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2.5.2 Vibratory Ground Motion

This section provides a detailed description of the vibratory ground motion assessment that was carried out for the VEGP ESP site resulting in the development of the VEGP ESP site Safe Shutdown Earthquake (SSE) ground motion. This assessment was performed to address seismic hazard update guidance in Regulatory Guide 1.165 Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion, Rev. 0, March 1997, (RG 1.165), and meet the SSE requirements in paragraph (d) of 10CFR 100.23. The starting point for this site assessment is the EPRI-SOG probabilistic seismic hazard analysis (PSHA) evaluation (**EPRI NP-6395-D 1989**).

Section 2.5.2.1 through Section 2.5.2.4 document the review and update of the available EPRI seismicity, seismic source, and ground motion models. Section 2.5.2.5 summarizes information about the seismic wave transmission characteristics of the ESP site with reference to more detailed discussion of all engineering aspects of the subsurface in Section 2.5.4.

Section 2.5.2.6 describes the development of the horizontal SSE ground motion for the VEGP ESP site. The selected SSE ground motion is based on the risk-consistent / performance-based approach from NUREG/CR-6728 (**McGuire et al. 2001**) and ASCE 43-05 (**ASCE 2005**). Site-specific horizontal ground motion amplification factors are developed using site-specific estimates of near-surface soil and rock properties. These amplification factors are then used to scale the hard rock spectra to develop Uniform Hazard Spectra (UHS) accounting for site-specific conditions using Approach 2A of NUREG/CR-6769. Horizontal SSE spectra are developed from these soil Uniform Hazard Spectra (UHS) using the performance-based approach of ASCE 43-05. The SSE motion is defined at the free ground surface of a hypothetical outcrop of the highest competent in situ layer. This is at the top of the Blue Bluff Marl, at a depth of 86 ft. See Sections 2.5.4 and 2.5.2.5 for further discussion of the subsurface conditions.

Section 2.5.2.7 describes vertical SSE spectra, developed by scaling the horizontal SSE by a frequency-dependent vertical-to-horizontal (V/H) factor

The SSE spectra that are described in this section are considered a performance goal-based (risk-informed) site specific safe shutdown earthquake response spectra. The SSE spectra and its specific location at a free ground surface reflects the seismic hazard in terms of a PSHA and geologic characteristics of the site. The SSE spectra defined in this section would be expected to be modified as appropriate to develop ground motion for design considerations.

2.5.2.1 Seismicity

The seismic hazard analysis conducted by EPRI (NP-6395-D 1989) relied on an analysis of historical seismicity in the Central and Eastern United States (CEUS) to estimate seismicity

parameters (rates of activity and Richter b-values) for individual seismic sources. The historical earthquake catalog used in the EPRI analysis was complete through 1984. The earthquake data for the site region occurring since 1984 was reviewed and used to update the EPRI catalog.

2.5.2.1.1 Regional Seismicity Catalog Used for 1989 EPRI Seismic Hazard Analysis Study

Many seismic networks record earthquakes in the CEUS. A large effort was made during the EPRI seismic hazard analysis 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, that duplicate earthquakes have been eliminated, that non-earthquakes (e.g., mine blasts and sonic booms) have been eliminated, and that significant events in the historical record have not been missed. Thus, the EPRI catalog (**EPRI NP-4726-A 1988**) forms a strong basis on which to estimate seismicity parameters.

2.5.2.1.2 Updated Seismicity Data

NRC Regulatory Guide 1.165, Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion, Revision 0, March 1997 (RG 1.165) specifies that earthquakes of Modified Mercalli Intensity (MMI) greater than or equal to IV or magnitude greater than or equal to 3.0 should be listed for seismic sources “any part of which is within a radius of 200 mile (320 km) of the site (the site region).” In updating the EPRI catalog a latitude-longitude window of 30° to 37° N, 78° to 86° W was used. This window incorporates the 200 mi (320 km) radius “site region” and all seismic sources contributing significantly to VEGP ESP site earthquake hazard. Figure 2.5.1-1 shows the VEGP ESP site and its associated site region. Figures 2.5.2-1 through 2.5.2-6 show this site region and the defined latitude-longitude window.

The updated catalog was compiled from the following sub-catalogs:

EPRI Catalog. The various data fields of the EPRI catalog are described in EPRI NP-4726-A 1988.

SEUSSN Catalog. The SEUSSN catalog is available from the Virginia Tech Seismological Observatory FTP site (**SEUSSN 2005**). On the June 3, 2005 date of the catalog update, the SEUSSN catalog had 2,483 records dating from March 1698 to December 2003 within the site region latitude-longitude window. Of these, 1,355 records occurred in 1985 or later.

ANSS Catalog. The ANSS catalog (**ANSS 2005**) was searched on June 3, 2005, for all records within the site region latitude-longitude window, resulting in 1,710 records from 1928 to April 14, 2005. Of these, 1,375 records occurred in 1985 or later.

The Southeastern US Seismic Network (SEUSSN) and Advanced National Seismic System (ANSS) catalogs were used for the temporal update (1985 to present) of the EPRI seismicity catalog. The SEUSSN has coverage over the entire site region (defined above) and is the primary catalog used to compile the national ANSS seismicity catalog. While the SEUSSN catalog is taken as the preferred catalog, some additional events listed only in the ANSS catalog are also included in the update.

The magnitudes given in both catalogs were converted to best or expected estimate of m_b magnitude ($E[m_b]$, also called Emb), using the conversion factors given as equation 4-1 and Table 4-1 in EPRI NP-4726-A 1988:

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

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

where Md is duration or coda magnitude and ML is "local" magnitude.

Equation 4-2 of EPRI (NP-4726-A 1988) indicates that the equation from which m_b^* or Rmb is estimated from the best estimate of magnitude $E[m_b]$ or Emb and the variance of m_b , σ_{mb}^2 , or Smb^2 is:

$$m_b^* = E[m_b] + (1/2) \cdot \ln(10) \cdot b \cdot \sigma_{mb}^2 \quad \text{(Equation 2.5.2-3)}$$

where $b = 1.0$.

Values for σ_{mb}^2 or Smb were estimated for the two catalogs, and m_b [Rmb] was assigned to each event added to the updated catalog.

The result of the above process was a catalog of 61 earthquakes shown in Table 2.5.2-1 as the update of the EPRI NP-4726-A seismicity catalog recommended for the site region. For the purpose of recurrence analysis, these should be considered independent events.

The 61 events in the 30° to 37° N, 78° to 86° W latitude-longitude window, incorporating the 200 mi (320 km) radius site region, from 1985 to April 2005 with Emb magnitude 3.0 or greater have been incorporated into a number of figures, including tectonic features discussed in Section 2.5.1 and EPRI Earth Science Team source maps in this section.

2.5.2.2 Geologic Structures and EPRI Seismic Source Model for the Site Region

As described in Section 2.5.1, a comprehensive review of available geological, seismological, and geophysical data has been performed for the VEGP ESP site region and adjoining areas. The following sections summarize seismic source interpretations from the 1989 EPRI probabilistic seismic hazard analysis (PSHA) study (**EPRI NP-6395-D 1989**) and from relevant post-EPRI seismic source characterization studies and the updated interpretations of new and existing sources based on more recent data.

Since publication of the EPRI seismic source model, significant new information has been developed for assessing the earthquake source that produced the 1886 Charleston earthquake. This new information shows that the Charleston seismic source should be updated according to RG 1.165. Paleoliquefaction features and other new information published since the 1986 EPRI project (**EPRI NP-4726 1986**) have significant implications regarding the geometry, M_{\max} , and recurrence of M_{\max} in the Charleston seismic source. Results from the 1989 EPRI study also show that the Charleston seismic source is the most significant contributor to seismic hazard at the VEGP ESP site (**EPRI NP-6395-D 1989**). Thus, an update of the Charleston seismic source has been developed as part of the work performed for this ESP application. Details of the Updated Charleston Seismic Source (UCSS) model are presented in Section 2.5.2.2.4 and in a separate Engineering Study Report (**Bechtel 2006d**).

Sensitivity studies were performed to evaluate the potential significance of the UCSS model to seismic hazard at the VEGP ESP site, as described in detail in Section 2.5.2.4. Based on this analysis, it is found that the UCSS interpretations for the Charleston area show that the Charleston seismic source still dominates the seismic hazard at the VEGP ESP site. These new interpretations of the possible locations, sizes, and recurrence intervals of large earthquakes in the Charleston area form a strong basis with which to calculate the seismic ground motion hazard for the site.

2.5.2.2.1 Summary of EPRI Seismic Sources

This section summarizes the seismic sources and parameters used in the 1986 EPRI project (**EPRI NP-4726 1986**). The description of seismic sources is limited to those sources within 200 mi of the VEGP ESP site (i.e., the site region) and those at distances greater than 200 mi that may affect the hazard at the VEGP ESP site.

In the 1986 EPRI project, six independent Earth Science Teams (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 1986 EPRI project were Bechtel Group, Dames & Moore, Law Engineering, Rondout Associates, Weston Geophysical Corporation, and Woodward-Clyde Consultants. Each team produced a report (volumes 5 through 10 of EPRI NP-4726) providing detailed descriptions of how they identified and defined seismic sources. The results were implemented into a PSHA study (**EPRI NP-6395-D 1989**). 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 NP-6452-D (1989) summarized the parameters used in the final PSHA calculations, and this reference is the primary source for the seismicity parameters used in this current ESP application. Each EST provides more detailed descriptions

of the rationale and methodology used in evaluating tectonic features and establishing the seismic sources (refer to volumes 5 through 10 of EPRI NP-4726).

The most significant seismic sources (**EPRI NP-6395-D 1989**) developed by each EST are shown in Figures 2.5.2-1 through 2.5.2-6. For the 1989 EPRI seismic hazard calculations, a screening criterion was implemented to identify those sources whose combined hazard exceeded 99 percent of the total hazard from all sources, for two ground motions measures (**EPRI NP-6395-D 1989**). These sources are identified in the descriptions below as “primary” seismic sources. Other sources, which together contributed less than one percent of the total hazard from all sources for the two ground motion measures, are identified in the descriptions below as “additional” seismic sources. Earthquakes with body-wave magnitude $m_b \geq 3.0$ are also shown in Figures 2.5.2-1 through 2.5.2-6 to show the spatial relationships between seismicity and seismic sources. Earthquake epicenters include both events from the EPRI earthquake catalog and for the period between 1985 and April 2005 as described in Section 2.5.2.1.2.

The maximum magnitude, interdependencies, and probability of activity for each EPRI EST’s seismic sources are presented in Tables 2.5.2-2 through 2.5.2-7. These tables present the parameters assigned to each source within 200 mi of the VEGP ESP site and include primary and additional seismic sources as defined above. The tables also indicate whether new information has been identified that would lead to a revision of the source’s geometry, maximum magnitude, or recurrence parameters. The seismicity recurrence parameters (a- and b-values) used in the seismic hazard studies were computed for each 1-degree latitude and longitude cell that intersects any portion of a seismic source.

The nomenclature used by each EST to describe the various seismic sources in the CEUS varies from team to team. In other words, a number of different names may have been used by the EPRI teams to describe the same or similar tectonic features or sources, or one team may describe seismic sources that another team does not. For example, the Charleston seismic source was modeled by each team but was called the Charleston Area and Charleston Faults by the Bechtel Group team; the Charleston Seismic Zone by the Dames & Moore, Law, and Weston teams; and Charleston by the Rondout and Woodward-Clyde teams. Each team’s source names, data, and rationale are included in its team-specific documentation (volumes 5 through 10 of EPRI NP-4726).

The EPRI PSHA study expressed maximum magnitude (M_{max}) values in terms of body-wave magnitude (m_b), whereas most modern seismic hazard analyses describe M_{max} in terms of moment magnitude (**M**). To provide a consistent comparison between magnitude scales, this study relates body-wave magnitude to moment magnitude using the arithmetic average of three equations, or their inversions, presented in Atkinson and Boore (1995), Frankel et al (1996), and EPRI TR-102293 (1993). The conversion relations are very consistent for magnitudes 4.5 and

greater and begin to show divergence at lower magnitudes. Throughout this section, the largest assigned values of M_{max} distributions assigned by the ESTs to seismic sources are presented for both magnitude scales (m_b and M) to give perspective on the maximum earthquakes that were considered possible in each seismic source. For example, EPRI m_b values of M_{max} are followed by the equivalent M value.

The following sections describe the most significant EPRI sources (both primary and additional seismic sources) for each EST with respect to the VEGP ESP site. Assessment of these and other EPRI sources within the site region shows that the EPRI source parameters (M_{max} , geometry, and recurrence) are sufficient to capture the current understanding of the seismic hazard in the site region.

Except for the Charleston seismic source, no new geological, geophysical, or seismological information in the literature published since the EPRI NP-6395-D source model suggests that these sources should be modified. Each EST's characterization of the Charleston seismic source was replaced by four alternative source geometries. For each geometry, large earthquake occurrences (M 6.7 to 7.5) were modeled with a range of mean recurrence rates, and smaller earthquakes (m_b from 5 to 6.7) were modeled with an exponential magnitude distribution, with rates and b-values determined from historical seismicity. Also, all surrounding sources for each team were redrawn so that the new Charleston source geometries were accurately represented as a "hole" in the surrounding source, and seismic activity rates and b-values were recalculated for the modified surrounding sources, based on historical seismicity. Further details and the results of sensitivity analyses performed on the modified seismic sources are presented in Section 2.5.2.4.

2.5.2.2.1.1 Sources Used for EPRI PSHA – Bechtel Group

Bechtel Group identified and characterized six primary seismic sources. All six of these primary seismic sources are located within the site region (200 mi); they are:

- Charleston Area (H)
- Charleston Faults (N3)
- Atlantic Coastal Region (BZ4)
- S Appalachians (BZ5)
- SE Appalachians (F)
- NW South Carolina (G)

Bechtel Group also characterized four additional seismic sources. These additional seismic sources are:

- Eastern Mesozoic Basins (13)
- Bristol Trends (24)

- Rosman Fault (15)
- Belair Fault (16)

Primary and additional seismic sources characterized by the Bechtel Group team within the site region are listed in Table 2.5.2-2. A map showing the locations and geometries of the Bechtel primary seismic sources is provided in Figure 2.5.2-1. Following is a brief discussion of each of the primary seismic sources characterized by the Bechtel Group team..

Charleston Area (H). The Charleston Area source (H) is located about 60 mi from the VEGP ESP site. This oblong combination source area is defined based on the historic earthquake pattern (including the Middleton Place-Summerville and Bowman seismic zones), is elongated northwest-southeast, and encompasses all of source zone N3 (described below). Sources H and N3 are interdependent; if N3 is active, it is unlikely that H is active, and vice versa. The largest M_{max} assigned by Bechtel Group to this zone is m_b 7.4 (**M** 7.9), reflecting its assumption that Charleston-type earthquakes are produced within this zone.

Charleston Faults (N3). The Charleston Faults (N3) source zone is a small area set within the Charleston Area (H) source zone and encompassing a number of identified and postulated faults in the Charleston, South Carolina, area, including the Ashley River, Charleston, and Woodstock faults. Source N3 is located approximately 85 mi from the VEGP ESP site. Sources H and N3 are interdependent; if N3 is active, it is unlikely that H is active, and vice versa. According to EPRI NP-4726, this combination was created for computational simplicity. The largest M_{max} assigned by the Bechtel Group team to this zone is m_b 7.4 (**M** 7.9), reflecting its assumption that Charleston-type earthquakes are produced within this zone.

Atlantic Coastal Region (BZ4). The VEGP ESP site is located within the Atlantic Coastal Region background source (BZ4). Source BZ4 is a large background zone that extends from offshore New England to Alabama and encompasses portions of the Coastal Plain from Georgia to southern Virginia. The largest M_{max} assigned by the Bechtel Group team to this zone is m_b 7.4 (**M** 7.9), reflecting its assumption that there is a small probability that a Charleston-type earthquake could occur within this region.

S Appalachians (BZ5). The Southern Appalachians background source (BZ5) is located about 10 mi from the VEGP ESP site. This source is a large background region that extends from New York to Alabama, including portions of the Southern Appalachians, Piedmont, and Coastal Plain. The largest M_{max} assigned by the Bechtel Group team to this zone is m_b 6.6 (**M** 6.5).

SE Appalachians (F). The VEGP ESP site is located about 10 mi from the Southeastern Appalachians source (F), a combination source zone that includes parts of Georgia and the Carolinas and flanks the southwest and northeast borders of Zone G (described below). Source Zone F is mutually exclusive with Zone G; if F is active, G is inactive, and vice versa. The largest M_{max} assigned by the Bechtel Group team to this zone is m_b 6.6 (**M** 6.5).

NW South Carolina (G). The VEGP ESP site is located about 10 mi from the Northwestern South Carolina combination source (G). Source Zone G is mutually exclusive with Zone F; if G is active, F is inactive, and vice versa. The largest M_{\max} assigned by the Bechtel Group team to this zone is m_b 6.6 (**M 6.5**).

2.5.2.2.1.2 Sources Used for EPRI PSHA – Dames & Moore

Dames & Moore identified and characterized five primary seismic sources. All five of these seismic sources are located within the site region; they are:

- Charleston Seismic Zone (54)
- Charleston Mesozoic Rift (52)
- S Appalachian Mobile Belt (Default Zone) (53)
- S Cratonic Margin (Default Zone) (41)
- S Coastal Margin (20)

Dames & Moore also identified seven additional seismic sources within the site region. These sources are:

- Appalachian Fold Belts (4)
- Kink in Fold Belt (4A)
- Jonesboro Basin (49)
- Buried Triassic Basins (50)
- Florence Basin (51)
- Dunbarton Triassic Basin (65)
- Combination Zone 4A-4B-4C-4D (C01)

Primary and additional seismic sources characterized by the Dames & Moore team within the site region are listed in Table 2.5.2-3. A map showing the locations and geometries of the Dames & Moore primary seismic sources is provided in Figure 2.5.2-2. Following is a brief discussion of these primary seismic sources.

Charleston Seismic Zone (54). The Charleston Seismic Zone (54) is a northwest-southeast oriented polygon located about 45 mi from the VEGP ESP site. This source includes the Ashley River, Woodstock, Helena Banks, and Cooke faults, as well as the Bowman and Middleton Place-Summerville seismic zones and was designed to capture the occurrence of Charleston-type earthquakes. The largest M_{\max} assigned by the Dames & Moore team to this zone is m_b 7.2 (**M 7.5**).

Charleston Mesozoic Rift (52). The Charleston Mesozoic Rift source (52) is a large polygon located less than 5 mi from the VEGP ESP site. This source extends from offshore South

Carolina to Gulf Shore Florida, including portions of the South Carolina and Georgia Coastal Plain. The largest M_{max} assigned by the Dames & Moore team to this zone is m_b 7.2 (**M 7.5**).

S Appalachian Mobile Belt (Default Zone) (53). The VEGP ESP site is located within the Southern Appalachian Mobile Belt (Default Zone) source (53). This default zone comprises crustal rocks that have undergone several periods of divergence and convergence. The source is bounded on the east by the East Coast magnetic anomaly and on the west by the westernmost boundary of the Appalachian gravity gradient. The largest M_{max} assigned by the Dames & Moore team to this zone is m_b 7.2 (**M 7.5**).

S Cratonic Margin (Default Zone) (41). The Southern Cratonic Margin (Default Zone) source is located about 65 mi from the VEGP ESP site. This large default zone is located between the Appalachian Fold Belt (4) and the Southern Appalachian Mobile Belt (53) and includes the region of continental margin deformed during Mesozoic rifting. Located within this default zone are many Triassic basins and border faults. The largest M_{max} assigned by the Dames & Moore team to this zone is m_b 7.2 (**M 7.5**).

S Coastal Margin (20). The Southern Coastal Margin regional source (20) is located approximately 90 mi from the VEGP ESP site. This zone is roughly parallel to the rifted continental margin from Texas to Alabama and incorporates a region of diffuse seismicity. Located within this source is a down-warped wedge of miogeosynclinal sediments of Cretaceous age and younger. The largest M_{max} assigned by the Dames & Moore team to this zone is m_b 7.2 (**M 7.5**).

2.5.2.2.1.3 Sources Used for EPRI PSHA – Law Engineering

Law Engineering identified and characterized 15 primary seismic sources all within the site region; They are:

- Charleston Seismic Zone (35)
- Eastern Basement (17)
- Reactivated E Seaboard Normal (22)
- Brunswick, NC Background (108)
- Mesozoic Basins (8 – Bridged) (C09)
- 8 – 35 (C10)
- 22 – 35 (C11)
- Eight mafic pluton sources (M33 and M36 through M42)

Law Engineering also characterized five additional seismic sources within the site region that do not contribute to 99 percent of the hazard at the VEGP ESP site. These are:

- Eastern Basement Background (217)
- Eastern Piedmont (107)
- 22 – 24 – 35 (GC13)
- 22 – 24 (GC12)
- Mesozoic Basins (8)

Primary and additional seismic sources characterized by the Law Engineering team within the site region are listed in Table 2.5.2-4. A map showing the locations and geometries of the Law Engineering primary seismic sources is provided in Figure 2.5.2-3. Following is a brief discussion of Law's primary seismic sources

Charleston Seismic Zone (35). The Charleston Seismic Zone source (35) is a northeast-southwest elongated polygon that includes the Charleston, Ashley River, and Woodstock faults, as well as parts of the offshore Helena Banks fault and most of the more recently discovered liquefaction features identified by Amick (1990). This source was designed to capture the occurrence of Charleston-type earthquakes. This source is located about 75 mi from the VEGP ESP site and overlaps with the Reactivated E Seaboard Normal (22; described below) and Buried Mesozoic Basins (8; not a 99 percent contributor) sources. The largest M_{max} assigned by the Law Engineering team to this zone is m_b 6.8 (**M 6.8**).

Eastern Basement (17). The VEGP ESP site is located 90 mi from the Eastern Basement (17) source. This source was defined as an area containing pre-Cambrian and Cambrian normal faults, developed during the opening of the proto-Atlantic Ocean, in the basement rocks beneath the Appalachian decollement. The Giles County and eastern Tennessee zones of seismicity are included in this source. The largest M_{max} assigned by the Law Engineering team to this zone is m_b 6.8 (**M 6.8**).

Reactivated E Seaboard Normal (22). The VEGP ESP site is located within the Reactivated Eastern Seaboard Normal (22) source. This source was characterized as a region along the eastern seaboard in which Mesozoic normal faults are reactivated as high-angle reverse faults. The Law Engineering team assigned a single M_{max} of m_b 6.8 (**M 6.8**) to this zone.

Brunswick, NC Background (108). The VEGP ESP site is located within the Brunswick NC Background source zone (108). The source 108 site represents a zone defined by a low-amplitude, long-wavelength magnetic anomaly pattern. The Law Engineering team interpreted this pattern as possibly indicating a zone of Mesozoic extended crust. The largest M_{max} assigned by the Law Engineering team to this zone is m_b 6.8 (**M 6.8**).

Mesozoic Basins (8 – Bridged) (C09). The VEGP ESP site is located within the Mesozoic Basins (C09) source, which comprises eight bridged basins. This source was defined based on northeast-trending sediment-filled troughs in basement rock bounded by normal faults. The largest M_{max} assigned by the Law Engineering team to this zone is m_b 6.8 (**M 6.8**).

8 – 35 (C10). The VEGP ESP site is located within the 8 – 35 combination source (C10). The largest M_{max} assigned by the Law Engineering team to this zone is m_b 6.8 (**M 6.8**).

22 – 35 (C11). The VEGP ESP site is located within the 22 – 35 combination source (C11). The largest M_{max} assigned by the Law Engineering team to this zone is m_b 6.8 (**M 6.8**).

Eight Mafic Pluton Sources (M33 and M36 through M42). The Law Engineering team identified a number of mafic pluton sources, eight of which are located within about 130 mi of the VEGP ESP site. The Law Engineering team considered pre- and post-metamorphic plutons in the Appalachians to be stress concentrators and, thus, earthquake sources. Law Engineering assigned a single M_{max} of m_b 6.8 (**M 6.8**) to all mafic pluton sources.

2.5.2.2.1.4 Sources Used for EPRI PSHA – Rondout Associates

Rondout Associates characterized two primary seismic sources both within the site region; they are:

- Charleston (24)
- South Carolina (26)

Rondout Associates also identified eight additional seismic sources within the site region. These are:

- Appalachian (49)
- Background 49 (C01)
- 49 + 32 (C09)
- Grenville (50)
- Background 50 (C02)
- 50 (02) + 12 (C07)
- Southern Appalachians (25)
- Tennessee-VA Border Zone (27)

Primary and additional seismic sources characterized by the Rondout Associates team within the site region are listed in Table 2.5.2-5. A map showing the locations and geometries of the Rondout Associates primary seismic sources is provided in Figure 2.5.2-4. Following is a brief discussion of both of these primary seismic sources.

Charleston (24). The Charleston source is a northwest-southeast-oriented area set within the larger South Carolina (26) source and located about 35 mi from the VEGP ESP site. Source 24 includes the Helena Banks, Charleston, Ashley River, and Woodstock faults, as well as the Bowman and Middleton Place-Summerville seismic zones, and was designed to capture the

occurrence of Charleston-type earthquakes. The largest M_{\max} assigned by the Rondout Associates team to this zone is m_b 7.0 (**M 7.2**).

South Carolina (26). The VEGP ESP site is located within the South Carolina source (26). The South Carolina source (26) is a northwest-southeast elongated area that surrounds, but does not include, Source 24 (described above). Source 26 includes most of South Carolina except the Charleston area. The largest M_{\max} assigned by the Rondout Associates team to this zone is m_b 6.8 (**M 6.8**).

2.5.2.2.1.5 Sources Used for EPRI PSHA – Weston Geophysical

Weston Geophysical identified and characterized 12 primary seismic sources, all within the site region; they are:

- Charleston Seismic Zone (25)
- South Carolina (26)
- Southern Coastal Plain (104)
- 103 – 23 – 24 (C19)
- 104 – 22 (C20)
- 104 – 25 (C21)
- 104 – 22 – 26 (C23)
- 104 – 22 – 25 (C24)
- 104 – 28BCDE – 22 (C26)
- 104 – 28BCDE – 22 – 25 (C27)
- 26 – 25 (C33)
- 104 – 28BE – 25 (C35)

Weston Geophysical also characterized 13 additional seismic sources within the site region. These sources are:

- 104 – 26 (C22)
- 104 – 28BE – 26 (C34)
- 104 – 28BCDE (C25)
- 104 – 28BCDE – 22 – 26 (C28)
- Zone of Mesozoic Basin (28B)
- 28A through E (C01)
- Southern Appalachians (103)
- 103 – 23 (C17)

- 103 – 24 (C18)
- Zone of Mesozoic Basin (28D)
- Zone of Mesozoic Basin (28E)
- Appalachian Plateau (102)
- New York-Alabama-Clingman (24)

Primary and additional seismic sources characterized by the Weston Geophysical team are listed in Table 2.5.2-6. A map showing the locations and geometries of the Weston Geophysical primary seismic sources is provided in Figure 2.5.2-6. Following is a brief discussion of each of the Weston Geophysical team's primary seismic sources.

Charleston Seismic Zone (25). The Charleston Seismic Zone source is an irregularly shaped hexagon centered just northeast of Charleston, South Carolina, and located about 60 mi from the VEGP ESP site. This source includes the Helena Banks, Charleston, Ashley River, and Woodstock faults, but does not include the Bowman seismic zone. This source was designed to capture the occurrence of Charleston-type earthquakes. The largest M_{max} assigned by the Weston Geophysical team to this zone is m_b 7.2 (**M 7.5**).

South Carolina (26). The South Carolina source (26) is a large area covering most of South Carolina and the VEGP ESP site. The largest M_{max} assigned by the Weston Geophysical team to this zone is m_b 7.2 (**M 7.5**).

Southern Coastal Plain (104). The Southern Coastal Plain source (104) extends from New York to Alabama and from the Towaliga-Lowdenville-Kings Mountain fault trends on the west to the offshore East Coast magnetic anomaly on the east. Source 104 was designed to include the Central Virginia seismic zone, the Charleston seismic zone, and a number of Mesozoic basins. The largest M_{max} assigned by the Weston Geophysical team to this zone is m_b 6.6 (**M 6.5**).

Nine Combination Zones: (103 – 23 – 24 (C19); 104 – 22 (C20); 104 – 25 (C21); 104 – 22 – 26 (C23); 104 – 22 – 25 (C24); 104 – 28BCDE – 22 (C26); 104 – 28BCDE – 22 – 25 (C27); 26 – 25 (C33); and 104 – 28BE – 25 (C35)). Weston Geophysical specified a number of combination seismic source zones, nine of which are primary sources for the VEGP ESP site. The largest M_{max} assigned by the Weston Geophysical team to these combination zones is m_b 6.6 (**M 6.5**).

2.5.2.2.1.6 Sources Used for EPRI PSHA – Woodward-Clyde Consultants

Woodward-Clyde Consultants identified and characterized five primary seismic sources, all five located within the site region; they are:

- Charleston (includes "none of the above," NOTA) (30)
- S Carolina Gravity Saddle (Extended) (29)

- SC Gravity Saddle No. 2 (Combo C3) (29A)
- SC Gravity Saddle No. 3 (NW Portion) (29B)
- Vogtle Background

Woodward-Clyde Consultants also identified two additional seismic sources within the site region. These sources are:

- Blue Ridge Combo (31)
- Blue Ridge Combination – Alternate Configuration (31A)

Primary and additional seismic sources characterized by the Woodward-Clyde team within the site region are listed in Table 2.5.2-7. A map showing the locations and geometries of the Woodward-Clyde primary seismic sources is provided in Figure 2.5.2-5. Following is a brief discussion of each of the primary seismic sources identified by the Woodward-Clyde team.

Charleston (includes NOTA) (30). The Charleston seismic source (30) is a northeast-southwest-oriented rectangle that includes most of the Charleston earthquake MMI IX and X area and the Charleston Ashley River and Woodstock faults. Source 30 is located about 70 mi from the VEGP ESP site and was designed to capture the occurrence of Charleston-type earthquakes. The Charleston source (30) is mutually exclusive with Sources 29, 29A, and 29B; if 30 is active, the other three are inactive, and vice versa. The largest M_{\max} assigned by the Woodward-Clyde Consultants team to this zone is m_b 7.5 (**M 8.0**).

S Carolina Gravity Saddle (Extended) (29). The South Carolina Gravity Saddle (Extended) source (29) covers most of South Carolina and parts of Georgia, including the VEGP ESP site. The South Carolina Gravity Saddle source (29) is mutually exclusive with Sources 29A, 29B, and 30; if 29 is active, the other three are inactive, and vice versa. The largest M_{\max} assigned by the Woodward-Clyde Consultants team to this zone is m_b 7.4 (**M 7.9**), reflecting its assumption that Charleston-type earthquakes can occur in this zone.

SC Gravity Saddle No. 2 (Combo C3) (29A). The South Carolina Gravity Saddle No. 2 source (29A) is an irregularly shaped polygon set within the larger area of Source 29. The SC Gravity Saddle No. 2 source (29A) is mutually exclusive with Sources 29, 29B, and 30; if 29A is active, the other three are inactive, and vice versa. The largest M_{\max} assigned by the Woodward-Clyde Consultants team to this zone is m_b 7.4 (**M 7.9**), reflecting its assumption that Charleston-type earthquakes can occur in this zone.

SC Gravity Saddle No. 3 (NW Portion) (29B). The South Carolina Gravity Saddle No. 3 source (29B) is an irregularly shaped polygon set within the larger area of Source 29 and includes the VEGP ESP site. The SC Gravity Saddle No. 3 source (29B) is mutually exclusive with Sources 29, 29A, and 30; if 29B is active, the other three are inactive, and vice versa. The largest M_{\max} assigned by the Woodward-Clyde Consultants team to this zone is m_b 7.0 (**M 7.2**).

Vogtle Background. The VEGP ESP Background source is a large box containing the VEGP ESP site and covering most of South Carolina and Georgia as well as parts of adjoining states and extending offshore. This source is a background zone defined as a rectangular area surrounding the VEGP ESP site and is not based on any geological, geophysical, or seismological features. The largest M_{max} assigned by the Woodward-Clyde Consultants team to this zone is m_b 6.6 (**M 6.5**).

2.5.2.2.2 Post-EPRI Seismic Source Characterization Studies

Since the EPRI (NP-4726 1986, NP-6395-D 1989) seismic hazard project, three recent studies have been performed to characterize seismic sources within the VEGP ESP site region for PSHAs. These studies include the US Geological Survey's (USGS) National Seismic Hazard Mapping Project (**Frankel et al. 1996, 2002**), the South Carolina Department of Transportation's seismic hazard mapping project (**Chapman and Talwani 2002**), and the Nuclear Regulatory Commission's Trial Implementation Project (TIP) study (**Savy et al. 2002**). These three studies are described below (i.e., Section 2.5.2.2.2.1 through 2.5.2.2.2.3). Based on review of recent studies it was determined that an update of the Charleston seismic source for the EPRI (NP-4726 1986, NP-6395-D 1989) seismic hazard project was required. This update is presented in Section 2.5.2.2.2.4. In addition, at the perimeter of the VEGP ESP site region is what is now identified as the Eastern Tennessee Seismic Zone (ETSZ). The significance of the ETSZ on the VEGP ESP seismic hazard is discussed in Section 2.5.2.2.2.5.

2.5.2.2.2.1 US Geological Survey Model (**Frankel et al. 2002**)

In 2002, the USGS produced updated seismic hazard maps for the conterminous United States based on new seismological, geophysical, and geological information (**Frankel et al. 2002**). The 2002 maps reflect changes to the source model used to construct the previous version of the national seismic hazard maps (**Frankel et al. 1996**). The most significant modifications to the CEUS portion of the source model include changes in the recurrence, M_{max} , and geometry of the Charleston and New Madrid sources. Unlike the EPRI models that incorporate many local sources, the USGS source model in the CEUS includes only five sources: the Extended Margin background, Stable Craton background, Charleston, Eastern Tennessee, and New Madrid (Table 2.5.2-8). Except for the Charleston and New Madrid zones, where earthquake recurrence is modeled by paleoliquefaction data, the hazard for the large background or "maximum magnitude" zones is largely based on historical seismicity and the variation of that seismicity.

As part of the 2002 update of the National Seismic Hazard Maps, the USGS developed a model of the Charleston source that incorporates available data regarding recurrence, M_{max} , and geometry of the source zone. The USGS model uses two equally weighted source geometries, one an areal source enveloping most of the tectonic features and liquefaction data in the greater

Charleston area and the second a north-northeast-trending elongated areal source enveloping the southern half of the southern segment of the East Coast fault system (ECFS) (Table 2.5.2-8 and Figure 2.5.2-7). The Frankel et al. (2002) report does not specify why the entire southern segment of the ECFS is not contained in the source geometry. For M_{max} , the study defines a distribution of magnitudes and weights of M 6.8 [.20], 7.1 [.20], 7.3 [.45], 7.5 [.15]. For recurrence, Frankel et al. (2002) adopt a mean paleoliquefaction-based recurrence interval of 550 years and represent the uncertainty with a continuous lognormal distribution.

2.5.2.2.2.2 South Carolina Department of Transportation Model (Chapman and Talwani 2002)

Chapman and Talwani (2002) created probabilistic seismic hazard maps for the South Carolina Department of Transportation (SCDOT). In the SCDOT model, treatment of the 1886 Charleston, South Carolina, earthquake and similar events dominates estimates of hazard statewide.

The SCDOT model employs a combination of line and area sources to characterize Charleston-type earthquakes in three separate geometries and uses a slightly different M_{max} range (M 7.1 to 7.5) than the USGS 2002 model (Table 2.5.2-9 and Figure 2.5.2-8). Three equally-weighted source zones defined for this study include (1) a source capturing the intersection of the Woodstock and Ashley River faults, (2) a larger Coastal South Carolina zone that includes most of the paleoliquefaction sites, and (3) a southern ECFS source zone. The respective magnitude distributions and weights used for M_{max} are M 7.1 [.20], 7.3 [.60], 7.5 [.20]. The mean recurrence interval used in the SCDOT study is 550 years, based on the paleoliquefaction record.

2.5.2.2.2.3 The Trial Implementation Project Study (Savy et al. 2002)

The Lawrence Livermore National Laboratory TIP study focuses on seismic zonation and earthquake recurrence models for two nuclear plant sites in the southeastern US, namely the VEGP ESP site and the Watts Bar site in Tennessee. The TIP study uses an expert elicitation process to characterize the Charleston seismic source, considering published data through 1996. The TIP study identifies multiple alternative zones for the Charleston source and for the South Carolina–Georgia seismic zone, as well as alternative background seismicity zones for the Charleston region. However, the TIP study focuses primarily on implementing the Senior Seismic Hazard Advisory Committee (SSHAC) PSHA methodology (SSHAC 1997) and was designed to be as much of a test of the methodology as a real estimate of seismic hazard. As a result, its findings are not included explicitly in this report.

2.5.2.2.2.4 Updated Charleston Seismic Source (UCSS) Model (Bechtel 2006d)

It has been nearly 20 years since the six EPRI ESTs evaluated hypotheses for earthquake causes and tectonic features and assessed seismic sources in the CEUS (EPRI NP-4726

1986). The EPRI Charleston source zones developed by each EST are shown in Figure 2.5.2-10 and summarized in Table 2.5.2-10. Several studies that post-date the 1986 EPRI EST assessments have demonstrated that the source parameters for geometry, M_{max} , and recurrence of M_{max} in the Charleston seismic source need to be updated to capture a more current understanding for both the 1886 Charleston earthquake and the seismic source that produced this earthquake. In addition, recent PSHA studies of the South Carolina region (**Savy et al. 2002; Chapman and Talwani 2002**) and the southeastern United States (**Frankel et al. 2002**) have developed models of the Charleston seismic source that differ significantly from the earlier EPRI characterizations. Therefore, the Charleston seismic source was updated as part of this ESP application.

The UCSS model is summarized below and presented in detail in Bechtel (2006d). Methods used to update the Charleston seismic source follow guidelines provided in RG 1.165. An SSHAC Level 2 study was performed to incorporate current literature and data and the understanding of experts into an update of the Charleston seismic source model. This level of effort is outlined in the SSHAC (1997) report, which provides guidance on incorporating uncertainty and the use of experts in PSHA studies.

The UCSS model incorporates new information to re-characterize geometry, M_{max} , and recurrence for the Charleston seismic source. These components are discussed in the following sections. Paleoliquefaction data imply that the Charleston earthquake process is defined by repeated, relatively frequent, large earthquakes located in the vicinity of Charleston, indicating that the Charleston source is different from the rest of the eastern seaboard.

2.5.2.2.4.1 UCSS Geometry

The UCSS model includes four mutually exclusive source zone geometries (A, B, B', and C; Figure 2.5.2-9). The latitude and longitude coordinates that define these four source zones are presented in Table 2.5.2-11. Details regarding each source geometry are given below. The four geometries of the UCSS 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, shown in Figures 2.5.1-18 and 2.5.1-19, 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. Table 2.5.2-10 provides a subset of the Charleston tectonic features differentiated by pre- and post-EPRI (**EPRI NP-4726 1986**) information. In addition, pre- and post-1986 instrumental seismicity, $m_b \geq 3$, are shown on Figures 2.5.1-18 and 2.5.1-19. Seismicity continues to be concentrated in the Charleston region in the Middleton Place–Summerville seismic zone (MPSSZ), which has been used to define the intersection of the Woodstock and Ashley River faults (**Tarr et al. 1981; Madabhushi and Talwani 1993**).

Notably, two earthquakes in 2002 (m_b 3.5 and 4.4) are located offshore of South Carolina along the Helena Banks fault zone in an area previously devoid of seismicity of $m_b > 3$. A compilation of the EPRI EST Charleston source zones is provided in Figure 2.5.2-10 as a comparison to the UCSS geometries shown in Figure 2.5.2-9.

Geometry A - Charleston

Geometry A is an approximately 100 x 50 km, northeast-oriented area centered on the 1886 Charleston meizoseismal area (Figure 2.5.2-9). 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 incorporates the 1886 earthquake MMI X isoseismal (**Bollinger 1977**), 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 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 envelopes instrumentally located earthquakes spatially associated with the MPSSZ (**Tarr et al. 1981; Tarr and Rhea 1983; Madabhushi and Talwani 1993**).

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. Geometry A envelopes (1) the meizoseismal area of the 1886 earthquake, (2) the area containing the majority of local tectonic features (although many have large uncertainties associated with their existence and activity, as described earlier), (3) the area of ongoing concentrated seismicity, and (4) the area of greatest density of 1886 liquefaction and prehistoric liquefaction. These observations show that future earthquakes having magnitudes comparable to the Charleston earthquake of 1886 most likely will occur within the area defined by Geometry A. A weight of 0.70 is assigned to Geometry A (Figure 2.5.2-11). 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-trending faults parallel to the long axis of the zone.

Geometries B, B', and C

While the preponderance of evidence supports the assessment that the 1886 Charleston meizoseismal area and Geometry A define the area where future events will most likely be centered, it is possible that the tectonic feature responsible for the 1886 earthquake either extends beyond or lies outside 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' are assessed to represent a larger source zone, while Geometry C represents the southern segment of the East Coast fault system as a possible source zone. The combined geometries of B and B' are assigned a weight of 0.20, and Geometry C is assigned a weight of 0.10. Geometry B' a subset of B, formally defines the onshore coastal area as a source (similar to the SCDOT coastal source zone) that would restrict earthquakes to the onshore region. Geometry B, which includes the onshore and offshore regions, and Geometry B' are mutually exclusive and given equal weight in the UCSS model. Therefore, the resulting weights are 0.10 for Geometries B and B'.

Geometry B - Coastal and Offshore Zone

Geometry B is a coast-parallel, approximately 260 x 80 km source area that (1) incorporates all of Geometry A, (2) is elongated to the northeast and southwest to capture other, more distant liquefaction features in coastal South Carolina (**Amick 1990; Amick et al. 1990a, 1990b; Talwani and Schaeffer 2001**), and (3) extends to the southeast to include the offshore Helena Banks fault zone (**Behrendt and Yuan 1987; Figure 2.5.2-9**). 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 northeastern and southwestern extents of Geometry B are controlled by the mapped extent of paleoliquefaction features [e.g., (**Amick 1990; Amick et al. 1990a, 1990b; Talwani and Schaeffer 2001**)].

The location and timing of paleoliquefaction features in the Georgetown and Bluffton areas to the northeast and southwest of Charleston have suggested to some researchers that the earthquake source may not be restricted to the Charleston area (**Obermeier et al. 1989; Amick et al. 1990a; Talwani and Schaeffer 2001**). A primary reason for defining Geometry B is to account 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 (**Behrendt and Yuan 1987**). 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 (Figures 2.5.2-9 and 2.5.1-19). 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 considered new data since the EPRI studies. The EPRI earthquake catalog (**EPRI NP-4726-A 1988**) was devoid of any events

($m_b \geq 3.0$) offshore from Charleston. The recent offshore seismicity also post-dates the development of the USGS and SCDOT source models that exclude any offshore Charleston source geometries.

A low weight of 0.10 is assigned to Geometry B (Figure 2.5.2-11), 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, Geometry B is represented in the model by a series of closely spaced, northeast-trending faults parallel to the long axis of the zone.

Geometry B' - Coastal Zone

Geometry B' is a coast-parallel, approximately 260 x 50 km source area that incorporates all of Geometry A, as well as the majority of reported paleoliquefaction features (**Amick 1990; Amick et al. 1990a, 1990b; Talwani and Schaeffer 2001**). Unlike Geometry B, however, Geometry B' does not include the offshore Helena Banks fault zone (Figure 2.5.2-9).

The Helena Banks fault system is excluded from Geometry B' to recognize that the preponderance of the data and evaluations support the assessment that the fault system is not active and because most 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 (the closed bull's eye centered onshore north of downtown Charleston, Figure 2.5.1-19). An onshore source for the 1886 earthquake as well as the 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, a weight of 0.10 is assigned to Geometry B' and reflects the assessment that Geometry B' has a much lower probability of being the source zone for Charleston-type earthquakes than Geometry A (Figure 2.5.2-11). To confine the rupture dimension to within the source area and to maintain a preferred northeast fault orientation, Geometry B' is represented in the model by a series of closely spaced, northeast-trending faults parallel to the long axis of the zone.

Geometry C - East Coast Fault System - South (ECFS-s)

Geometry C is an approximately 200 x 30 km, north-northeast-oriented source area enveloping the southern segment of the proposed East Coast fault system (ECFS-s) shown in Figure 3 of Marple and Talwani (2000) (Figures 2.5.2-9 and 2.5.2-12). The USGS hazard model (**Frankel et al. 2002**) (Figure 2.5.2-7) incorporates the ECFS-s as a distinct source geometry (also known as the zone of river anomalies [ZRA]); however, as described earlier, the USGS model

truncates the northeastern extent of the proposed fault segment. The South Carolina Department of Transportation hazard model (**Chapman and Talwani 2002**) also incorporates the ECFS-s as a distinct source geometry; however, this model extends the southern segment of the proposed East Coast fault system farther to the south than originally postulated by Marple and Talwani (2000) to include, in part, the distribution of liquefaction in southeastern South Carolina (**Chapman 2005b**) (Figure 2.5.2-9).

In this ESP evaluation the area of Geometry C is restricted to envelope the original depiction of the ECFS-s by Marple and Talwani (2000). Truncation of the zone to the northeast as shown by the 2002 USGS model is not supported by available data, and the presence of liquefaction in southeastern South Carolina is best captured in Geometries B and B', rather than extending the ECFS-s farther to the south than defined by the data of Marple and Talwani (2000).

A low weight of 0.10 is assigned to Geometry C to reflect the assessment that Geometries B, B', and C all have equal, but relatively low, likelihood of producing Charleston-type earthquakes (Figure 2.5.2-11). As with the other UCSS geometries, Geometry C is represented 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. (1985, 1991) and Bollinger (1992), a 20-km-thick seismogenic crust is assumed for the UCSS. To model the occurrence of earthquakes in the characteristic part of the Charleston distribution ($M > 6.7$), 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 km. Modeled fault rupture areas are assumed to have a width-to-length aspect ratio of 0.5, conditional on the assumed maximum fault width of 20 km. To obtain M_{max} earthquake rupture lengths from magnitude, the Wells and Coppersmith (1994) empirical relationship between surface rupture length and M for earthquakes of all slip types is used.

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

2.5.2.2.2.4.2 UCSS Maximum Magnitude

The six EPRI ESTs developed a distribution of weighted M_{max} values and weights to characterize the largest earthquakes that could occur on Charleston seismic sources. On the low end, the Law Engineering team assessed a single M_{max} of m_b 6.8 to seismic sources it considered capable of producing earthquakes comparable in magnitude to the 1886 Charleston

earthquake. On the high end, four teams defined M_{max} upper bounds ranging between m_b 7.2 and 7.5. For this ESP application, the m_b magnitude values have been converted to moment magnitude (**M**) as described previously. The m_b value and converted moment magnitude value for each team are shown below. The range in **M** for the six ESTs is 6.5 to 8.0.

<u>Team</u>	<u>Charleston M_{max} range</u>
Bechtel Group	m_b 6.8 to 7.4 (M 6.8 to 7.9)
Dames & Moore	m_b 6.6 to 7.2 (M 6.5 to 7.5)
Law Engineering	m_b 6.8 (M 6.8)
Rondout	m_b 6.6 to 7.0 (M 6.5 to 7.2)
Weston Geophysical	m_b 6.6 to 7.2 (M 6.5 to 7.5)
Woodward-Clyde Consultants	m_b 6.7 to 7.5 (M 6.7 to 8.0)

The **M** equivalents of EPRI m_b estimates for Charleston M_{max} earthquakes show that the upper bound values are similar to, and in two cases exceed, the largest modern estimate of **M** 7.3 \pm 0.26 (**Johnston 1996**) for the 1886 earthquake. The upper bound values for five of the six ESTs also exceed the preferred estimate of **M** 6.9 by Bakun and Hopper (2004) for the Charleston event. The EPRI M_{max} estimates are more heavily weighted toward the lower magnitudes, with the upper bound magnitudes given relatively low weights by several ESTs (Tables 2.5.2-2 through 2.5.2-7). Therefore, updating the M_{max} range and weights to reflect the current range of technical interpretations is warranted for the UCSS.

Based on assessment of the currently available data and interpretations regarding the range of modern M_{max} estimates (Table 2.5.2-12), the UCSS model modifies the USGS magnitude distribution (**Frankel et al. 2002**) to include a total of five discrete magnitude values, each separated by 0.2 **M** units (Figure 2.5.2-11). The UCSS M_{max} distribution includes a discrete value of **M** 6.9 to represent the Bakun and Hopper (2004) best estimate of the 1886 Charleston earthquake magnitude, as well as a lower value of **M** 6.7 to capture a low probability that the 1886 earthquake was smaller than the Bakun and Hopper (2004) mean estimate of **M** 6.9. Bakun and Hopper (2004) do not explicitly report a 1-sigma range in magnitude estimate of the 1886 earthquake, but do provide a 2-sigma range of **M** 6.4 to **M** 7.2.

The UCSS magnitudes and weights are as follows:

M	Weight	
6.7	0.10	
6.9	0.25	Bakun and Hopper (2004) mean
7.1	0.30	
7.3	0.25	Johnston (1996) mean
7.5	0.10	

This results in a weighted M_{max} mean magnitude of **M** 7.1 for the UCSS, which is slightly lower than the mean magnitude of **M** 7.2 in the USGS model (**Frankel et al. 2002**).

2.5.2.2.2.4.3 UCSS Recurrence Model

In the 1989 EPRI study (**EPRI NP-6395-D 1989**), the six EPRI ESTs used an exponential magnitude distribution to represent earthquake sizes for their Charleston sources. Parameters of the exponential magnitude distribution were estimated from historical seismicity in the respective source areas. This resulted in recurrence intervals for M_{\max} earthquakes (at the upper end of the exponential distribution) of several thousand years.

The current 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_b 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 (**Frankel et al. 2002**). In the second distribution, M_{\max} earthquakes ($M \geq 6.7$) are treated according to a characteristic model, with discrete magnitudes and mean recurrence intervals estimated through analysis of geologic data, including paleoliquefaction studies. In this document, M_{\max} 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 $M < 6.7$ and the earthquake catalog and between the occurrence of large earthquakes ($M \geq 6.7$) 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.

M_{\max} Recurrence

This section describes how the UCSS model determines mean recurrence intervals for M_{\max} earthquakes. The UCSS model incorporates geologic data to characterize the recurrence intervals for M_{\max} 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 were based on a truncated exponential model using historical seismicity (**EPRI NP-4726 1986; NP-6395-D 1989**). The truncated exponential model also provided the relative frequency of all earthquakes greater than m_b 5.0 up to M_{\max} in the EPRI PSHA. The recurrence of M_{\max} earthquakes in the EPRI models was 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 (**Talwani and Schaeffer 2001**).

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 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 reevaluates the paleoearthquake record interpreted by Talwani and Schaeffer (2001) based on that study's compilation of sites with paleoliquefaction features.

Talwani and Schaeffer (2001) compiled 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 were corrected for past variability in atmospheric ^{14}C using well established calibration curves and converted to "calibrated" (approximately calendric) ages. From their compilation of calibrated radiocarbon ages from various geographic locations, Talwani and Schaeffer (2001) correlated individual earthquake episodes. They identified an individual earthquake episode based on samples with a "contemporary" age constraint that had overlapping calibrated radiocarbon ages at approximately 1-sigma confidence interval. The estimated age of each earthquake was "calculated from the weighted averages of overlapping contemporary ages" (**Talwani and Schaeffer 2001**) (p. 6,632). They defined as many as eight events from the paleoliquefaction record (named 1886, A, B, C, D, E, F, and G in order of increasing age), and offered two scenarios to explain the distribution and timing of paleoliquefaction features (Table 2.5.2-13).

The two scenario paleoearthquake records proposed by Talwani and Schaeffer (2001) have different interpretations for the size and location of prehistoric events (Table 2.5.2-13). In their Scenario 1, the four prehistoric events that produced widespread liquefaction features similar to the large 1886 Charleston earthquake (A, B, E, and G) are interpreted to be large, 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** 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, Charleston-type events. Furthermore, Events C and D are combined into a large Event C'. Talwani and Schaeffer (2001) 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. The paleoliquefaction record along the South Carolina coast extends from 1886 to the mid-Holocene (**Talwani and Schaeffer 2001**). The consensus of the scientists who have evaluated these data (**Talwani and Schaeffer 2001; Talwani 2005; Obermeier 2005**) is that the paleoliquefaction record of earthquakes is complete only for the most recent ~2,000 years and that it is possible that liquefaction events are missing from the older portions of the record. The suggested incompleteness of the paleoseismic 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 (**Talwani and Schaeffer 2001**). While this assertion may be true, it cannot be ruled out that the paleoliquefaction record is complete back to the mid-Holocene.

2-Sigma Analysis of Event Ages

Analysis of the coastal South Carolina paleoliquefaction record is based on the Talwani and Schaeffer (2001) data compilation. As described above, Talwani and Schaeffer (2001) use calibrated radiocarbon ages with 1-sigma error bands to define the timing of past liquefaction episodes in coastal South Carolina. The standard in paleoseimology, however, is to use calibrated ages with 2-sigma (95.4 percent confidence interval) error bands [e.g., (**Sieh et al. 1989; Grant and Sieh 1994**)]. Likewise, in paleoliquefaction studies, to more accurately reflect the uncertainties in radiocarbon dating, the use of calibrated radiocarbon dates with 2-sigma error bands (as opposed to narrower 1-sigma error bands) is advisable (**Tuttle 2001**). The Talwani and Schaeffer (2001) 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 (2001) have been 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 which 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 2.5.2-13. Paleoearthquakes have been distinguished based on grouping paleoliquefaction features that have contemporary radiocarbon samples with overlapping calibrated ages. Event ages have then been defined by selecting the age range common to each of the samples. For example, an event defined by overlapping 2-sigma sample ages of 100–200 cal yr BP and 50–150 cal yr BP would have an event age of 50–150 cal yr BP. The UCSS study considers the “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 2-sigma analysis identified six distinct paleoearthquakes in the data presented by Talwani and Schaeffer (2001). 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 2.5.2-13). Additionally, the UCSS 2-sigma analysis suggests that Talwani and Schaeffer (2001) Events F and G may have been a single, large event, defined in the UCSS as F'. One important difference between the UCSS result and that of Talwani and Schaeffer (2001) 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 2.5.2-13). Therefore, in the UCSS, all earthquakes in the 2-sigma analysis have been interpreted to represent large, Charleston-type events. Analysis suggests that there have been four large earthquakes in the most-recent, ~2,000-year portion of the record (1886 and Events A, B, and C'). In the entire ~5,000-year paleoliquefaction record, there is evidence for six large, Charleston-type earthquakes (1886, A, B, C', E, F'; Table 2.5.2-13).

Recurrence intervals developed from the earthquakes recorded by paleoliquefaction features assume that these features were produced by large M_{max} events and that both the ~2,000-year and ~5,000-year records are complete. However, the UCSS mentions at least two concerns regarding the use of the paleoliquefaction record to characterize the recurrence of past M_{max} events. First, it is possible that the paleoliquefaction features associated with one or more of these pre-1886 events were produced by multiple moderate-sized events closely spaced in time. If this were the case, then the calculated recurrence interval would yield artificially short recurrence for M_{max} , since it was calculated using repeat times of both large (M_{max}) 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 (1811, 1811, 1812)
- North Anatolian Fault (1999 and 1999)
- San Andreas Fault (1812 and 1857)

Therefore the UCSS acknowledges the distinct possibility that M_{max} occurs less frequently than what is calculated from the paleoliquefaction record.

A second concern is that the recurrence behavior of the M_{max} event may be highly variable through time. For example, the UCSS considers it unlikely that **M 6.7 to M 7.5** events have occurred on a Charleston source at an average repeat time of about 500 to 600 years (**Talwani and Schaeffer 2001**) 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 5,000 years have clear geomorphic expression (**Rockwell et al. 2000**). 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 inter-event times (e.g., about 400 years between Events A and B) are included in a record with long inter-event times (e.g., about 1,900 years between Events C' and E).

Recurrence Rates

The UCSS model calculates two average recurrence intervals covering two different time intervals, which are used as two recurrence branches on the logic tree (Figure 2.5.2-11). The first average recurrence interval is based on the four events that occurred within the past ~2,000 years. This time period is considered to represent a complete portion of the paleoseismic record based on published literature [e.g., (**Talwani and Schaeffer 2001**)] and feedback from those researchers questioned (**Talwani 2005; Obermeier 2005**). These events include 1886, A, B, and C' (Table 2.5.2-13). The average recurrence interval calculated for the most recent portion of the paleoliquefaction record (four events over the past ~2,000 years) is given 0.80 weight on the logic tree (Figure 2.5.2-11).

The second average recurrence interval is based on events that occurred within the past ~5,000 years. This time period represents the entire paleoseismic record based on paleoliquefaction data (**Talwani and Schaeffer 2001**). These events include 1886, A, B, C', E, and F' as listed in Table 2.5.2-13. As mentioned previously, published papers and researchers questioned suggest that the older part of the record (older than ~2,000 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 average recurrence interval calculated for the ~5,000-year record (six events) is given 0.20 weight on the logic tree (Figure 2.5.2-11). The 0.80 and 0.20 weighting of the ~2,000-year and ~5,000-year paleoliquefaction records, respectively, reflect incomplete knowledge of both the current short-term recurrence behavior and the long-term recurrence behavior of the Charleston source.

The mean recurrence intervals for the most-recent ~2,000-year and past ~5,000-year records represent the average time interval between earthquakes attributed to the Charleston seismic source. The mean recurrence intervals and their parametric uncertainties were calculated according to the methods outlined by Savage (1991) and Cramer (2001). The methods provide a description of mean recurrence interval, with a best estimate mean T_{ave} and an uncertainty described as a lognormal distribution with median $T_{0.5}$ and parametric lognormal shape factor $\sigma_{0.5}$.

The lognormal distribution is one of several distributions, including the Weibull, Double Exponential, and Gaussian, among others, used to characterize earthquake recurrence (Ellsworth et al. 1999a). Ellsworth et al. (1999a) and Matthews et al. (2002) 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 (WGCEP 2003). 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 (Cornell and Winterstein 1988; Ellsworth et al. 1999a). This is the case for Charleston, where 120 years have elapsed since the 1886 earthquake and the mean recurrence interval determined over the past ~2,000 years is about 548 years. The UCSS study has chosen to calculate average recurrence interval using a lognormal distribution because its statistics are well known (NIST/SEMATECH 2006) and it has been used in numerous studies [e.g.,(Savage 1991; WGCEP 1995; Cramer 2001)].

The average interval between earthquakes is expressed as two continuous lognormal distributions. The average recurrence interval for the ~2,000-year record, based on the three most recent inter-event times (1886-A, A-B, B-C'), has a best estimate mean value of 548 years and 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 ~5,000-year record, based on five inter-event times (1886-A, A-B, B-C', C'-E, E-F'), has a best estimate mean value of 958 years and 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 ~2,000-year record is between 409 and 690 years; for the ~5,000-year record, it is between 452 and 1,564 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 M_{\max} recurrence.

The mean recurrence interval values used in the UCSS model are similar to those determined by earlier studies. Talwani and Schaeffer (2001) 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 ~2,000 years; in their Scenario 2, large earthquakes have occurred with an average recurrence of 523 ± 100 years over the past ~2,000 years. Talwani and Schaeffer (2001) state that, "In anticipation of additional data we suggest a recurrence rate between 500 and 600 years for M 7+ earthquakes at Charleston". For the ~2,000-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 (2001). The best-estimate mean recurrence interval value of 548 years is comparable to the midpoint of the Talwani and Schaeffer (2001) best-estimate range of 500 to 600 years. The best estimate mean recurrence interval value from the ~5,000-year

paleoseismic record of 958 years is outside the age ranges reported by Talwani and Schaeffer (2001), although they did not determine an average recurrence interval based on the longer record.

In the updated seismic hazard maps for the conterminous United States, Frankel et al. (2002) use a mean recurrence value of 550 years for characteristic earthquakes in the Charleston region. This value is based on the above-quoted 500–600 year estimate from Talwani and Schaeffer (2001). Frankel et al. (2002) 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 (Cornell 1968). 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 ~2,000-year and ~5,000-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 ~2,000-year and ~5,000-year records, respectively; and (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.

2.5.2.2.2.5 Eastern Tennessee Seismic Zone

The Eastern Tennessee Seismic Zone (ETSZ) is one of the most active seismic zones in Eastern North America. This region of seismicity in the southern Appalachians is described in Section 2.5.1.1.4.6. Despite its high rate of activity, the largest known earthquake was magnitude 4.6 (**Chapman et al 2002**). No evidence for larger prehistoric earthquakes, such as paleoliquefaction features, has been discovered (**Chapman et al 2002; Wheeler 2005**). While the lack of large earthquakes in the relatively short historical record cannot preclude the future occurrence of large events, there is a much higher degree of uncertainty associated with the assignment of Mmax for the ETSZ than other CEUS seismic source zones, such as New Madrid and Charleston, where large historical earthquakes are known to have occurred.

The EPRI source model (**EPRI NP-4726 1986**) includes various source geometries and parameters to represent the seismicity of the ETSZ. All but one of the EPRI Earth Science Teams (ESTs) modeled local source zones to capture this area of seismicity and some ESTs included more than one zone. The Law team did not include a specific, local source for the ETSZ, however the ETSZ and Giles County seismic zones were included in a larger seismic source zone called the Eastern Basement (17). A wide range of Mmax values and associated probabilities were assigned to these sources to reflect the uncertainty of multiple experts from

each EST. The moment magnitude (**M**) equivalents of body-wave magnitude (m_b) M_{max} values assigned by the ESTs range from **M** 4.8 to 7.5. The Dames & Moore sources for the ETSZ included the largest upper-bound M_{max} value of **M** 7.5. Sources from the Woodward-Clyde and Rondout teams were also assigned large upper-bound M_{max} values of **M** 7.2.

Subsequent hazard studies have used M_{max} values within the range of maximum magnitudes used by the six EPRI models. Collectively, upper-bound maximum values of M_{max} used by the EPRI teams ranged from **M** 6.3 to 7.5. Using three different methods specific to the Eastern Tennessee seismic source, Bollinger (1992) estimated an M_{max} of **M** 6.3. The USGS source model assigns a single M_{max} value of **M** 7.5 for the ETSZ (**Frankel et al 2002**). Both of these more recent estimates of M_{max} for the ETSZ are captured by the range of M_{max} values used in EPRI (NP-4726 1986). Therefore, it is concluded that no new information has been developed since 1986 that would require a significant revision to the EPRI seismic source model.

For the VEGP ESP site, the contribution to hazard from the ETSZ sources in the EPRI study was minimal. With the exception of the Law source 17 (Eastern Basement), none of the ETSZ sources contributed more than one percent of the site hazard, and thus were excluded from the final hazard calculations (**EPRI NP-6452-D 1989**). The ground motion hazard at the VEGP ESP site is dominated by the Charleston seismic source, and the inclusion of new recurrence values for Charleston based on paleoliquefaction serves to increase the relative contribution of Charleston with respect to any distant source, such as the ETSZ. No modifications to the EPRI parameters for ETSZ source zones were made as part of this ESP study.

2.5.2.3 Correlation of Seismicity with Geologic Structures and EPRI Sources

The final part of the review and update of the 1989 EPRI seismic source model was a correlation of updated seismicity with the 1989 model source. The EPRI seismicity catalog covers earthquakes in the CEUS through 1984, as described in Section 2.5.2.1. Figures 2.5.2-1 through 2.5.2-6 shows the distribution of earthquake epicenters from both the EPRI (pre-1985) and updated (post-1984 through April 2005) earthquake catalogs in comparison to the seismic sources identified by each of the EPRI ESTs.

Comparison of the additional events of the updated earthquake catalog 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 would suggest a new seismic source not captured by the EPRI seismic source model.
- The updated catalog does not show a pattern of seismicity that would require significant revision to the geometry of any of the EPRI seismic sources.

- The updated catalog neither shows nor suggests any increase in M_{\max} for any of the EPRI seismic sources.
- The updated catalog does not imply a significant change in seismicity parameters (rate of activity, b-value) for any of the EPRI seismic sources (see also Section 2.5.2.4.2).

2.5.2.4 Probabilistic Seismic Hazard Analysis and Controlling Earthquakes

PSHA is an accepted method for determining seismic design levels (RG 1.165). The PSHA developed here relies on seismic source inputs from the EPRI-SOG study (**EPRI NP-6395-D 1989a**), which is accepted by the NRC (RG 1.165), on updates to those sources as described in Section 2.5.2.2, and on ground motion models (**EPRI 1009684 2004**) that have been accepted under other ESP applications.

The final SSE ground motion for the VEGP ESP site is developed using a performance-based approach, which has as its foundation a well-justified PSHA for the VEGP ESP site. Ground motion levels corresponding to mean annual frequencies of exceedance (MAFEs) of 10^{-4} to 10^{-6} are developed, because this range encompasses the range of motions necessary to establish the SSE ground motion under several criteria.

The seismic hazard at the VEGP ESP was first calculated using the assumptions of the EPRI (NP-6395-D 1989) study. This was to confirm that the 1989 results could be replicated. Then the seismic sources were updated with the UCSS models, including sources surrounding the Charleston source for each team, as described in Section 2.5.2.2.2. Also, the EPRI (1009684 2004) ground motion model was adopted for calculations of seismic hazard at seven structural frequencies. Sensitivity studies were conducted to determine the effects of these changes.

The seismic hazard was calculated for hard rock conditions for a range of ground motions corresponding to a range of annual frequencies of exceedance. This hard rock hazard formed the basis with which to integrate the effects of surficial materials on ground motion, to calculate the seismic hazard at a horizon appropriate for seismic design. The ASCE 43-05 2005 procedure was used to recommend an appropriate SSE seismic spectrum. This procedure requires ground motion amplitudes and slopes of seismic hazard curves in the range of 10^{-4} to 10^{-5} annual frequency of exceedance. To obtain a full design spectrum from structural frequencies of 0.1 to 100 Hz, a smooth site-specific spectral shape was fit to the seven structural frequencies for which specific seismic hazard calculations were made.

2.5.2.4.1 1989 EPRI Probabilistic Seismic Hazard Analysis, Deaggregation, and 1 Hz, 2.5 Hz, 5 Hz, and 10 Hz Spectral Velocities

PSHA calculations were initially made using the original 1989 EPRI-SOG seismic sources and ground motion assumptions (**EPRI NP-6395-D 1989**). The purpose of this calculation was to validate Risk Engineering Inc.'s (REI) proprietary FRISK88 seismic hazard code, the EPRI-SOG

seismic sources, the EPRI-SOG source combinations, and the EPRI-SOG attenuation equations, as modeled by the FRISK88 code. The results used in this replication were the peak ground acceleration (PGA) results available for VEGP site (see Appendix E, Table 3-103 of **(EPRI NP-6395-D 1989)**).

Seismic sources used to represent the seismic hazard for each of the six teams in the EPRI-SOG study are shown in Table 2.5.2-14. These are the primary sources used for the VEGP site in the original EPRI-SOG study, as documented in the EQHAZARD input files transmitted by EPRI.

The ground motion attenuation relations and their relative weights used in this analysis are those specified in the EPRI-SOG study (see Table 4-1 of **(EPRI NP-6395-D 1989)**). Following Table 4-1 of EPRI NP-6395-D, a standard deviation of (log) amplitude of 0.5 was assumed for each ground motion equation. These equations were used to calculate hard rock hazard.

The VEGP site is classified in EPRI NP-6395-D 1989 as a “Soil V” site (see Table 2-2 of **(EPRI NP-6395-D 1989)**). The site amplification factor versus PGA for this site class is shown in Figure 2-6 of EPRI NP-6395-D. To avoid having to apply site amplification factors to the rock curves, the results calculated here were compared to original EPRI-SOG hard rock results received from EPRI.

Results of this seismic hazard calculation are compared to the EPRI-SOG results in Table 2.5.2-15.

Agreement is excellent, generally within 5.1 percent in hazard for amplitudes up to 1g. For the 85 percent, replication is slightly less accurate, with a difference of -11.5 percent and -11.7 percent at 0.05g and 0.1g, respectively. This slight difference is of less concern, because the mean hazard curve is used to develop the SSE ground motions. Comparison plots of the mean, median, and 85 percent PGA hazard curves are shown in Figures 2.5.2-13 through 2.5.2-15.

This comparison validates the FRISK88 code, the EPRI-SOG seismic sources, the EPRI-SOG source combinations, and the EPRI-SOG attenuation equations.

2.5.2.4.2 Effects of New Regional Earthquake Catalog

The effects of the new regional earthquake catalog were examined by comparing seismicity rates in two regions critical to seismic hazard at the VEGP ESP site: the Charleston, South Carolina, region and the local region in South Carolina and into Georgia around the VEGP ESP site. The importance of these regions to seismic hazard is addressed in Section 2.5.2.4.6. The effects of two seismicity catalogs were compared: (1) the EPRI-SOG **(EPRI NP-4726-A 1988)** earthquake catalog (through 1984) and (2) the EPRI-SOG catalog updated to include more recent seismicity (Section 2.5.2.1). The fundamental question to be addressed is whether or not the seismicity recorded since 1984 indicates that the seismic activity rates used in the EPRI-

SOG study (**EPRI NP-6395-D 1989**) are inadequate or insufficiently conservative for assessment of the seismic hazard at the VEGP ESP site.

Seismicity rates were assessed for two sources in the site region, as follows: (1) a small rectangular source around the Charleston seismicity and (2) a triangular-shaped source representing seismicity in South Carolina and a strip of Georgia incorporating the VEGP ESP site. Figure 2.5.2-16 shows a map of these two sources, along with the earthquakes from the EPRI-SOG catalog and from the updated catalog.

The seismicity in these two sources was investigated by running program EQPARAM (from the EPRI EQHAZARD package), first for the original EPRI catalog and then using the updated EPRI catalog (through April 2005). Full smoothing of a- and b-values was selected for the comparison because this was a common choice of many of the ESTs in the EPRI-SOG study. Further, if comparisons were made on an individual degree-cell basis, the rates in some cells might increase and in others might decrease; furthermore, for a source such as the triangular South Carolina source, a composite rate would have to be used to compare seismic rates using the earthquake catalog through 1984 to those using the earthquake catalog through April 2005. The choice of full smoothing achieves this composite rate directly and automatically, since it is a composite rate for the entire source.

From the a- and b-values calculated with EQPARAM, recurrence rates were calculated for different magnitudes. Figures 2.5.2-17 and 2.5.2-18 compare the annual recurrence rates for the Charleston source and for the triangular South Carolina source, respectively. For the rectangular Charleston source, the updated catalog indicates that seismicity rates are about the same. For the triangular South Carolina source, the updated catalog indicates that seismicity rates have decreased when the seismicity from 1985 to April 2005 is added.

The conclusion is that the seismicity recorded since 1984 does not indicate that seismic activity rates have increased in those sources contributing most to the hazard at the VEGP ESP site under the assumptions of the EPRI-SOG study. Therefore, for original sources of the EPRI-SOG teams and the original seismicity rates from the EPRI-SOG (**EPRI NP-4726-A 1988**) earthquake catalog (through 1984) were used here for calculations of seismic hazard. These rates give an accurate estimate of seismicity for Charleston sources, and are slightly conservative for local sources, when compared to rates from the updated (through April 2005) catalog. Where the geometries of EPRI-SOG sources were modified to account for new information on the Charleston earthquake source (see Section 2.5.2.4.4 below), new seismicity rates were calculated using the updated earthquake catalog (through April 2005) in order to use the most recent information available.

2.5.2.4.3 New Maximum Magnitude Information

Geological and seismological data published since the 1986 EPRI seismic source model are presented in Section 2.5.1. Based on a review of these data, there are no significant changes in the EPRI M_{max} parameters, with the exception of the Charleston seismic source. A summary of M_{max} values for each EPRI EST is provided in Tables 2.5.2-2 through 2.5.2-7.

Changes to M_{max} for the Charleston seismic source are discussed in Section 2.5.2.2.2 and in a separate Engineering Study Report (**Bechtel 2006d**).

2.5.2.4.4 New Seismic Source Characterizations

The effect of new geoscience information is to modify the interpretations for the Charleston seismic source. The EPRI-SOG teams used an exponential model to represent earthquakes for sources in the Charleston area, and some teams adopted interpretations that included (with a low weight) the possibility that a specific Charleston source did not exist (i.e. that large earthquakes could occur in a large region in the eastern US). The new interpretation of the Charleston source (see Section 2.5.2.2.2) indicates that a source of large earthquakes in the Charleston area exists with weight 1.0 and that large magnitudes occur with a rate of occurrence unrelated to the rate of smaller magnitudes. Typical recurrence intervals for large Charleston earthquakes for the EPRI-SOG teams were on the order of 2,000 years, whereas the new information indicates recurrence intervals of 500–1,000 years.

In addition, the geometry of the Charleston sources has changed. Some EPRI-SOG teams drew relatively broad zones within which a Charleston-size earthquake could occur or specified (under some interpretations) that Charleston-size earthquakes were not restricted to southeast South Carolina but could occur over broad areas. The new geologic and tectonic information presented in Section 2.5.2.2.2 describes a relatively restricted zone within which Charleston-size earthquakes are modeled.

These changes in rate of occurrence and location of Charleston sources generally have the effect of increasing seismic hazard at the VEGP ESP site, compared to the EPRI-SOG study. It is not possible to determine the specific effect of one change, because (for example) changing the geometry of the Charleston source affects the geometries and seismicity rates of local sources and background sources for each EPRI-SOG team. The total effect of the new geoscience information is taken into account in the revised PSHA results presented in Section 2.5.2.4.6.

Figure 2.5.2-19 (reproducing Figure 2.5.2-9 content relevant to this discussion) shows the geometry of the four sources used to characterize the Charleston seismic source (Section 2.5.2.2.2).

To update the EPRI-SOG model, these four geometries of the Charleston source were overlaid onto each of the six EPRI-SOG team sources, and new geometries were created for all

EPRI-SOG team sources surrounding the Charleston source. Figure 2.5.2-20a shows an example of the original geometry, and Figures 2.5.2-20b through 2.5.2-20e show the new geometries created for the Rondout team, source 26. The purpose in creating the new geometries was to ensure that, in incorporating the new Charleston sources, no area was left without seismicity. Seismicity parameters for the new EPRI-SOG team source geometries were calculated using the same methodology and same smoothing assumptions as in the EPRI-SOG project and using the updated seismicity catalog (through April 2005). This procedure ensured that the principles underlying the seismicity representations for each EPRI-SOG team source surrounding Charleston were maintained.

The four geometries used to represent the Charleston source were modeled, for seismic hazard calculations, with parallel faults striking northeast-southwest and spaced at 10 km intervals. This spacing was narrow enough not to affect the calculated hazard (i.e., a spacing of 5 km would not have produced significantly different results). Activity rates for the faults were equally divided among the faults, and they were represented as vertical faults from the surface to a depth of 20 km. A rupture length equation (given magnitude) was used to represent a finite rupture length, and an aspect ratio (width-to-length) of 0.5 was assumed. The specific equation selected was for surface rupture length for all rupture types from Wells and Coppersmith (1994).

A characteristic earthquake was modeled for the new Charleston source geometries, with the following magnitudes and weights (Figure 2.5.2-11):

<u>M</u>	<u>Weight</u>
6.7	0.1
6.9	0.25
7.1	0.3
7.3	0.25
7.5	0.1

The magnitudes and weights were discussed in Section 2.5.2.2.4.2. The rate of occurrence of the characteristic earthquake was modeled with two 5-point discrete distributions representing (respectively) the 2,000-year and 5,000-year paleoliquefaction intervals described in Section 2.5.2.2.4.3. These distributions are as follows:

<u>2,000-Year Interval</u>		<u>5,000-Year Interval</u>	
<u>Activity Rate</u>	<u>Weight</u>	<u>Activity Rate</u>	<u>Weight</u>
1.22 x 10 ⁻³	0.101	3.65 x 10 ⁻⁴	0.101
1.45 x 10 ⁻³	0.244	6.12 x 10 ⁻⁴	0.244
1.77 x 10 ⁻³	0.310	9.20 x 10 ⁻⁴	0.310
2.16 x 10 ⁻³	0.244	1.38 x 10 ⁻³	0.244
2.78 x 10 ⁻³	0.101	2.32 x 10 ⁻³	0.101

These distributions give mean activity rates of 1.823×10^{-3} and 1.044×10^{-3} , respectively, which correspond to recurrence intervals of 548 years and 958 years, and have logarithmic shape factors of 0.25 and 0.51, as described in Section 2.5.2.2.2.4.3.

In addition to the characteristic earthquake, smaller earthquakes were modeled for each of the four source geometries for magnitudes between the lower-bound magnitude ($m_b = 5.0$) and M_{max} value of $m_b = 6.7$, with an exponential magnitude distribution. The activity rate and b-value for this distribution were determined using the EPRI-SOG catalog, EQPARAM software, and full smoothing of seismicity parameters across the source. For this exponential model, the rectangular geometries of the Charleston sources were assumed (see Figure 2.5.2-19), with earthquakes uniformly distributed within the source.

The source combinations of the EPRI-SOG teams were reviewed and modified to accurately incorporate the four new Charleston seismic sources into each team’s model. This generally resulted in four times as many source combinations, because a single Charleston source was being replaced by four alternative Charleston sources. As an example, the Rondout team originally had one source combination applicable to the VEGP ESP site:

<u>Source Combination</u>	<u>Weight</u>	<u>Sources</u>
1	1.0	26, 24

The revised model for the Rondout team had four source combinations applicable to the VEGP ESP site:

<u>Source Combination</u>	<u>Weight</u>	<u>Sources</u>
1	0.7	Charleston-A, 26-A
2	0.1	Charleston-B, 26-B
3	0.1	Charleston-B', 26-B'
4	0.1	Charleston-C, 26-C

where, for example, “26-A” indicates Rondout source 26 with new Charleston source geometry A removed. See Figures 2.5.2-20b through 2.5.2-20e for maps of these source geometries.

Incorporating this new geoscience information into the PSHA for the VEGP ESP site ensures that the PSHA results reflect the most recent information and interpretations of seismicity in the southeastern US. This provides a strong basis for the SSE ground motions.

2.5.2.4.5 New Ground Motion Models

The ground motion models developed by the 2004 EPRI-sponsored study (**EPRI 1009684 2004**) were used to examine the effects on seismic hazard of current estimates of seismic shaking as a function of earthquake magnitude and distance. For general area sources, nine estimates of median ground motion are combined with four estimates of aleatory uncertainty, giving 36 combinations. For fault sources in rifted regions, which applies to the ECFS fault segments, 12

estimates of median ground motion are combined with four estimates of aleatory uncertainty, giving 48 combinations. When both area sources and faults are active, a specific correlation of area source models and fault source models is used to represent ground motion models that might apply together. These families of models (36 for area sources, 48 for fault sources) represent the epistemic uncertainty in ground motion, and contribute to the epistemic uncertainty in seismic hazard.

Conclusions regarding a comparison of the EPRI NP-6395-D (1989) ground motion models with the EPRI 1009684 (2004) ground motion models depend on the specific magnitude, distance, and structural frequency being compared. Some comparison plots are shown in EPRI 1009684. In general, median ground motion amplitudes are similar at high frequencies. At low frequencies, the EPRI 1009684 models show lower median ground motions, because these models incorporate the possibility of a two-corner seismic source. Seismic hazard is affected by the median ground motion and also by the standard deviation. The EPRI 1009684 standard deviations are universally higher than those of EPRI NP-6395-D, which leads to higher seismic hazards.

2.5.2.4.6 Updated EPRI Probabilistic Seismic Hazard Analysis, Deaggregation, and 1 Hz, 2.5 Hz, 5 Hz, and 10 Hz Spectral Accelerations Incorporating Significant Increases Based on the Above Sensitivity Studies

Sensitivity studies were conducted to determine which magnitudes and distances contribute most to the seismic hazard at the VEGP ESP site. This was done following the guidelines of RG 1.165, modified for use in calculating SSE spectra using a performance-based procedure. Specifically, the seismic hazard was deaggregated at mean annual frequencies of exceedance (MAFEs) of 10^{-4} , 10^{-5} , and 10^{-6} . Deaggregations were conducted for two sets of spectral frequencies: a “high-frequency” set consisting of 10 Hz and 5 Hz and a “low-frequency” set consisting of 2.5 Hz and 1 Hz. Figure 2.5.2-21 shows a mean uniform hazard spectrum (UHS) for hard rock conditions at the VEGP ESP site for several MAFEs from 10^{-4} to 10^{-6} , and Table 2.5.2-16 lists the values of the mean UHS for hard rock conditions for these MAFEs for frequencies of 100 Hz (PGA), 25 Hz, 10 Hz, 5 Hz, 2.5 Hz, 1 Hz, and 0.5 Hz.

Figures 2.5.2-22 through 2.5.2-27 show the magnitude-distance deaggregations for three MAFEs and for the high- and low-frequency sets. For the low frequencies, earthquakes from the Charleston sources dominate the hazard at all MAFEs considered. For the high frequencies, local earthquakes contribute substantially to the hazard at 10^{-5} and dominate the contribution to hazard at the 10^{-6} MAFE level.

Figure 2.5.2-28 and 2.5.2-29 show marginal magnitude distributions from the deaggregations for high- and low-frequencies, respectively, for the three MAFEs. For the low frequencies, the large

earthquakes from the Charleston dominate the hazard at all three MAFEs. For the high frequencies, large earthquakes dominate 10^{-4} but the smaller earthquakes dominate 10^{-6} .

Figures 2.5.2-30 and 2.5.2-31 show marginal distance distributions from the deaggregations for high- and low-frequencies, respectively, for the three MAFEs. These deaggregations are consistent with those for magnitude, in terms of the contribution of large earthquakes from the Charleston sources.

The contribution of the Charleston sources to hazard can be understood by plotting and comparing hazard curves from individual sources. Figure 2.5.2-32 shows such a comparison, using as an example the sources from the Rondout team (which is the simplest interpretation). Figure 2.5.2-32, for 10 Hz spectral acceleration, shows that the main Charleston source (geometry A, marked “C-A” in Figure 2.5.2-32, with a weight of 0.7) dominates for MAFEs of 10^{-3} to 10^{-4} but that the local source “RND-26-A” dominates for lower MAFEs (below about 3×10^{-5}). At the 10^{-6} MAFE, most of the contribution to total hazard is from the local source. Figure 2.5.2-33, showing hazard curves for the Rondout team for 1 Hz spectral acceleration, indicates that the Charleston sources dominate the total hazard at all MAFEs (at least above 10^{-7}). Note that in both Figures 2.5.2-32 and 2.5.2-33, the mean hazard curve for each source includes the probability that that source is active. Thus, the hazard curves for Charleston sources B, B', and C (labeled C-B, C-B', and C-C) are lower than the hazard curve for Charleston source A (labeled C-A), primarily because the former three have much lower probabilities of activity than does source A.

These results indicate that seismic sources representing earthquakes in the Charleston region have a large contribution to seismic hazard for hard rock conditions at the VEGP ESP site. The local seismic source representing seismicity in South Carolina also can have an important contribution to hazard for high frequency ground motion, particularly for MAFEs around 10^{-5} and lower.

2.5.2.5 Seismic Wave Transmission Characteristics of the Site

The uniform hazard spectra described in the preceding section are defined on hard rock (shear-wave velocity of 9,200 ft/sec), which is located more than 1,000 ft below the current ground surface at the VEGP ESP site. The subsurface materials at the VEGP ESP site are described in detail in Section 2.5.4. The material characterization is summarized in the following groups:

- I Upper Sand Stratum (Barnwell Group) – predominantly sands, silty sands, and clayey sands, with occasional clay seams. A Shelly Limestone (Utley Limestone) layer was encountered at the base of the Upper Sand Stratum or the top of the Blue Bluff Marl. The limestone contains solution channels, cracks, and discontinuities, and was the cause of severe fluid loss observed during drilling for the VEGP ESP site subsurface investigation.

- II Marl Bearing Stratum (Blue Bluff Marl or Lisbon Formation) – slightly sandy, cemented, calcareous clay.
- III Lower Sand Stratum (comprises several formations from the Still Branch just beneath the Blue Bluff Marl to the Cape Fear just above the Dunbarton Triassic Basin rock) – fine to coarse sand with interbedded silty clay and clayey silt.
- IV Dunbarton Triassic Basin Rock – red sandstone, breccia, and mudstone, weathered along the upper 120 ft.
- V Paleozoic Crystalline Rock – a competent rock with high shear-wave velocity that underlies the Triassic Basin rock. The non-capable Pen Branch fault, forms the boundary between the Triassic Basin and Paleozoic basement rocks (see Section 2.5.1.2.4 for a detailed discussion of the Pen Branch fault).

The Upper Sand Stratum (Barnwell Group) will be removed because it is not considered competent material. It is susceptible to liquefaction (Section 2.5.4.8) and dissolution-related ground deformation (Section 2.5.3.8.2); also the shear-wave velocity of the Upper Sand Stratum is generally below 1000 ft/sec, see Table 2.5.4-6.

Therefore the highest in situ competent material for the VEGP ESP site is the Blue Bluff marl at 86 ft depth. Its shear-wave velocity is greater than 1000 ft/sec with the average value of 2,354 ft/sec (Section 2.5.4.4.2.1). For soil characteristics like those found at the VEGP ESP site, the "free ground surface" of a hypothetical outcrop is judged compatible with the words "free ground surface" in 100.23 (d) (1) of 10 CFR Part 100 and the guidance provided in NUREG-0800 Section 3.7.1 on defining the "free ground surface." Therefore the VEGP ESP SSE is defined in the free field on the free ground surface of a hypothetical outcrop of the Blue Bluff Marl.

All safety-related structures will be founded on structural backfill that will be placed on top of the Blue Bluff Marl after complete removal of the Upper Sand Stratum. The structural fill will be a sandy or silty sand material following the guidelines used during construction of VEGP Units 1 and 2.

To determine the SSE at the 86-ft depth of the top of the Blue Bluff Marl it is necessary to adjust the uniform hazard hard rock spectra (presented in Section 2.5.2.4) for amplification or deamplification as vibratory ground motion is propagated through the subsurface materials above the 9,200 ft/s shear-wave velocity horizon. This section describes the analyses performed to develop site amplification functions associated with the different hard rock ground motions presented in Section 2.5.2.4. These site amplification functions are used in Section 2.5.2.6 along with the hard rock ground motions to develop site-specific SSE ground motion.

2.5.2.5.1 Development of Site Amplification Functions

2.5.2.5.1.1 Methodology

The method adopted here to account for the effects of surficial soils on seismic hazard follows the procedure in NUREG/CR-6728 and NUREG/CR-6769 (McGuire et al. 2001, 2002), described as “Approach 2A.” This procedure requires 6 steps:

1. The seismic hazard is calculated for hard rock conditions for the seven structural frequencies, over a range of ground motion amplitudes, resulting in a range of annual frequencies of exceedance.
2. For ground motion amplitudes corresponding to annual frequencies of 10^{-4} , 10^{-5} , and 10^{-6} , the seismic hazard is deaggregated for high frequencies (HF) and low frequencies (LF), as described in Section 2.5.2.4.6, to determine the dominant magnitudes and distances for those amplitudes and frequencies.
3. HF hard rock spectra are developed to represent earthquakes dominating the 5-10 Hz ground motions, and LF hard rock spectra are developed to represent earthquakes dominating the 1-2.5 Hz ground motions. These hard rock spectra represent the mean magnitude and distance of earthquakes that dominate the seismic hazard for those structural frequencies.
4. The rock and soil column is modeled, and soil amplitudes are calculated at the control point elevation for input hard rock motions corresponding to frequencies of exceedance of 10^{-4} , 10^{-5} , and 10^{-6} . These calculations are made separately for ground motions dominating the HF hard rock motion and the LF hard rock motion, and the input motions have a spectrum determined by the HF or LF hard rock spectral shape, as appropriate. Multiple hard rock motions are used, and multiple soil column properties are used, so that the mean soil amplitudes can be determined accurately.
5. The soil amplification factors (AFs) are developed at 300 frequencies using analyses described in this section based on the HF and LF hard rock spectral shapes. The AFs represent the mean spectral acceleration (SA) at the control point, divided by input SA at hard rock, at each frequency. At each frequency, the envelope motion is determined. This is the motion (HF or LF) that gives the higher mean soil motion, for that structural frequency and MAFE. At frequencies above 8 Hz, this is always the HF motion. At frequencies below 2 Hz, this is always the LF motion. At intermediate frequencies, the envelope motion depends on the frequency and the MAFE.
6. The uniform hazard response spectra at MAFEs of 10^{-4} and 10^{-5} at the control point location are calculated as follows. Starting from the 10^{-4} and 10^{-5} SA hard rock values (from the hazard calculations described in 2.5.2.4) at the seven structural frequencies, interpolation is performed between those SA values to obtain 10^{-4} and 10^{-5} SA values at

the 300 structural frequencies using the HF and LF spectral shapes for hard rock. The choice of HF or LF is based on the envelope motion determined in the previous step. The UHS for 10^{-4} at the control point location is calculated by multiplying the hard rock 10^{-4} SA values at the 300 frequencies by the mean AFs for 10^{-4} from step 5, again using the HF or LF mean AF corresponding to the envelope motion. (At some intermediate frequencies between 2 and 8 Hz, the HF and LF AFs are weighted in order to achieve a smooth transition between HF and LF spectra.) The UHS for 10^{-5} is calculated in a similar way, using the 10^{-5} rock SA values and the 10^{-5} AFs.

This gives an accurate calculation of the soil hazard at the desired control point elevation. In step 3, it is sufficiently accurate to use the mean magnitude to generate spectral shapes for the HF and LF spectra (Approach 2A of NUREG/CR-6728 and NUREG/CR-6769 (**McGuire et al. 2001, 2002**)). Using multiple magnitudes (Approach 2B of NUREG/CR-6728 and NUREG/CR-6769) does not materially affect the calculated soil spectra, as documented in NUREG/CR-6769 (**McGuire et al. 2002**).

From the 10^{-4} and 10^{-5} SA values at the control point elevation, design spectra are calculated using the procedure recommended by ASCE 43-05 2005. This procedure is used to establish the SSE spectral amplitudes at the 300 structural frequencies. To obtain a final horizontal SSE, spectrum smoothing of the raw spectral shape is performed as described in 2.5.2.6.3.

2.5.2.5.1.2 Base Case Soil/Rock Column and Uncertainties

Development of a base case soil/rock column, is described in Section 2.5.4. Summaries of the low strain shear wave velocity, material damping, and strain-dependency properties of the base case materials, as these parameters are used in the site response analyses, are provided below in Section 2.5.2.5.1.2.1. Section 2.5.2.5.1.2.2 describes the methodology and results of randomization to address the uncertainties in soil/rock column parameters.

2.5.2.5.1.2.1 Base Case Soil/Rock Column

2.5.2.5.1.2.1.1 Soil Column

The base case shear-wave velocity model for the soil column is provided in Figure 2.5.4-7, and the corresponding values are listed in Table 2.5.4-11. The base case assumes that the uppermost 86 feet of native material will be excavated and replaced with structural fill. Shear-wave velocity was not measured for the compacted backfill during the ESP subsurface investigation (APPENDIX 2.5A). Interpolated values based on measurements made on fill for existing Units 1 and 2 (**Bechtel 1984**) are used instead. The backfill shear-wave velocity values are summarized in Table 2.5.4-10 (these values are also included in Table 2.5.4-11).

The variation with strain of shear modulus and damping of the soil were developed for two sets of degradation relationships:

- Based on relationships developed for EPRI (**EPRI TR-102293 1993**) and
- Based on relationships developed for SRS (**Lee 1996**).

The EPRI relationships are widely used and accepted in the industry and, while the SRS curves were developed for the adjacent SRS site, the Blue Bluff Marl soil unit at the ESP site has higher velocities than the corresponding soil unit at the SRS site. Analyses are performed for both sets of degradation curves and equally weighted in developing the final spectral amplification factors. Details of the derivation and extension of the degradation curves are presented in Section 2.5.4.7.2.

The base case degradation curves for shear modulus and damping for the EPRI-based assumption are presented in Figures 2.5.4-9 and 2.5.4-11, respectively. The base case degradation curves for shear modulus and damping for the SRS-based assumption are presented in Figures 2.5.4-10 and 2.5.4-12, respectively. The corresponding tables of values are presented in Table 2.5.4-12 and 2.5.4-13, for the EPRI-based and SRS-based relationships, respectively.

Unit weights, derived from the ESP laboratory testing program (APPENDIX 2.5A) for the shallow soils and calculation (**WSRC 1998**) for the deep sands are provided in Table 2.5.4-4.

2.5.2.5.1.2.1.2 Rock Column

Due to the geometry of the Pen Branch fault, the shear-wave velocity character of the Triassic Basin and Paleozoic crystalline rocks below the Coastal Plain sediments, and the possible presence of a low velocity zone between the Triassic Basin and the Paleozoic crystalline rocks a set of six (6) rock column models were used in combination with the base case soil column, described above, to adequately model uncertainty in the rock/soil column for site response analysis.

As discussed in Section 2.5.4.2.5, a rock density of 2.75 gm/cc (172 pcf) is used for the crystalline rock, and 2.53 gm/cc (158 pcf) for the Triassic rock. Based on inspection of Figures 2.5.4-11 and 2.5.4-12, the low strain damping of soils is on the order of 0.5 percent, which generally increases to 0.6 percent to 2 percent for strain compatible conditions. Rock, which would be expected to have lower damping than soil, was therefore assumed to behave as a linearly elastic material with one percent damping for all rock types.

The above-described shear-wave velocity profile, degradation relationships, and material densities were then used to develop randomized soil/rock profiles described in the following section.

2.5.2.5.1.2.2 Randomization of Site Profiles

To account for variations in shear-wave velocity across the site, sixty artificial profiles were generated using the stochastic model described in EPRI (**EPRI TR-102293 1993**) and extended in Toro (1996), with some modifications to account for the conditions at the VEGP ESP site. These artificial profiles represent the soil/rock column from the top of the Paleozoic crystalline rock (with a shear-wave velocity of 9,200 feet/s) to the ground surface. This model uses as inputs the following quantities: (1) the median shear-wave velocity profile, which is equal to the base-case soil and rock profiles defined in Sections 2.5.2.5.1.2.1.1 and 2.5.2.5.1.2.1.2; (2) the logarithmic standard deviation of shear-wave velocity as a function of depth, which is set to 10 percent for the structural backfill, is set to values obtained from soil-randomization studies performed at the SRS site (**Toro 1997; Toro 2005**) for the soil strata, and is set to values consistent with the six rock-column models described in Section 2.5.2.5.1.2.1.2; (3) the correlation coefficient between velocities in adjacent layers, which is taken from the second SRS soil-randomization study referenced above; (4) the probabilistic characterization of layer thickness as a function of depth, which is taken from the second SRS soil-randomization study referenced above, modified to allow for sharp changes in the base-case velocity profile; and (5) the depth to bedrock, which is randomized to account for the range of depths associated with the Pen Branch fault described in Section 2.5.2.5.1.2.1.2.

Figure 2.5.2-34 depicts the summary statistics for the 60 shear-wave velocity profiles. It is worth noting that the depth to the Blue Bluff Marl and to the Triassic Basin rock vary little between the profiles, and that the logarithmic standard deviation in shear-wave velocity is lower than typical values (e.g., (**Toro 1996**)). These features are a consequence of the availability of shear-wave velocity data from the VEGP ESP site and from the nearby SRS, and of the uniformity exhibited by these data. As a consequence of this uniformity, the average amplification factors computed from site-response calculations using these profiles may not be as smooth as those obtained using artificial profiles with more variability.

The degradation curves for shear modulus and damping were also randomized to account for the epistemic and aleatory uncertainty in these properties. These randomizations used as input the following quantities: (1) the median degradation curves, which are equal to the base-case degradation curves in Sections 2.5.2.5.1.2.1.1 and 2.5.2.5.1.2.1.2; (2) the uncertainties in the degradation properties of soil, which are taken from Costantino (1996), except for the engineered backfill, for which they are reduced by 1/3; and (3) the uncertainty in the damping ratio for the Triassic Basin rock, which is represented by a 5-95 percentile range of 0.7-1.5, which corresponds to a logarithmic standard deviation of 0.41. For each randomized velocity profile, one set of randomized degradation curves was generated for the EPRI curves and another set was generated for the SRS curves.

2.5.2.5.1.3 Development of Low-Frequency and High-Frequency Target Spectra

Spectrum-compatible target spectra were developed for the two different frequency ranges: HF (5-10 Hz) and LF (1-2.5 Hz), as defined in Reg. Guide 1.165, at each of three annual probability levels (10^{-4} , 10^{-5} , and 10^{-6}). The target spectra are based on the computed mean magnitude (Mbar) and distance (Dbar) values from the deaggregation of the hazard curves. For the HF cases (5-10 Hz), only those sources less than 105 km were used to compute the Mbar and Dbar values. For the LF cases (1-2.5 Hz), only those sources at distances greater than 105 km were used to compute the Mbar and Dbar values. This distinction was made based on the noted dominance of the Charleston source for low frequencies and long return periods. The computed Mbar and Dbar results were based on the average of the 5 – 10 Hz values for the HF cases and the average of the 1 – 2.5 Hz for the LF cases. These computed values are given in Table 2.5.2-17. Based on the similar Mbar and Dbar values for each of the three probability levels for the HF and LF cases, a single Mbar and Dbar pair was selected for each of the HF and LF cases.

Given the Mbar and Dbar values, the Central and Eastern United States spectral shape (log-average of the single and double corner source models) from NUREG/CR-6728 (**McGuire et al. 2001**) were computed for both the HF and LF cases. These spectral shapes were scaled to the corresponding uniform hazard spectral (UHS) values (see Table 2.5.2-16) at 7.5 Hz and 1.75 Hz for the HF and LF cases, respectively. An additional requirement that the envelop spectrum of the scaled target spectra for a given annual probability level be no less than 90 percent of the UHS was applied. In any case for which this requirement was not met, either the scaled HF or LF target spectrum was increased to meet this requirement at the seven frequencies at which the hard rock UHS is computed. For the HF case, this requirement caused an increase of the 25 Hz spectral acceleration value at the 10^{-6} probability level. For the LF case at all three probability levels, the scaled LF spectra fall below the 90 percent UHS limit at 1 and 0.5 Hz. Thus, the scaled LF spectra were increased to 90 percent of the UHS value for the 1 and 0.5 Hz values, and for frequencies less than 0.5 Hz, the spectral shape of the LF spectrum scaled to the 90 percent of the 0.5 Hz UHS value was used.

The scaled spectra were interpolated (log-log) to the recommended sampling rate of 100 equally log spaced values per frequency decade. The HF and LF target spectra for the three annual probability levels used to develop the spectrum-compatible time histories are shown in Figures 2.5.2-35a and b.

2.5.2.5.1.4 Selection of Seed Time Histories

The selection of the seed input time histories used in the spectral matching procedure was guided by the deaggregation results described in the previous section. For the HF case, the recommended Mbar and Dbar values are 5.6 and 12 km. For the low frequency case, the recommended Mbar and Dbar values are 7.2 and 130 km. These values were considered

appropriate for all three MAFEs. Based on these recommended magnitude and distance values, a total of 30 seed time histories were selected for both the HF and LF cases.

Based on the limited number of strong ground motion acceleration time histories from stations located in the Eastern North America, 58 of the 60 selected seed input time histories were recorded at stations located in other regions than the Eastern North America. The additional two seed time histories that are used for the HF case were recorded in Eastern Canada. Time histories were selected based on the database of recorded strong ground motion records, recommended magnitude and distance values, and shear-wave velocities in the top 30 meters at recording sites of greater than 600 m/sec (about 1,970 ft/sec). The selected seed time histories are listed in Table 2.5.2-18A and Table 2.5.2-18B, for the HF and LF cases, respectively.

The spectral matching was performed based on a given horizontal target spectra with a spectral damping of 5 percent. The spectral matching procedure is a time domain spectral matching procedure and emphasis was placed on maintaining the phasing characteristics of the initial time history in the final modified spectrum-compatible time history. In addition, emphasis was placed on maintaining the characteristic of the normalized Arias intensities (the integral of the square of the acceleration-time history, a ground motion parameter that captures the potential destructiveness of an earthquake) of the initial and final modified spectrum-compatible time histories. The spectral matching criteria given in NUREG/CR-6728 (**McGuire et al. 2001**) were used to check the average spectrum from the 30 time histories for a given frequency range (high- or low-frequency) and annual probability level. This is the recommended procedure in NUREG/CR-6728 (**McGuire et al. 2001**) when multiple time histories are being generated and used.

The selected 60 seed time histories were first matched to their respective 10^{-6} high and low frequency target spectra. As an example, the acceleration, velocity, and displacement time histories for one of the thirty 10^{-6} HF target spectrum seed time histories are shown in Figure 2.5.2-45a. The final modified spectrum-compatible acceleration, velocity, and displacement time histories (matched to the 10^{-6} HF target spectrum) are plotted in Figure 2.5.2-45b. Figure 2.5.2-46 shows the 10^{-6} HF target spectrum (thick grey line), the response spectrum from the initial acceleration time history scaled to the target PGA value (thin blue line), and the response spectrum from the final modified spectrum-compatible time history (thin red line). The initial and final modified spectrum-compatible normalized Arias intensities for this example are plotted in Figure 2.5.2-47. These results are representative of the goodness of fit for all spectrum-compatible time histories. For the 10^{-5} probability level, the final modified spectrum-compatible time histories from the 10^{-6} probability level were used as the input time histories for the spectral matching. In a similar fashion, the final modified spectrum-compatible time histories for the 10^{-5} probability level were used as the input time histories for the spectral matching at the 10^{-4} probability level. The results of the spectral matching for the high and low frequency cases at

each of the three annual probability levels are shown in Figures 2.5.2-36a through f. These spectrum-compatible time histories were used in the site response analysis presented in the next section.

2.5.2.5.1.5 Site Response Analyses

The site response analyses were conducted using randomized shear-wave velocity profiles and soil modulus and damping relationships discussed in Section 2.5.2.5.1.2.1.3 to account for variation in the dynamic soil properties across the VEGP ESP Site. Two separate sets of degradation relationships for shear modulus and damping were applied in the site response analyses: EPRI-based curves and SRS-based curves (see Section 2.5.2.5.1.2). As described in Section 2.5.4.7.2, the EPRI degradation curves were extended to just over 3 percent strain and the SRS degradation curves to 2 percent strain. The depth to hard rock ($V_s > 9200$ fps) was also randomized to reflect its uncertainty. All site response analyses assumed that the sedimentary rock below 1049 ft (depth to bottom of Coastal Plain sediments) remains linear during earthquake shaking with one percent damping for all rock types. This randomization process resulted in 60 randomized soil/rock profiles (that included combinations of depths to hard rock and degradation relationships) for each family of degradation curves (i.e., EPRI or SRS). Additional details about the generation of profiles for the site response analyses are included in Section 2.5.2.5.1.2.

Each of the 60 randomized soil profiles were paired with 30 seed time histories (each time history was applied to two of the randomized soil profiles) for each of the hard rock input motions (i.e., 30 time histories for the HF spectra and 30 time histories for the low frequency spectra). Three different mean annual frequency of exceedance events (10^{-4} , 10^{-5} , and 10^{-6} , see Section 2.5.2.5.1.3) were analyzed for each profile - seed time history pairing in order to calculate the amplification at the top of Blue Bluff Marl (86-ft depth) resulting from input motion at the 9,200 ft/s shear-wave velocity horizon.

The computer program SHAKE (**Bechtel 2000**) was used to perform these analyses. Amplification between the top of Blue Bluff Marl (86-ft depth) and the input motion, in terms of five percent damped acceleration spectral ratios, was extracted from each analysis resulting in 720 spectral amplifications (see Table 2.5.2-19).

The mean of the site amplification functions for each group of 60 randomized soil profiles was used to develop site amplification factors for the VEGP ESP Site, as described in NUREG/CR-6728 (**McGuire et al. 2001**).

Figure 2.5.2-37 depicts the mean spectral amplification results of a typical analysis for HF content of a 10^{-4} MAFE seismic event using EPRI degradation curves. The average curve shown was determined by averaging the logarithms of amplification values for each frequency. As described in Section 2.5.2.5.1.2.1.1, analyses are performed for both sets of degradation

curves and equally weighted in the subsequent development of the final spectral amplification factors.

In order to implement site response analysis Approach 2A, as discussed in Section 2.5.2.5.1.1, the amplification factors are prepared as a function of hard rock input motion. Tables 2.5.2-20a and 2.5.2-20b present the amplification factors at the top of the Blue Bluff Marl {depth 86 feet} for input rock motions corresponding to 10^{-4} , 10^{-5} , and 10^{-6} HF and LF MAFE spectra respectively (see Figures 2.5.2-35a and b). These results are presented for 30 structural frequencies, including the seven structural frequencies at which seismic hazards were calculated.

2.5.2.6 Safe Shutdown Earthquake Ground Motion

2.5.2.6.1 Criterion for SSE

The criterion used to calculate the recommended design spectrum comes from ASCE 43-05 (**ASCE 2005**). This criterion is based on the mean seismic hazard curves for multiple structural frequencies at the prescribed elevation, taking into account the effect of rock and soil above the hard rock horizon. The spectral amplitudes at this elevation corresponding to a mean annual frequency of exceedance (MAFE) of 10^{-4} are scaled so that structures and components designed to the scaled spectral amplitudes will achieve a target performance goal corresponding to a mean annual frequency of onset of significant inelastic deformation (FOSID) of 10^{-5} per year. The soil hazard curves that form the basis for this calculation were developed following Approach 2A as described in Section 2.5.2.5.1.1.

2.5.2.6.2 Discrete Frequency SSE Response Spectrum Amplitudes

Table 2.5.2-21 shows ground motion amplitudes corresponding to MAFEs of 10^{-4} , 10^{-5} , and (for information purposes only) 10^{-6} for hard rock conditions (thirty structural frequencies are tabulated including, the seven frequencies developed in Section 2.5.2.4 and an additional twenty three frequencies from the 300 frequency values per step 6 of 2.5.2.5.1.1). Table 2.5.2-21 also shows ground motion amplitudes for the free ground surface of a hypothetical outcrop point of the highest competent in situ layer (top of Blue Bluff Marl); these were calculated from the hard rock motions and the amplification factors of Section 2.5.2.5.

The SSE (the design response spectrum (DRS) in the nomenclature of the ASCE 43-05 (**ASCE 2005**)) is derived from the amplitudes for MAFEs of 10^{-4} and 10^{-5} in Table 2.5.2-21. That is, the Amplitude Ratio, A_R , of 10^{-5} to 10^{-4} amplitudes is determined for spectral accelerations (SA) at each structural frequency:

$$A_R = SA(10^{-5})/SA(10^{-4}) \quad (\text{Equation 2.5.2-4})$$

and the SSE is calculated as:

$$\text{SSE} = \text{SA}(10^{-4}) \times \max(1.0, 0.6 A_R^{0.8}) \quad (\text{Equation 2.5.2-5})$$

Table 2.5.2-22 shows thirty of the SSE values calculated from Equation 2.5.2-5, at the free ground surface of a hypothetical outcrop of the top of Blue Bluff Marl. In Table 2.5.2-22, the last term in Equation 2.5.2-5, $0.6 A_R^{0.8}$, is indicated as “DF2” in the table.

2.5.2.6.3 Full SSE Spectrum

The SSE values at the 300 structural frequencies, thirty of which are provided in Table 2.5.2-22, are used to define the raw SSE ground motion response spectrum. This spectrum is then smoothed by a running average filter for the 100-points-per-decade spectral amplitudes above 1 Hz, but is constrained to go through the seven structural frequencies at which hazard calculations were made. (An exception was made for 5 Hz, where the site amplification analysis indicated a trough, so the 5 Hz SSE value was smoothed based on amplitudes at adjacent frequencies, which raised the 5 Hz SSE value slightly and improved the shape of the spectrum.) This step smooths out the spectral peaks and troughs above 1 Hz that are not statistically significant, but maintains the low-frequency peaks and troughs representing lower-mode soil column response for this site.

Figure 2.5.2-38 shows the raw spectrum and the smoothed SSE Spectrum. The smoothed spectrum is the VEGP ESP horizontal SSE and is specified at the free ground surface of a hypothetical outcrop of the top of the Blue Bluff marl. Figure 2.5.2-44 also shows the VEGP ESP horizontal SSE.

2.5.2.7 Vertical SSE Spectrum.

The method to develop the vertical SSE is to develop a vertical-to-horizontal scaling factor [V/H], which is then applied to the horizontal SSE, presented above.

2.5.2.7.1 Development of V/H

Reg. Guide 1.60 presents acceptable standard response spectral shapes as a function of frequency that may be considered for the seismic design of nuclear power plants. These shapes are given for both horizontal and vertical ground motions as a function of damping. The shapes are independent of peak ground acceleration (PGA), which is used as a scaling factor. The ratio of the vertical to horizontal spectral shapes results in a V/H scaling function that is a value of 2/3 for frequencies less than 0.25 Hz, 1.0 for frequencies higher than 3.5 Hz, and varies between 2/3 and 1 for frequencies between 0.25 and 3.5 Hz.

A significant increase in the number of strong ground motion observations and advances in earthquake ground motion modeling since the publication of Reg. Guide 1.60 suggest that the

V/H ratios implied in Reg. Guide 1.60 may not be appropriate for a given site (**EPRI TR-102293 1993; McGuire et al. 2001**). The horizontal and vertical ground motions and the V/H ratios are observed to depend on magnitude, distance, site conditions, and regional tectonic setting (e.g. western US [WUS] vs. central and eastern US [CEUS]), which presents distinctive characteristics of earthquake source, attenuation along regional path, and shallow crust).

NUREG/CR-6728 (**McGuire et al. 2001**) presents V/H ratios for soft rock WUS sites and hard rock CEUS sites as a function of horizontal peak acceleration, as a proxy for the combined dependence on magnitude and distance. While the WUS rock V/H ratios are based on the significant empirical database of WUS strong ground motion, there are too few CEUS recordings to develop empirically-based CEUS V/H relations. NUREG/CR-6728 follows up on a technique presented in EPRI TR-102293 of using earthquake ground motion modeling to develop CEUS rock V/H. Due to assumptions and the estimation of various required parameters, the explicit results of the CEUS modeling are not considered robust, but can be used as guidelines for the difference between V/H ratios for WUS and CEUS rock sites. For the rock CEUS V/H ratios NUREG/CR-6728 uses the WUS ratios and modifies them based on the difference in trends obtained between WUS and CEUS rock sites from their modeling studies. For example, a peak in the V/H ratio is expected to occur at higher frequencies for CEUS than for WUS sites because site kappa values in the CEUS are typically lower than in the WUS.

The VEGP ESP site, however, is a deep soil site, not a hard rock site. V/H relations for soil sites are not given in NUREG/CR-6728 (**McGuire et al. 2001**), and, again, an insufficient number of ground motion observations have been made to develop empirical CEUS relationships for soil sites. Appendix J of NUREG/CR-6728, however, does discuss the use of modeling by which V/H ratios can be developed for CEUS soil sites. The method mirrors that used in NUREG/CR-6728 in developing the CEUS rock V/H relations, and can be represented by the following formula:

$$V/H_{CEUS,Soil} = V/H_{WUS,Soil,Empirical} * [V/H_{CEUS,Soil,Model} / V/H_{WUS,Soil,Model}] \quad (\text{Equation 2.5.2-6})$$

The first term of Equation 2.5.2-6 can be a readily available WUS relationship, such as Abrahamson and Silva (1997), which presents both vertical and horizontal ground motion attenuation relations for deep soil sites. Magnitude and distance is specified, which allows hazard contribution-appropriate specification for a given location.

The second term is a WUS-to-CEUS “transfer function” to modify the WUS ratios from the first term to give the required $V/H_{CEUS,Soil}$. The development of this second term entails ground motion modeling of both CEUS [numerator] and WUS [denominator] ground motions appropriate for the given site (e.g., the major contributing or controlling earthquake by magnitude and distance) and considers the site-specific conditions. The model for developing $V/H_{WUS,Soil,Model}$ considers generic site soil conditions, as implicitly considered in the

$V/H_{WUS,Soil,Empirical}$ term. The model for developing $V/H_{CEUS,Soil,Model}$ model can consider as site-specific soil conditions as possible.

Upon developing $V/H_{CEUS,Soil}$ from Eq. 2.5.2-6, the vertical SSE response spectrum is then defined by

$$S_{aSSE,Vertical} = S_{aSSE,Horizontal} * V/H_{CEUS,Soil} \quad (\text{Equation 2.5.2-7})$$

As discussed above, the first term on the right-hand side of Equation 2.5.2-6 can be implemented using the ground motion attenuation relationship of Abrahamson and Silva (1997). The development of the WUS-to-CEUS transfer function (the second right-hand side term of Equation 2.5.2-6) needs significant analytical effort, contains potentially significant uncertainties, and requires a number of assumptions. Two studies guide the development of a best estimate of $V/H_{CEUS,Soil}$ and, through Equation 2.5.2-7, the definition of the vertical SSE response spectrum.

2.5.2.7.1.1 Estimate of V/H from NUREG/CR-6728

Appendix J of NUREG/CR-6728 (McGuire et al. 2001) discusses various characteristics of vertical strong motions and, building upon the work presented in EPRI TR-102293, presents the methodology to estimate V/H for CEUS rock and soil sites. This method is that represented by Equation 2.5.2-6, above. A generic CEUS soil column is considered in their presentation of the method. In the appendix, plots of the numerator and denominator of the WUS-to-CEUS transfer function are shown, Figures J-32 and J-31, respectively, for M6.5 and a suite of distances [1, 5, 10, 20, and 40km]. An estimate of the WUS-to-CEUS transfer function can be made for M6.5 at the given distances using these results shown in these figures.

As discussed above, the SSE response spectrum is based on slopes of the 10^{-4} and 10^{-5} ground motion hazard curves and the scaling of the 10^{-4} ground motions. For a hypothetical outcrop point at the 86-foot depth top of the Blue Bluff Marl, the resulting horizontal SSE ground motions at the seven spectral control points are generally only slightly higher than the 10^{-4} ground motion levels. That is, the horizontal SSE is dominated by the 10^{-4} ground motion.

In reviewing the high-frequency distance deaggregation at the 10^{-4} hazard level (Figure 2.5.2-30), about one-quarter of the hazard is coming from “near” events, or about distances less than 20 km, while about three-quarters of the hazard is coming from “far” events, or distances centered at about 130 km. In reviewing the corresponding distance deaggregation at the 10^{-5} hazard level in the same figure, the bimodal nature of the deaggregation is yet apparent, but the relative contribution of the near and far events is about the same.

In reviewing the low-frequency magnitude-distance deaggregations at both the 10^{-4} and 10^{-5} hazard levels (Figure 2.5.2-31), hazard contribution is clearly dominated by the distant event centered on about 130 km.

The magnitudes and distances that can be attributed to the near and far events are taken as those used in the development of the high-frequency and low-frequency target spectra for the site response analysis: **M5.6** at a distance of 12 km and **M7.2** at a distance of 130 km, respectively.

Figure 2.5.2-39 is a plot of the first term of Equation 2.5.2-6 for both near and far events using the attenuation relationship of Abrahamson and Silva (1997).

Figure 2.5.2-40 is a plot of estimates of the second term of Equation 2.5.2-6 (ratio of V/H ratios) developed as the quotient of the curves in NUREG/CR-6728 (McGuire et al. 2001) Figure J-32 and J-31 for highest available distances of 10, 20, and 40 km. The Appendix J figures are given only for **M6.5**. Therefore, an estimate of an equivalent ground motion proxy magnitude and distance must be made to estimate the second term of Equation 2.5.2-6. The **M6.5**, 20 km curve may be considered a reasonable proxy for the “near” event of **M5.6** at 12 km. The greatest distance given in the two figures of Appendix J is 40 km, so this has to be used as the proxy, along with the associated **M6.5**, for the “far” event of **M7.2** at 130 km. Given the trend of the V/H values (decreasing with distance for a given magnitude), it is expected that the “far” event proxy may be conservative (high in value), as compared to the value expect if equivalent ratio of ratio curves had been explicitly available for **M7.2** at 130 km. Figure 2.5.2-40 shows the recommended “near” and “far” versions of the second term of Equation 2.5.2-6. Some smoothing has been applied that may be reflecting certain aspects (peaks, valleys) of the response reflecting the generic soil models used.

Figure 2.5.2-41 is a plot of $V/H_{\text{CEUS,Soil}}$ of Equation 2.5.2-6 considering both “near” and “far” events. Given the observations made earlier with regard to the relative contributions of the deaggregation “near” and “far” events to the 10^{-4} and 10^{-5} hazards, and the relative contribution of these two hazard levels to the horizontal SSE design response spectrum, the “near” and “far” estimates of $V/H_{\text{CEUS,Soil}}$ are weighted approximately 1:3, resulting in the final $V/H_{\text{CEUS,Soil}}$ shown in Figure 2.5.2-41, as derived from the available results in NUREG/CR-6728.

2.5.2.7.1.2 Estimate of V/H from Lee (2001)

As a second estimate of the required V/H ratio, the results of the study for the MOX Fuel Fabrication Facility [MFFF] at the Savannah River Site are considered (Lee 2001). The methodology used in that study followed the same approach as presented in NUREG/CR-6728 and EPRI TR-102293, and used in the section above, with the primary exception that the function $V/H_{\text{CEUS,Soil,Model}}$ of Equation 2.5.2-6 is developed using a site-specific model of the soil

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Southern Nuclear Operating Company
Project Number: 00737
Vogtle Electric Generating Plant Early Site Permit Application
Site Safety Analysis Report Section 2.5.2 Supplement 3

Ladies and Gentlemen:

By letter AR-06-1579, dated August 14, 2006, Southern Nuclear Operating Company (SNC) submitted an application to the U.S. Nuclear Regulatory Commission (NRC) requesting an Early Site Permit (ESP) for two additional reactors at the Vogtle Electric Generating Plant (VEGP) site near Waynesboro, Georgia. The application was submitted in accordance with Part 52, Subpart A of Title 10 of the Code of Federal Regulations. Based on subsequent discussions with the NRC regarding ESP Application Site Safety Analysis Report (SSAR) Section 2.5.2, *Vibratory Ground Motion*, SNC is revising its methodology that was used to generate the seismic spectra. Thus, the enclosure to this letter contains a new SSAR Section 2.5.2 designated Supplement 3. This new section will replace the original Revision "0" version and the Supplement 2 portion of Section 2.5.2 previously provided by SNC, and will be incorporated into the next full revision of the application. The new SSAR Section 2.5.2 is identified as Revision "0-S3."

This material does not contain restricted data or other defense information that requires separation from the unclassified information in accordance with 10 CFR 50.33(j) pursuant to 10 CFR 52.17(a)(1).

If you have any questions regarding this letter, please contact Mr. J. T. Davis at (205) 992-7692.

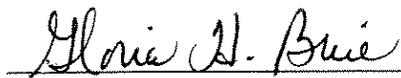
Respectfully submitted,

SOUTHERN NUCLEAR OPERATING COMPANY



Joseph A. (Buzz) Miller

Sworn to and subscribed before me this 13 day of September, 2006


Gloria H. Bui
Notary Public

JAM/BJS/dmw

Enclosure: Vogtle Early Site Permit Application Site Safety Analysis Report Section 2.5.2
Supplement 3

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Southern Nuclear Operating Company

AR-06-2036

Enclosure

Vogtle Early Site Permit Application

Site Safety Analysis Report

Section 2.5.2

Supplement 3