayman trough (Figure 2.5.2-217). Seismicity also appears concentrated near its eastern end near where the western and eastern segments of the Oriente fault form a transtensional step-over (Figure 2.5.2-217). The largest earthquakes from the Phase 2 catalog associated with this source are the 1917 M_w 7.20 and 1992 M_w 6.80 events.

The slip rate distribution [and weights] for the western Oriente fault is 8 [0.1], 11 [0.7], and 13 [0.2] millimeters/year based on the GPS results of DeMets et al. (Reference 230) and DeMets and Wiggins-Grandison (Reference 229). The significant weight (0.4) given to seismic coupling ratios less than 1.0 is based on the thin, warm crust of the Cayman Trough that typifies the south side of the fault for most of its length (Reference 326), low seismic coupling ratios noted globally for oceanic transform faults (Reference 299), and the lack of large earthquakes historically (Table 2.5.2-221).

The Mmax distribution [and weights] for the western Oriente fault is M_w 7.5 [0.3], 7.7 [0.4], and 8.0 [0.3] (Table 2.5.2-217). These values are based on rupture

dimensions 300 to 490 kilometers long and 6 to 10 kilometers wide. Values higher than M_w 8.0 are obtained using empirical magnitude-rupture length relations for lengths greater than about 300 kilometers. However, these higher values are countered by the fact that longer rupture lengths involve very warm and thin crust near the mid-Cayman spreading center. The Mmax distribution exceeds the historical maximum magnitude earthquakes recorded near the eastern portion of this source in 1917 (M_w 7.2) and 1992 (M_w 6.8) (Subsection 2.5.2.1.3).

2.5.2.4.4.3.2.3 Oriente Fault — Eastern

At closest approach, the eastern Oriente fault source is located about 445 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.1.2 provides discussion of the geologic, geodetic, and seismic characteristics of the Oriente fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The eastern Oriente fault source is associated with abundant seismicity along its length, with an apparent concentration of epicenters along its west-central portion, just offshore of southernmost Cuba near the city of Santiago de Cuba (Figure 2.5.2-217). The largest earthquake from the Phase 2 catalog associated with this source is the historical 1766 M_w 7.53 event.

The slip rate distribution and weighting for the eastern Oriente fault are identical to the western Oriente fault source. The seismic coupling ratio on the eastern Oriente fault is assigned a value of 1.0 given the repeated large earthquakes on the fault historically (Table 2.5.2-221).

The Mmax distribution [and weights] for the eastern Oriente fault is M_w 7.5 [0.2], 7.7 [0.6], and 7.9 [0.2] (Table 2.5.2-217). These values are based on rupture dimensions about 140 to 200 kilometers long (from mapped segments on the Oriente fault and Santiago deformed belt in Reference 222) and 15 to about 40 kilometers wide (References 326, 327, and 331). Values higher than M_w 7.9 are obtained using the empirical strike-slip magnitude-area relations of Hanks and Bakun (Reference 262) and WGCEP (Reference 337) for rupture widths greater than about 20 kilometers. These higher values are not used given the recognition that rupture dimensions involving widths greater than 20 kilometers would likely occur on the Santiago deformed belt with a strong reverse-oblique component, and this style of faulting is not captured in the strike-slip empirical databases. Instead, empirical values for the “all slip type” relation of Wells and Coppersmith (Reference 334) that yield an upper limit of M_w 7.9 are preferred for the larger rupture dimensions. The Mmax distribution exceeds the historical maximum magnitude earthquake of M_w 7.53 in June 1766 (Table 2.5.2-221).

2.5.2.4.4.3.2.4 Septentrional Fault

At closest approach, the Septentrional fault source is located about 545 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.2.1 provides discussion of the geologic, geodetic, and seismic characteristics of the Septentrional fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The Septentrional fault source is associated with abundant seismicity along its entire length (Figure 2.5.2-217). The largest earthquakes from the Phase 2 catalog associated with this source are the historical 1842 M_w 8.23 and 1887 M_w 7.93 events.

The slip rate distribution [and weights] for the Septentrional fault is 6 [0.2], 9 [0.6], and 12 [0.2] millimeters/year based on the geologic slip rate of Prentice et al. (Reference 304) and GPS-based results of Manaker et al. (Reference 273). The seismic coupling ratio on the Septentrional fault is assigned a value of 1.0 given the repeated large to great earthquakes on the fault historically (Table 2.5.2-221).

The Mmax distribution [and weights] for the Septentrional fault is M_w 8.0 [0.5] and 8.25 [0.5] (Table 2.5.2-217). These values are based on the magnitude estimates of the historical 1842 rupture (Table 2.5.2-221). Equal weight is given to the lower magnitude estimate for this earthquake partially based on recognizing that strike-slip earthquakes greater than magnitude M_w 7.9 to 8.0 are exceedingly rare in the instrumental record globally. These values are consistent with rupture dimensions of about 350 kilometers long and 15 to 18 kilometers wide.

2.5.2.4.4.3.2.5 Northern Hispaniola Fault — Western

At closest approach, the western Northern Hispaniola fault source is located about 550 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.2.2 provides discussion of the geologic, geodetic, and seismic characteristics of the Northern Hispaniola fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The western Northern Hispaniola fault source is associated with abundant seismicity along its entire length, with an especially high concentration of epicenters along its central and eastern portions (Figure 2.5.2-217). The largest earthquake from the Phase 2 catalog associated with this source is the 1953 M_w 6.93 event.

The slip rate distribution [and weights] is 4 [0.2], 6 [0.7], 8 [0.1] millimeters/year based on the GPS results of Calais et al. (Reference 220) and Manaker et al. (Reference 273). The source is modeled with a seismic coupling ratio of 1.0 based on goodness-of-fit with elastic block and fault modeling (Reference 273).

The Mmax distribution [and weights] for the western portion of the Northern Hispaniola fault is M_w 7.8 [0.2], 8.0 [0.6], and 8.3 [0.2] (Table 2.5.2-217). These values are based on rupture dimensions of 200 to 350 kilometers long and 30 to 60 kilometers wide (assumed locking depth of 12 to 20 kilometers and fault dip of 20° to 25°). The Mmax distribution exceeds the historical maximum magnitude earthquake of M_w 6.93 in May 1953 recorded at the eastern end of this source (Table 2.5.2-221). Earthquakes on the south-dipping western Northern Hispaniola fault are assumed to occur on the fault's surface trace.

2.5.2.4.4.3.2.6 Northern Hispaniola Fault — Eastern

At closest approach, the eastern Northern Hispaniola fault source is located about 760 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.2.2 provides discussion of the geologic, geodetic, and seismic characteristics of the Northern Hispaniola fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The eastern Northern Hispaniola fault source is associated with abundant seismicity along its entire length, much of which appears in map view to the south of the surface trace of this south-dipping fault (Figure 2.5.2-217). The largest earthquake from the Phase 2 catalog associated with this source is the 1946 M_w 7.90 event.

The slip rate distribution and weighting for the eastern fault source are identical to the western fault source. Similarly, the seismic coupling ratio on the eastern portion of the Northern Hispaniola fault is 1.0 given the modeling results of Manaker et al. (Reference 273) and the historical great earthquake on the fault in August 1946 (Table 2.5.2-221).

The Mmax distribution (and weights) for the eastern Northern Hispaniola fault is M_w 8.0 [0.2], 8.3 [0.6], and 8.6 [0.2] (Table 2.5.2-217). These values are based on the 1946 M_w 7.90 historical event and rupture dimensions about 200 to 400 kilometers long and 50 to about 100 kilometers wide (assumed locking depths of 20 to 35 kilometers and fault dip of 20° to 25°). Earthquakes on the south-dipping eastern Northern Hispaniola fault are assumed to occur on the fault's surface trace.

2.5.2.4.4.3.2.7 Swan Islands Fault — Western

At closest approach, the western Swan Islands fault source is located 620 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.1.1 provides discussion of the geologic, geodetic, and seismic characteristics of the Swan Islands fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The western Swan Islands fault source is associated with abundant seismicity along its entire length (Figure 2.5.2-217). The largest earthquake from the Phase 2 catalog associated with this source is the historical 1856 M_w 7.69 event.

The slip rate distribution [and weights] is 18 [0.2], 19 [0.6], and 20 [0.2] millimeters/year based on the GPS-derived relative plate motion rate of DeMets et al. (Reference 230). The seismic coupling ratio on the western Swan Islands fault is assigned a value of 1.0 given the possible repeated great earthquakes on the fault historically (Table 2.5.2-221).

The Mmax distribution [and weights] for the western Swan Islands fault is M_w 7.8 [0.2], 8.0 [0.7], and 8.3 [0.1] (Table 2.5.2-217). These values are based on the magnitude estimate of the historical M_w 7.69 1856 earthquake (Table 2.5.2-221). These values are consistent with rupture dimensions of about 350 to 500 kilometers long and 10 to 15 kilometers wide. The low weight assigned to the historical estimate of M 8.3 is based on recognizing that strike-slip earthquakes greater than magnitude M_w 7.9 to 8.0 are exceedingly rare in the instrumental record globally, and that only the largest rupture dimensions considered for the western Swan Islands fault source results in an empirical estimate of M_w 8.3.

2.5.2.4.4.3.2.8 Swan Islands Fault — Eastern

At closest approach, the eastern Swan Islands fault source is located 540 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.1.1 provides discussion of the geologic, geodetic, and seismic characteristics of the Swan Islands fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The eastern Swan Islands fault source is associated with abundant seismicity along its entire length, with an apparent concentration of epicenters located near its eastern end near the Cayman trough (Figure 2.5.2-217). No earthquakes from the Phase 2 catalog greater than or equal to M_w 6.75 are associated with this source.

The slip rate distribution and weighting are identical to the western Swan Islands fault source. The significant weight of 0.4 to seismic coupling ratios less than 1.0

is based on the thin, warm crust of the Cayman Trough that typifies the north side of the fault source for most of its length (Reference 326), low seismic coupling ratios noted globally for oceanic transform faults (Reference 299), and the lack of large earthquakes historically (Table 2.5.2-221).

The Mmax distribution [and weights] for the eastern Swan Islands fault is M_w 7.2 [0.4], 7.5 [0.5], and 7.7 [0.1] (Table 2.5.2-217). These values are based on rupture dimensions of 130 to 200 kilometers long (from mapping by Rosencrantz and Mann, Reference 310) and 8 to 15 kilometers wide. The low weight on the highest magnitude reflects the recognition that a rupture length of 200 kilometers would at least partially involve very warm and thin crust near the mid-Cayman spreading center, and thus a 15-kilometer wide average fault rupture is unlikely. No historical earthquakes greater than or equal to M_w 6.75 are recorded near this source (Reference 331) (Table 2.5.2-221).

2.5.2.4.4.3.2.9 Walton-Duanvale Fault

At closest approach, the Walton-Duanvale fault source is located 490 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.2.3 provides discussion of the geologic, geodetic, and seismic characteristics of the Walton-Duanvale fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The Walton-Duanvale fault source is associated with moderately abundant seismicity along its length, with an apparent concentration of epicenters located near its western end near the Cayman trough (Figure 2.5.2-217). Seismicity also appears concentrated at the eastern end of this source near Jamaica, where the left-lateral Walton-Duanvale and Enriquillo-Plantain Garden faults form a restraining bend. The largest earthquakes from the Phase 2 catalog associated with this source are the two approximately M_w 6.6 events that occurred in 1907 and 1957.

The slip rate distribution [and weights] is 6 [0.2], 8 [0.6], 10 [0.2] millimeters/year based on the GPS data of DeMets and Wiggins-Grandison (Reference 229). The weight of 0.3 for a seismic coupling ratio less than 1.0 is based on the thin, warm crust of the Cayman Trough that typifies the north side of the fault for much of its length (Reference 326), low seismic coupling ratios noted globally for oceanic transform faults (Reference 299), and the lack of large earthquakes historically (Table 2.5.2-221).

The Mmax distribution [and weights] for the Walton-Duanvale fault source is M_w 7.3 [0.3], 7.6 [0.6], and 7.8 [0.1] (Table 2.5.2-217). These values are based on rupture dimensions of 140 to 215 kilometers long and 6 to 10 kilometers wide. The Mmax distribution exceeds the historical maximum magnitude earthquakes of about M_w 6.6 in January 1907 and March 1957 recorded near the eastern portion of this source (Table 2.5.2-221).

2.5.2.4.4.3.2.10 Enriquillo-Plantain Garden Fault

At closest approach, the western Enriquillo-Plantain Garden fault source is located 560 miles from the Units 6 & 7 site (Figure 2.5.2-217). Subsection 2.5.1.1.2.3.2.3 provides discussion of the geologic, geodetic, and seismic characteristics of the Enriquillo-Plantain Garden fault. Table 2.5.2-217 summarizes source parameters for this fault source.

The Enriquillo-Plantain Garden fault source is associated with abundant seismicity along its length, with apparent concentrations of epicenters at its western and eastern ends (Figure 2.5.2-217). Multiple large historical earthquakes have ruptured along the Enriquillo-Plantain Garden fault (Reference 282), including from the Phase 2 catalog the 1692 M_w 7.78 earthquake near Jamaica and the 1751 M_w 7.28 and 1770 M_w 7.53 earthquakes near Port-au-Prince, Haiti.

The slip rate distribution and weighting are identical to the Walton-Duanvale fault source. The seismic coupling ratio on the Enriquillo-Plantain Garden fault source is assigned a value of 1.0 given the repeated large earthquakes on the fault historically (Table 2.5.2-221) and the goodness-of-fit with elastic block and fault modeling (Reference 273).

The Mmax distribution [and weights] for the Enriquillo-Plantain Garden fault is M_w 7.5 [0.2], 7.7 [0.6], and 7.9 [0.2] (Table 2.5.2-217). These values are based on rupture dimensions of about 120 to 250 kilometers long (from mapping by Mann et al., Reference 276) and 15 to about 18 kilometers wide. The Mmax distribution is comparable to the upper estimates of historical earthquakes attributed to this source, including the June 1692 M_w 7.78, the October 1751 M_w 7.28, the June 1770 M_w 7.53, and the April 1860 M_w 6.73 earthquakes (Table 2.5.2-221)}.

Based on the slip rates and maximum magnitudes considered for this fault source, the 2010 M_w 7.0 Haiti earthquake, which occurred within the Enriquillo fault zone, is predictable (Subsection 2.5.1.1.2.3.2.3) and completely within the magnitude and recurrence assessments incorporated into the updated PSHA for the Units 6 & 7 site.

2.5.2.4.4.3.3 Comparison of Seismic Source Parameters with USGS Initial Seismic Hazard Maps for Haiti

The USGS initial seismic hazard maps for Haiti by Frankel et al. (Reference 235) are based on the available information on seismic source parameters and seismicity data obtained immediately following the M_w 7.0 January 12, 2010, Haiti earthquake (Reference 235). They emphasize the preliminary nature of their model, indicating that it was developed in response to the urgent need for earthquake hazard information and that, "more extensive logic trees will be developed to better capture the uncertainty in key parameters" (Reference 235, p. 1).

Frankel et al. (Reference 235) characterize a total of seven fault sources, four of which also are included in the seismic source characterization of Cuba and the North America-Caribbean plate boundary region developed as part of the updated PSHA for the Units 6 & 7 site. The four seismic sources common to both Frankel et al.'s model (Reference 235) and the model developed for the 6 & 7 site study include the following sources: the Enriquillo-Plantain Garden fault, Septentrional fault, Northern Hispaniola fault – eastern, and Northern Hispaniola fault – western (Subsection 2.5.2.4.4.3.2). The three seismic sources included in Frankel et al.'s model (Reference 235) that are not included in the PSHA update at the Units 6 & 7 site are: the Muertos Trough Neiba segment, the Muertos Trough central segment, and the Matheux Neiba fault sources. The Muertos Trough segments are not included in the Units 6 & 7 site characterization because of their great distance from the site (about 1210 kilometers [750 miles] at their nearest approach). Likewise, the Matheux Neiba fault is not included in the Units 6 & 7 site characterization because of its great distance from the site (1045 kilometers [650 miles] at its nearest approach) and its estimated slip rate of 1 millimeter/year (Reference 235) is an order of magnitude lower than other included sources more proximal to the site with equivalent or greater Mmax values.

Table 2.5.2-222 presents a comparison of seismic source parameters from the Frankel et al. (Reference 235) and the Units 6 & 7 site characterizations. In general, there is good agreement between source parameters from these two characterizations. The assigned range of Mmax values equals or exceeds the characteristic magnitude (M_{char}) values defined for the equivalent Frankel et al. (Reference 235) sources. The assigned range of slip rate values to the Enriquillo-Plantain Garden fault and Northern Hispaniola fault – western sources envelops or exceeds the equivalent values from Frankel et al.'s characterization (Reference 235). The assigned range of slip rate values to the Septentrional fault and Northern Hispaniola fault – eastern sources is less than the values defined for

the equivalent Frankel et al.'s sources (Reference 235). However, Frankel et al.'s slip rate estimates for the Septentrional and eastern Northern Hispaniola faults (Reference 235) exceed recently published geodetic and geologic estimates (Subsection 2.5.2.4.4.3.2).

2.5.2.4.4.3.4 Hazard Sensitivity Calculations

PTN RAI 02.05.01-14

Hazard sensitivity calculations were performed to assess the significance of certain aspects of the PSHA for the Turkey Point Units 6 & 7 site. Calculations were performed to assess the potential impact of: (1) the Walkers Cay fault, (2) several faults within Cuba, and (3) different approaches to modeling the Cuba areal source zone.

2.5.2.4.4.3.4.1 Walkers Cay Fault Hazard Sensitivity Calculation

The Walkers Cay fault lies northeast of the Turkey Point Units 6 & 7 site and straddles the 200-mile site region boundary (Figure 2.5.1-366). Subsection 2.5.1.1.1.3.2.2 describes geologic and seismic reflection data for the Walkers Cay fault. Based on the available data that suggest possible faulting of the seafloor, Quaternary activity on the Walkers Cay fault cannot be precluded. For this reason, a hazard sensitivity calculation was performed to assess the potential impact of a Walkers Cay fault source on the PSHA for the Turkey Point Units 6 & 7 site.

The geometry of the Walkers Cay fault source is based on the mapping of Mullins and Van Buren (Reference 355). For the purposes of the hazard sensitivity calculation, the Walkers Cay fault is assumed to have a vertical dip angle and a rupture depth from 0–15 kilometers (0-9 miles). The characteristic magnitude for the Walkers Cay fault source is based on the empirical surface rupture length-magnitude regression from Wells and Coppersmith (Reference 334) for all fault types, assuming a surface rupture length equal to the 33-kilometer (21-mile) mapped length of the fault. This regression provides a median value of M_w 6.8. Uncertainty associated with this value is accounted for in the hazard sensitivity calculation by allowing earthquakes of 0.2 magnitude units larger or smaller than the characteristic event. The characteristic magnitude distribution [and weights] assigned to the Walkers Cay fault source is: M_w 6.6 [0.2], 6.8 [0.6], 7.0 [0.2].

There are no data with which to directly determine the late Quaternary slip rate on the Walkers Cay fault. There are, however, data and observations that can be used to constrain possible slip rate values for the Walkers Cay fault source. The slip rate distribution in millimeters/year [and weights] assigned to the Walkers Cay

fault source for the hazard sensitivity calculation is: 0.001 [0.2], 0.01 [0.6], 0.05 [0.2]. The largest weight in this distribution is accorded to a slip rate of 0.01 millimeters/year, which appears to represent a limiting rate beyond which there would be a significant likelihood that vertical separations of Quaternary and Pliocene deposits would be sufficiently large to be observable within the presently available data. Also, the lack of perturbations observed in structure contours of Miocene- and Cretaceous-age contacts in the vicinity of the Walkers Cay fault suggests that the total amount of vertical separation across the fault likely is on the order of tens of meters or less. PTN RAI 02.05.01-14

For the purpose of the hazard sensitivity calculation, a characteristic earthquake recurrence model (Reference 356) but with no contribution from an exponential portion of the recurrence curve at lower magnitudes is assumed for the Walkers Cay fault source. Walkers Cay fault hazard is calculated using the Mid-Continent crustal model and non-rifted coefficients from the EPRI 2004 attenuation relations.

The results of the sensitivity study indicate that adding the Walkers Cay fault to the total hazard results in 10^{-4} mean annual frequency of exceedance (MAFE) amplitudes that are 0.3 percent higher at 1 Hz and 0.5 percent higher at 10 Hz, and annual frequencies of exceedance, at the FSAR 10^{-4} MAFE amplitudes, that are 0.7 percent higher at 1 Hz and 1.0 percent higher at 10 Hz. As such, the results of the hazard sensitivity calculation based on the conservative seismic source characterization of the Walkers Cay fault indicate that further consideration of the Walkers Cay fault for the Turkey Point Units 6 & 7 site hazard is unwarranted due to its insignificant contribution to site hazard.

2.5.2.4.4.3.4.2 Cuba Hazard Sensitivity Calculations

PTN RAI 02.05.02-4

This subsection describes the characterization and results of intraplate Cuba seismic sources for use in a hazard sensitivity calculation performed to assess the potential impact on the Turkey Point Units 6 & 7 PSHA. As described in Subsection 2.5.1.1.1.3.2.4, it is unclear which, if any, of the faults in intraplate Cuba are capable tectonic sources. For this reason, hazard sensitivity calculations were performed to assess the potential impact of intraplate Cuba seismic sources. The seismic source parameters for both areal and fault sources used in these hazard sensitivity calculations were developed through the use of the SSHAC Level 2 methodology (Reference 318). Subsection 2.5.2.4.4.3.1 describes the SSHAC Level 2 methodology.

For the SSHAC Level 2 study of Cuba seismic sources, the TI team comprised Dean Ostenaa, Roland LaForge, Scott Lindvall, and Ross Hartleb. Participatory

peer review was provided by Robert Creed. A total of eleven experts were contacted by the TI team with questions regarding the sensitivity calculations. These experts include geologists, seismologists, and hazard analysts from Cuba, the U.S., and elsewhere (Table 2.5.2-232). The level of detail provided to the TI team by the experts varies (Table 2.5.2-232). Some experts provided detailed responses and interacted with the TI team, whereas other experts provided only terse responses. Four experts either declined to participate or did not respond at all. PTN RAI 02.05.02-4

2.5.2.4.4.3.4.2.1 Cuba Seismic Sources for Hazard Sensitivity Calculation

Based on review of published literature and interaction with experts, the TI team developed a seismic source characterization for intraplate Cuba seismic sources for use in a hazard sensitivity calculation to assess the impact on hazard at the Turkey Point Units 6 & 7 site. This subsection describes the characterization of both areal sources and fault sources for the hazard sensitivity calculations.

Three scenarios by which areal source zones are implemented in the hazard sensitivity calculations are summarized below and in Table 2.5.2-233.

- Single areal source zone scenario (Z1): In the single areal source zone model, a single areal source for Cuba is used, with a uniform seismicity rate throughout the zone that is based on observed seismicity from the Phase 2 earthquake catalog (Figure 2.5.2-271). This is the base case for the hazard sensitivity calculations and is the seismic source characterization for intraplate Cuba used in the PSHA (Subsection 2.5.2.4.6). The Z1 model results in a contribution to hazard that is intermediate between the Z6 and Z11% zone scenarios (Table 2.5.2-233).

- Elevated rate areal source zone scenario (Z11%): In the elevated rate zone scenario, a single areal source for Cuba is used, with a uniform seismicity rate throughout the zone that is based on observed seismicity from the Phase 2 earthquake catalog. The geometry of this zone is equivalent to that in the Z1 scenario. Unlike the Z1 scenario, however, the uniform rate for the Z11% scenario is based on a small subzone in northern Cuba (the “northern Cuba subzone” shown in Figure 2.5.2-271) that is located partially within the site region and that exhibits a higher rate of seismicity than surrounding regions. The seismicity rate from the northern subzone is approximately 11 percent higher than that for the entire Cuba areal source zone, and this higher rate is applied to the Z1 scenario. The Z11% scenario results in the highest contribution to hazard from the three zone scenarios (Table 2.5.2-233).