`UNITED STATES
NUCLEAR REGULATORY COMMISSION
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September 13, 2016

Mr. Randall K. Edington
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P.O. Box 52034, MS 7602
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SUBJECT: PALO VERDE NUCLEAR GENERATING STATION, UNITS 1, 2, AND 3 - STAFF ASSESSMENT OF INFORMATION PROVIDED UNDER TITLE 10 OF THE *CODE OF FEDERAL REGULATIONS* PART 50, SECTION 50.54(f), SEISMIC HAZARD REEVALUATIONS FOR RECOMMENDATION 2.1 OF THE NEAR-TERM TASK FORCE REVIEW OF INSIGHTS FROM THE FUKUSHIMA DAI-ICHI ACCIDENT AND STAFF CLOSURE OF ACTIVITES ASSOCIATED WITH RECOMMENDATION 2.1, "SEISMIC" (CAC NOS. MF5277, MF5278 AND MF5279)

Dear Mr. Edington:

On March 12, 2012, the U.S. Nuclear Regulatory Commission (NRC) issued a request for information under Title 10 of the *Code of Federal Regulations*, Part 50, Section 50.54(f) (hereafter referred to as the 50.54(f) letter) (Agencywide Documents Access and Management System (ADAMS) Accession No. ML12053A340). The purpose of that request was to collect information to facilitate NRC's determination if there is a need to update the design basis and systems, structures, and components important to safety to protect against the updated hazards at operating reactor sites.

By letter dated March 10, 2015, Arizona Public Service Company (the licensee), responded to this request for Palo Verde Nuclear Generating Station, Units 1, 2 and 3 (PVNGS).

The NRC staff has reviewed the information provided related to the reevaluated seismic hazard for PVNGS and, as documented in the enclosed staff assessment, determined that the licensee provided sufficient information in response to Enclosure 1, Items (1) - (9) of the 50.54(f) letter. The NRC staff concludes that the licensee responded appropriately and has completed its response to Enclosure 1, of the 50.54(f) letter. Furthermore, the NRC staff review concluded that the reevaluated seismic hazard is bounded by the plant's design-basis safe shutdown earthquake at most frequencies above 1 Hertz (Hz). Minor exceedances were noted at approximately 1.2 Hz and at greater than 35 Hz. However, as stated in an NRC letter dated October 27, 2015, (ADAMS Accession No. ML15194A015), these exceedances are considered "de minimis" (too minor to merit consideration).

As such, the NRC staff concludes that no further responses or regulatory actions associated with Phase 2 of Near-Term Task Force (NTTF) Recommendation 2.1 "Seismic" are needed for PVNGS. This closes out the NRC's efforts associated with Phase 1 and 2 of NTTF Recommendation 2.1 "Seismic" (CAC Nos. MF5277, MF5278 AND MF5279) for PVNGS.

If you have any questions, please contact me at (301) 415-1617 or at Frankie.Vega@nrc.gov.

Sincerely,

Frankie Vega, Project Manager
Hazards Management Branch
Japan Lessons-Learned Division
Office of Nuclear Reactor Regulation

Docket Nos. 50-528, 50-529, and 50-530

Enclosure:
Staff Assessment of Seismic
Hazard Evaluation and Screening Report for PVNGS

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STAFF ASSESSMENT BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO SEISMIC HAZARD AND SCREENING REPORT

PALO VERDE NUCLEAR GENERATING STATION, UNITS 1, 2, AND 3

DOCKET NOS. 50-528, 50-529, AND 50-530

1.0 INTRODUCTION

By letter dated March 12, 2012 (NRC, 2012a), the U.S. Nuclear Regulatory Commission (NRC or Commission) issued a request for information to all power reactor licensees and holders of construction permits in active or deferred status, pursuant to Title 10 of the *Code of Federal Regulations* (10 CFR), Section 50.54(f) "Conditions of license" (hereafter referred to as the "50.54(f) letter"). The request and other orders were issued in connection with implementing lessons-learned and taking regulatory action as a result of the 2011 accident at the Fukushima Dai-ichi nuclear power plant as documented in the "Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident" (NRC, 2011a). In particular, the NRC Near-Term Task Force (NTTF) Recommendation 2.1, and subsequent staff requirements memoranda (SRM) associated with Commission Papers SECY 11-0124 (NRC, 2011b) and SECY-11-0137 (NRC, 2011c), instructed the NRC staff to issue requests for information to licensees pursuant to 10 CFR 50.54(f).

Enclosure 1 to the 50.54(f) letter requests that applicable addressees perform a reevaluation of the seismic hazards at their sites using present-day NRC requirements and guidance to develop a ground motion response spectrum (GMRS).

The requested information section of Enclosure 1 requests that each applicable addressee provide the following information:

(1) Site-specific hazard curves (common fractiles and mean) over a range of spectral frequencies and annual exceedance frequencies,

(2) Site-specific, performance-based GMRS developed from the new site-specific seismic hazard curves at the control point elevation,

(3) Safe Shutdown Earthquake (SSE) ground motion values including specification of the control point elevation,

(4) Comparison of the GMRS and SSE. A high-frequency evaluation (if necessary),

(5) Additional information such as insights from NTTF Recommendation 2.3 walkdown and estimates of plant seismic capacity developed from previous risk assessments to inform NRC screening and prioritization,

(6) Interim evaluation and actions taken or planned to address the higher seismic hazard relative to the design basis, as appropriate, prior to completion of the risk evaluation (if necessary),

(7) Selected risk evaluation approach (if necessary),

(8) Seismic risk evaluation (if necessary), and

(9) Spent fuel pool (SFP) evaluation (if necessary).

Present-day NRC requirements and guidance with respect to characterizing seismic hazards use a probabilistic approach in order to develop a risk-informed performance-based GMRS for the site. Regulatory Guide (RG) 1.208, "A Performance-based Approach to Define the Site-Specific Earthquake Ground Motion" (NRC, 2007), describes an acceptable approach. As delineated in the 50.54(f) letter, if the re-evaluated seismic hazard, as characterized by the GMRS, is not bounded by the current plant design basis SSE, further seismic risk evaluation of the plant is merited.

By letter dated November 27, 2012 (Keithline, 2012), the Nuclear Energy Institute (NEI) submitted Electric Power Research Institute (EPRI) report "Seismic Evaluation Guidance: Screening, Prioritization, and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic" (EPRI, 2012), hereafter referred to as the SPID. The SPID provides guidance to support licensees when responding to the 50.54(f) letter in a manner that will address the Requested Information Items in Enclosure 1 of the 50.54(f) letter. By letter dated February 15, 2013 (NRC, 2013a), the NRC staff endorsed the SPID.

The required response section of Enclosure 1 to the 50.54(f) letter specifies that western U.S. (WUS) licensees provide their Seismic Hazard and Screening Report (SHSR) within 3 years after issuance of the 50.54(f) letter. The WUS licensees were granted an additional year to submit the SHSRs because their sites could not rely on the updated EPRI seismic ground motion models (GMMs) (EPRI, 2013) and seismic source characterization (SSC) models for the Central and Eastern U.S. (CEUS) that the CEUS licensees were able to rely upon (NRC, 2012b). As specified in Enclosure 1 to the 50.54 (f) letter, the WUS licensees used the Senior Seismic Hazards Advisory Committee (SSHAC) Level 3 process to develop the ground motion characterization (GMC) and SSC necessary for the more complex geology at WUS sites.

Industry also proposed that licensees perform an expedited assessment, referred to as the Augmented Approach, for addressing the requested interim evaluation (Item 6 above), which would use a simplified assessment to demonstrate that certain key pieces of plant equipment for core cooling and containment functions, given a loss of all alternating current (ac) power, would be able to withstand a seismic hazard up to two times the design-basis. By letter dated April 9, 2013, letter (Pietrangelo, 2013) the Nuclear Energy Institute (NEI) provided a revision to the 50.54 (f) letter schedule for plants needing to perform (1) the Augmented Approach by implementing the Expedited Seismic Evaluation Process and (2) a seismic risk evaluation. By letter dated May 7, 2013 (NRC, 2013b), the NRC determined that the modified schedule was acceptable.

2.0 REGULATORY BACKGROUND

The structures, systems, and components important to safety in operating nuclear power plants are designed either in accordance with, or meet the intent of Appendix A to 10 CFR Part 50, General Design Criteria (GDC) 2: "Design Bases for Protection Against Natural Phenomena," and Appendix A to 10 CFR Part 100, "Reactor Site Criteria." The GDC 2 states that structures, systems, and components important to safety at nuclear power plants shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions.

For initial licensing, each licensee was required to develop and maintain design bases that, as defined by 10 CFR 50.2, identify the specific functions that structures, systems, and components of a facility must perform, and the specific values or ranges of values chosen for controlling parameters as reference bounds for the design. The design bases for the systems, and components reflect appropriate consideration of the most severe natural phenomena that had been historically reported for the site and surrounding area, with sufficient margin to account for the limited accuracy, quantity, and period of time in which the historical data have been accumulated.

The seismic design bases for currently operating nuclear power plants were either developed in accordance with, or meet the intent of, GDC 2 and 10 CFR Part 100, Appendix A. Although the regulatory requirements in Appendix A to 10 CFR Part 100 are fundamentally deterministic, NRC regulations in 10 CFR Part 52 for determining the seismic design-basis ground motions for new reactor applications after January 10, 1997, requires that uncertainties be addressed through an appropriate analysis such as a probabilistic seismic hazard analysis (PSHA), as described in 10 CFR 100.23.

Section 50.54(f) of 10 CFR states that a licensee shall at any time before expiration of its license, upon request of the Commission, submit written statements, signed under oath or affirmation, to enable the Commission to determine whether or not the license should be modified, suspended, or revoked. On March 12, 2012, the NRC staff issued requests for licensees to reevaluate the seismic hazards at their sites using present-day NRC requirements and guidance, and identify actions planned to address plant-specific vulnerabilities associated with the updated seismic hazards.

2.1 Screening Evaluation Results

By letter dated March 10, 2015 (Cadogan, 2015a), Arizona Public Service Company (APS, the licensee) provided its SHSR for Palo Verde Nuclear Generating Station (PVNGS), Units 1, 2, and 3. The licensee's SHSR concluded that the site GMRS did not exceed the seismic design-basis for the PVNGS site within the frequency range of 1 to 10 Hertz (Hz). Therefore, the licensee would not conduct a seismic risk evaluation or a spent fuel pool (SFP) evaluation. Further, the licensee concluded that because the GMRS did not exceed the seismic design-basis above 10 Hz, a high frequency confirmation was not required. On April 10, 2015, the licensee submitted supplemental information to clarify the PVNGS seismic design and licensing basis, including the plant's SSE (Cadogan, 2015b).

On May 13, 2015 (NRC, 2015a), the NRC staff issued a letter providing the outcome of its screening and prioritization evaluation for WUS. The staff determined that additional time and interactions were required to better understand seismic hazards for the PVNGS. As such, the staff determined that the PVNGS "conditionally screened-in" for the purposes of prioritizing and conducting additional seismic risk evaluations.

On June 24, 2015, the NRC staff requested additional information and clarification on certain elements of the SHSR submittal (NRC, 2015b). The licensee provided its response on August 6, 2015 (Lacal, 2015). On October 27, 2015, the NRC staff had developed and reviewed sufficient information to determine that the PVNGS did not need to complete additional seismic risk evaluations (NRC, 2015c). In addition, the staff also confirmed that SFP and HF evaluations are not merited for PVNGS.

3.0 TECHNICAL EVALUATION

The NRC staff evaluated the licensee's submittal to determine whether the information provided by PVNGS in its submittal and subsequent replies to requests for additional information (RAI) responded appropriately to the requested information in Enclosure 1 of the 50.54(f) letter with respect to characterizing the reevaluated seismic hazard. In addition to evaluating the technical information, the NRC staff also determined if the process used to develop the re-evaluated seismic hazard was consistent with applicable guidance.

3.0.1 Summary of Regional Tectonic Setting

The PVNGS site is located in western Arizona, within the Southern Basin and Range (SBR) physiographic province. With respect to seismic hazards, the SBR is characterized by low rates of seismicity and low- to moderate-magnitude historical earthquakes. The diffuse patterns of sparse earthquakes do not align with known faults, and do not form alignments that would suggest the presence of large, deeper faults. The SBR is bounded by other physiographic or tectonic provinces that are characterized by higher rates of historical earthquakes, some of which are significantly larger than recorded in the SBR. Because of these spatial and temporal patterns of past recorded earthquakes and their potential impact on the hazard, delineating the boundaries of the SBR and adjacent tectonic provinces is an important part of the seismic hazards analysis.

There are few faults exposed in the SBR that are younger than about 2.6 million years (Myr) old (i.e., commonly called "Quaternary age"). Only a few geologic slip-rates are published for faults in the SBR province. These rates indicate that SBR normal faults are characterized by very slow slip-rates and long recurrence intervals (Pearthree et al., 1983). The SBR faults typically show normal displacements, but some faults with reverse and strike-slip fault displacements also occur in the SBR. In contrast, the adjacent tectonic provinces contain more abundant evidence of faulting during the last 2.6 Myr, and typically have faults that show significantly higher slip-rates, shorter recurrence intervals, and larger magnitude historic earthquakes than in the SBR.

Large strike-slip faults that are part of the Pacific-North America plate boundary are located approximately 240–300 kilometer (km) west of the PVNGS. Compared to SBR faults, these faults (such as the San Andreas Fault) have high slip-rates with repeated moderate- and large-magnitude earthquakes during the last 10,000 yr. The closest large strike-slip fault to PVNGS is the San Andreas Fault, which is approximately 240 km west of the PVNGS.

3.0.2 Summary of Local Geology

The PVNGS is located in a relatively flat intermountain valley named the Tonopah Desert Valley, which is cut by surface drainages that flow southward towards the Gila River. During the last several million years, surrounding drainages transported clastic sediments (i.e., clay, sand, and gravel) into the Tonopah Desert Valley to form an alluvial deposit that is about 130 m thick beneath the PVNGS site. This alluvial section rests above a thicker section (about 235 m thick) of older volcanic rocks and interbedded sediments, which formed about 15–20 Myr ago. Crystalline basement (i.e., pre-Cambrian granitic and metamorphic rocks) is located about 365 m beneath the PVNGS site (APS, 2013).

The nearest fault to the PVNGS site that shows evidence of movement in the last 2.6 Myr is the Sand Tank fault, which is located about 60 km south-southwest of the site. Although some other faults are mapped or buried within 60 km of the PVNGS site, there is no evidence of Quaternary activity on these faults. Thus, they are not considered in the seismic hazard reevaluation. Additional details of the site geological characteristics are provided in Cadogan (2015a) and the PVNGS FSAR (APS, 2013).

3.0.3 Senior Seismic Hazards Analysis Committee Approach to Developing a PSHA

Consistent with current NRC guidance and the 50.54(f) letter, the licensee used the SSHAC process to develop the SSC and GMC models for PVNGS. The SSHAC process was developed (Budnitz, 1997) as a formal approach that uses expert judgment to evaluate uncertainties in a PSHA for nuclear power plants. The process allows for the consideration of the complete set of seismological, geological, and geophysical data, models, and methods that are relevant to the seismic hazard analysis, which exist within the larger technical community. By following the evaluation process as described in the SSHAC guidelines (NRC, 2012c), the resulting PSHA represents the center, body, and range of technically defensible interpretations (i.e., considered the range of diverse technical interpretations from the larger technical community) (NRC, 2012c).

The development of the final site-specific hazard curves and associated seismic engineering inputs (e.g., GMRS or design spectra) are derived from three component studies, the SSC, GMC, and site response. The SSC and GMC together make up the PSHA. Components of the SSC and GMC are used to develop the inputs that populate the weighted branches of the PSHA logic tree (e.g., NRC, 2012c). These weighted branches are designed to account for epistemic uncertainty (i.e., uncertainty attributable to incomplete knowledge about a phenomenon that affects our ability to model it). A fundamental aspect of the SSHAC methodology is the distinct and separate treatment of epistemic uncertainty and aleatory uncertainty (i.e., uncertainty inherent in a random phenomenon). The outputs from the PSHA are a suite of probabilistic hazard curves (i.e., peak ground acceleration and spectral ground accelerations) for a reference rock or soil condition. Sections 3.1–3.3 of this staff assessment evaluate the SSC and GMC. Site response, which is not developed using the SSHAC process, is evaluated in Section 3.4 of this staff assessment.

As requested in the 50.54(f) letter (2012a), the licensee conducted Level 3 SSHAC studies for the SSC and GMC using the guidance in NUREG/CR-6372 (Budnitz, 1997), and NUREG–2117 (NRC, 2012c). The licensee served as the project sponsor for the SSHACs, and identified a project technical integrator who was the technical lead for the SSC or GMC. Technical integration teams (TI Teams) assisted the project technical integrator by developing and documenting the SSC or GMC models. The TI Team members served as both evaluator and integrator experts during the SSHAC process. An important part of the Level 3 SSHAC process is a participatory peer review panel (PPRP), which provides feedback to the TI Teams during the SSHAC process. The PPRP attended workshops and working meetings for each SSHAC, reviewed work products, and provided input to the TI Teams throughout SSC and GMC model development.

The SSHAC studies for both the SSC and GMC followed the same general process. Each TI Team developed a project plan and began development of a project database. They organized a series of workshops to discuss applicable data and models. Initial workshop(s) focused on the compilation and development of data needed to support the models, which were identified by resource experts. Subsequent workshop(s) focused on development of models and consideration of alternative models, which were supported by proponent experts. Observers, including NRC staff, also attended the workshops, along with the PPRP members. The TI Team then developed preliminary models, and performed initial hazard calculations and sensitivity analyses. These preliminary insights were discussed at an additional workshop, and the TI Team adjusted the models based on feedback from this workshop and additional discussions with the PPRP. The TI Team conducted the final hazard calculations and sensitivity analyses, and documented the results of the SSHAC study in a final project report. The PPRP reviewed the draft and final project reports, and documented the results of their review in a final letter to the TI Team, which is included in the SHSR (Cadogan, 2015a).

Additional details on the licensee's implementation of the SSHAC process are discussed and evaluated in the following sections, in the context of technical topics for SSC and GMC model development. In each topical area, the NRC staff's review identifies the most significant technical issues, and discusses how the NRC staff evaluated these issues during the review.

3.1 Seismic Source Characterization

The SSC for the PVNGS site represents the first stage of a PSHA. The specific goals of the SSC are to develop a catalog of historical seismicity surrounding the site, to define and characterize areal source zones that encompass and surround the site, and to identify and characterize geologic faults that have the potential to generate earthquakes that affect the site. To accomplish these goals, the licensee conducted a Level 3 SSHAC study that focused on developing an SSC for use in the PSHA (APS, 2015).

3.1.1 SSHAC Process for SSC

To develop the SSC for the PVNGS site, the TI Team compiled: existing information from the plant's licensing documents and technical information published in industry reports, other governmental agency reports (including U.S. Geological Survey (USGS) reports), and peer-reviewed literature. This compilation helped focus SSHAC Workshop 1 on identifying data needs, which considered a range of presentations from resource experts on April 9–10, 2013. As a result of SSHAC Workshop 1, the TI Team identified a number of additional data resources for developing the seismicity catalog and appropriate data processing techniques to integrate the seismicity data into a common framework. Based on discussions during the workshop, both the TI Team and the PPRP recognized the need to conduct additional geologic mapping investigations to better evaluate the potential for previously unidentified Quaternary-aged faults in the vicinity of the PVNGS site.

In preparation for Workshops 1 and 2, the TI Team used a previously developed SSHAC Level 2 PSHA (LCI, 2012) to perform initial hazard sensitivity analyses, which helped identify potentially significant issues for SSC model development. Both the TI Team and the PPRP acknowledged that although the previously developed PSHA (LCI, 2012) helped inform the development of the SSC, it was not used to anchor or restrict the development of new models in the SSC.

The SSHAC Workshop 2 (held September 24–25, 2013), focused on exploring alternative models and associated data that are most significant to seismic hazards at the PVNGS site. The TI Team focused much of its discussion on how to represent zones of seismicity at and around the site and on the range of approaches available to extrapolate patterns of historical seismicity to longer periods of time. The TI Team elicited input from multiple experts on available data, models, and methods, including alternative interpretations. Based on discussions during Workshop 2, both the TI Team and the PPRP recognized the need to consider how long-term versus short-term regional changes in crustal extension rates might affect interpretations of earthquake recurrence rates.

At SSHAC Workshop 3 (held April 23–24, 2014), the TI Team presented the initial SSC model and discussed its preliminary hazard sensitivity analyses. Much of the interaction between the PPRP and TI Team focused on the basis for developing SSC logic trees and the rationale for the associated weighting schemes, including consideration of alternative models and data uncertainties. The PPRP also used the hazard sensitivity analyses to focus attention on further refining data and models that had the most potential significance to the PSHA.

STAFF EVALUATION

Based on observations made during the SSHAC workshops and review of the associated documentation, the staff determines that the SSHAC workshops were conducted in a manner that is consistent with applicable NRC guidance (e.g., NRC, 2012c). The approach used to develop the SSC model is also consistent with the approach recommended in applicable NRC guidance, and no significant departures from that guidance were noted by staff. Issues of potential cognitive bias were discussed with the TI Team during each workshop, and sensitivity to this issue was addressed with the PPRP. The SSHAC documentation (APS, 2015; Cadogan, 2015a) provides an acceptably complete record of the approach used to develop the SSC model, and for the staff to conduct an independent review of the SSHAC and SSC model.

Based on observations made during the SSHAC workshops and review of the SSHAC documentation, the NRC staff concludes that a reasonable range of resource and proponent experts were engaged in the SSHAC workshops, and that a broad range of appropriate data and alternative models were considered. Based on observations from the workshops and staff's knowledge of the geology and seismology of the PVNGS site, the staff determines that the TI Team took appropriate steps to ensure that the resulting SSC model captures the center, body, and range of technically defensible information.

The success of a Level 3 SSHAC depends strongly on the effective review and engagement of the PPRP with the TI Team. To evaluate the effectiveness of the PPRP for SSC model development, the staff reviewed correspondences between the PPRP and TI Team, including comment and response logs and observed workshop interactions. The staff also observed open dialog between the TI Team and the PPRP at workshop meetings, which included several significant comments or suggestions from the PPRP that required appreciable effort by the TI Team to resolve. These SSC technical issues are discussed in Sections 3.1.3 and 3.1.4 of this staff assessment. Based on these observations, the staff concludes that the PPRP was actively engaged throughout the SSHAC process, and that the TI Team was responsive to issues or concerns raised by the PPRP (e.g., Cadogan, 2015a, Appendix C). The staff also concludes that the PPRP was effective and engaged throughout the SSC SSHAC, and that there were no unresolved PPRP issues at the end of the project.

In summary, based on the staff's review of SSHAC documentation, observations made at SSHAC workshops, and knowledge of the geological and seismological characteristics of the PVNGS region, the staff concludes that the licensee acceptably implemented a SSHAC Level 3 process to develop the SSC model.

3.1.2 Seismicity Catalog

The TI Team developed a catalog of historical seismicity for the PVNGS study, which used information from available published and unpublished earthquake catalogs, including from the Arizona Geological Survey, the Southern California Earthquake Data Center, the Center for Scientific Research and Higher Education at Ensenada, the University of California – Los Angeles, the USGS, and the Working Group on California Earthquake Probabilities. The TI Team considered historical seismicity out to a distance of 400 km from the PVNGS site, including large earthquakes located in Southern California and Northern Mexico.

The TI Team compiled an earthquake catalog for the PVNGS study and removed duplicate events. The TI Team then used a set of conversion equations to correct the historical earthquakes to the moment magnitude scale (**M**) for each earthquake in the resulting merged catalog, and then performed a declustering analysis to identify independent events and remove foreshocks or aftershocks. The initial composite catalog included 1,941 events spanning the years 1852 to 2012 with a moment magnitude **M**2.7 or greater. After declustering, the final catalog contained 1,048 events. Next, the TI Team evaluated the spatial and temporal completeness of the declustered earthquake catalog using standard methods. This completeness analysis informed the licensee's determination of magnitude recurrence rates for each of the seismic source zones.

STAFF EVALUATION

Based on observations at SSHAC workshop meetings and general knowledge of seismology in the PVNGS region, the NRC staff concludes that the TI Team adequately developed an earthquake catalog. The staff notes that the earthquake catalog extends to 400 km from the PVNGS site in order to include distant California and Mexico sources in the analysis. The NRC staff determined that although this area is larger than generally considered in many PSHAs (e.g., NRC, 2007), the inclusion of distant, large-magnitude earthquake sources is conservative. Based on review of the SSHAC documentation, the staff also concludes that the TI Team used acceptable methods for calculating uniform earthquake magnitudes to develop the composite catalog.

To confirm that the earthquake declustering analysis was reasonable, the NRC staff obtained the PVNGS composite earthquake catalog as it existed prior to the declustering analysis (NRC, 2015b). The NRC staff performed a confirmatory declustering analysis on the composite catalog using a declustering algorithm (Gardner and Knopoff (1974)), which also was one of the methods used by the TI Team. Figure 3.1.2-1 of this staff assessment shows the locations of the independent earthquakes within a radius of 400 km around the PVNGS site and Figure 3.1.2-2 shows the locations of the dependent earthquakes (i.e., aftershocks, foreshocks, and swarms). The two figures also show that within the boundaries of the SBR source zone (i.e., dotted line) that encompass the site, there are only a few dependent earthquakes. Using these analyses, the staff determined there are 911 dependent earthquakes out of 1,941 total earthquakes in the catalog. This result is reasonably similar to the 893 dependent earthquakes identified by the TI Team. Based on this confirmatory analysis the staff concludes that the declustering analysis conducted by the TI Team is reasonable.

In summary, the staff concludes that the seismicity catalog was developed consistent with RG 1.208 (NRC, 2007) and is therefore acceptable for use in the SSC model and resulting PSHA.

3.1.3 Areal Source Zones

Similar to the approach used for representing potential earthquake sources in the Central and Eastern U.S. (e.g., NRC, 2012b), the SSC model for PVNGS calculates the effect of potential earthquakes from two distinct types of sources: Quaternary-aged faults and areal source zones. Quaternary faults are discussed in Section 3.1.4 of this staff assessment. Areal source zones are used to account for a broad spatial distribution of earthquakes that cannot be associated with known faults. To evaluate the seismic hazards from areal source zones, the TI Team first considered how geologic and seismologic characteristics varied in the region extending approximately 400 km from the PVNGS site. The TI Team used multiple characteristics to define the areal source zones based on observed changes in, for example, patterns of historical seismicity, the orientation and age of geologic structures, and thickness of the Earth's crust. Based on its interpretation of these characteristics, the TI Team developed two alternative conceptual models for areal source zones: the Two-Zone Model and the Seismotectonic Model.

The Two-Zone Model separates the region into a western zone that is dominated by shear-tectonic features from interactions of the Pacific-North American plates and an eastern zone that is dominated by extensional tectonic features. The Seismotectonic Model further subdivides the Two-Zone Model into six smaller subzones, which loosely correspond to major physiographic provinces in the Southwestern U.S. During its review, the PPRP expressed concern that the Two-Zone Model may be unrealistic based on the level of geologic data that are available. The TI Team responded that the Two-Zone Model distinguishes the highly active plate boundary of California and Baja California from the less active areas to the east, and that this alternative model is included to capture the range of technically defensible interpretations. In addition, the TI Team gave the preferred Seismotectonic Model a weight of 0.8 in the PSHA, whereas the Two-Zone Model was given only a weight of 0.2. The PPRP agreed with the rationale for the weighting of the two models.

For each source zone, the TI Team used information from workshop presentations and the published literature to develop the characteristics of possible future earthquakes that represented the geological and seismological features of the source zone. Because earthquake characteristics (i.e., magnitude, rupture geometry, and recurrence rates) are based on the geologic structures (e.g., subsurface faults and thickness of seismogenic crust), the TI Team first assigned each zone a range of potential fault orientations, dips, and rupture mechanisms. The distribution of rupture mechanisms and orientations assigned for each areal source are based on the characteristics of mapped Quaternary faults and earthquake focal mechanisms. The TI Team determined distributions of seismogenic thickness for each zone by analyzing depths of historical earthquakes. To develop these thickness distributions in zones that lacked significant earthquake data, the TI Team used general geophysical information and expert judgment. To develop distributions for the maximum earthquake magnitude (M_{max}) in each zone, the TI Team considered the range of historical seismicity, crustal thickness, and the prevalence of Quaternary-aged faults in the source zone. For each areal source zone, the TI Team determined that the M_{max} distribution for all areal sources ranges from **M**6.8 to **M**7.9, with the exception of the Colorado Plateau subzone in the Seismotectonic Model, which used a range of **M**6.5 to **M**7.9. These M_{max} distributions encompass the largest known earthquakes in the source zones.

An important part of the source-zone models is how to represent patterns of earthquake recurrence in each zone or subzone. The TI Team considered alternative approaches for this representation, including a model where earthquake recurrence is the same at all points in each zone (spatially uniform occurrence of earthquakes), and models where earthquakes occur at different rates within each zone (spatially variable occurrence of earthquakes). The TI Team ultimately chose to incorporate the methodology adopted in NUREG–2115 (NRC, 2012b), which uses a spatially variable approach based on patterns of historical seismicity. The PPRP reviewed the bases for using this spatially variable approach, and agreed with the TI Team that this approach is reasonable. The TI Team developed three alternative models to represent spatially variable earthquake recurrence, each of which produced eight alternative earthquake recurrence maps. The resulting 24 recurrence maps were used to capture the uncertainty in recurrence rate.

STAFF EVALUATION

Based on observations made during the SSHAC workshops and review of the associated documentation, the staff concludes that an appropriate range of resource and proponent experts were engaged in the SSC workshops, and that a broad range of data and alternative models were considered in developing and characterizing the areal source zones. The staff notes that the areal source zones extend to 400 km from the PVNGS site in order to include distant California and Mexico sources in the analysis. The NRC staff determined that although this area is larger than generally considered in many PSHAs (e.g., NRC, 2007), the inclusion of distant, large-magnitude earthquake sources is conservative. The staff used these observations and their knowledge of the geology and seismology of the PVNGS site region to conclude that the resulting areal source zone models capture the center, body, and range of technically defensible information.

The NRC staff reviewed the information used by the TI Team to develop the source-zone models, and determines that use of the Two-Zone and Seismotectonic Models capture the uncertainty associated with a reasonable interpretation of the available alternative models. Based on review of the SSHAC documentation, the staff concludes that the TI Team provided a clear rationale for weighting the source-zone models in the PSHA. The staff also concludes that incorporation of both areal source-zone models into the SSC is a reasonable representation of the uncertainty associated with interpreting tectonic features in the Southwestern U.S.

The NRC staff evaluated the rationale for using the approach in NUREG–2115 (NRC, 2012b) to represent variations in earthquake recurrence within the areal source zones. The staff notes that the PPRP approved the use of this approach for the SSC model. A critical assumption for this approach is that the past pattern of low-to-moderate levels of historical seismicity provides a reasonable basis to predict the rate and magnitude distribution of future earthquakes (NRC, 2012b). These patterns are driven by large-scale changes in plate tectonics that change slowly over millions of years, which is a period of stability that exceeds the time period being considered in developing the PSHA. Based on the low-to-moderate seismicity in the source zones near the PVNGS site, the NRC staff concludes that application of the NUREG–2115 (NRC, 2012b) approach for modeling earthquake recurrence is acceptable.

In summary, as a result of this review, the NRC staff concludes that the areal source zones were developed consistent with applicable guidance and represent the center, body, and range of the technically defensible information. Therefore, the staff concludes that the areal source-zone models are acceptable for use in the SSC model and the resulting PSHA.

3.1.4 Fault Sources

The SSC for PVNGS calculates the effects of potential earthquakes that occur from both areal source zones (reviewed in Section 3.1.3), and from Quaternary-aged faults. To evaluate the seismic hazards from Quaternary faults, the TI Team developed a database of mapped Quaternary faults within at least 400 km of the PVNGS site; several larger faults located more than 400 km from the site also were included. Data sources included faults used to develop the 2008 National Seismic Hazard Mapping Project (NSHMP), (NSHMP, Petersen, et al., 2008) and faults in the Uniform California Earthquake Rupture Forecast model (UCERF3), (UCERF3, Field et al., 2013), as well as published geologic maps for Arizona and Mexico (e.g., Pearthree et al., 1983).

Workshop 1 participants and the PPRP recognized that existing geologic map coverage was incomplete in the region around the PVNGS site, which led to a concern that not all potentially significant Quaternary faults were identified. To address this concern, the TI Team conducted additional mapping investigations to identify potential Quaternary-aged faults (Cadogan, 2015a). These investigations focused on three principal areas: (1) evaluation of geomorphic features and existing map information around the US-Mexico border region; (2) additional geologic mapping within 40 km of the PVNGS site, which included evaluation of a potential 5-km-long, Quaternary-aged fault from Gilbert (1991); and (3) investigations of the Quaternary Sand Tank fault, which is located about 60 km southwest of the PVNGS site.

In Northern Mexico, the TI Team identified six previously unmapped Quaternary-aged faults, which were added to the SSC fault database. For the area within 40 km of the PVNGS site, additional geologic mapping conducted by the TI Team did not identify any Quaternary-aged faults; the TI Team further determined that the unnamed fault identified by Gilbert (1991) did not show evidence of Quaternary activity (Cadogan, 2015a). Investigations of the Sand Tank Fault focused on interpreting the fault length along buried segments and evaluating the characteristics of past motion on the fault.

Based on the published and newly developed information, the TI Team catalogued 168 Quaternary-aged faults within approximately 400 km of the PVNGS site. Most of these faults are located more than 100 km from the site and are concentrated in three areas: the active plate-boundary faults in Southern California and Baja California; faults in Northern Arizona within the Colorado Plateau transition zone; and faults to the southeast of PVNGS in the Mexican Highlands.

To develop the SSC model, the TI Team characterized the Quaternary faults by mapped location, geometry, depth, slip direction, slip rate, magnitude, and magnitude-frequency distribution function (Cadogan, 2015a). Because Quaternary faults in the UCERF3 model had been investigated in detail, the TI Team used a representative set of these characteristics for these faults directly in the SSC model. As an alternative to the UCERF3 model, the TI Team also used a layered fault model approach in order to accommodate changes in slip along strike of a fault source. The majority of fault sources in the SSC model, however, had limited characterization information available. For these faults, the TI Team used available information to develop fault slip-rates, including comparison of geomorphic features to analogous faults with well-constrained slip rates (APS, 2015). The TI Team also developed characteristic magnitudes for these fault sources based on fault dimensions and a range of published magnitude-scaling relationships (APS, 2015).

As part of the fault characterization effort, the TI Team performed sensitivity analyses during the SSC model development to identify faults that made potentially significant contributions to seismic hazards at the PVNGS site. These analyses determined that 18 of the 168 Quaternary faults contribute approximately 99 percent of the total seismic hazard from all faults at 1 Hz and 10 Hz spectral frequencies. The TI Team used the sensitivity analyses to focus investigations on the detailed characterization of the 18 significant faults while using more simplified characterizations for the remaining low-significance faults. Only these 18 significant faults were used in the final PSHA for PVNGS.

To help determine earthquake recurrence rates for faults, several subject-matter experts presented information at Workshop 2 on direct measurements of crustal deformation (i.e., extension) in Arizona. These deformation studies use high-resolution Global Positioning System (GPS) instruments to record very small changes in regional benchmark locations over months to years.

Some of the GPS-based studies suggest that in the southern part of the SBR, recent crustal extension rates might be appreciably larger than indicated by long-term rates calculated from geologic data alone (e.g., adding the amount of extension shown by faults in a region).

In response to questions by the PPRP, the TI Team conducted additional investigations to evaluate the uncertainties in relating GPS-based measurements of crustal extension to fault-slip rates. The TI Team observed that the scarcity of Quaternary-aged faults in central and southern Arizona indicates that long-term crustal extension rates should be low. The TI Team determined that in northern Arizona, the rate of crustal extension calculated from geologic information is about 75 percent of the extension rate measured from GPS data. However, in central and southern Arizona, the geologic information only accounted for 5–10 percent of the extension rate measured from GPS data. The TI Team also determined that the high extension rates measured by GPS data in Arizona also appear inconsistent with the low rates of historical seismicity in this area and the scarcity of surface ruptures from the types of large earthquakes that would likely accompany high extension rates.

The TI Team concluded that fault-slip rates based on geologic data are a more technically defensible representation of crustal deformation processes than rates based on GPS data. To incorporate the uncertainty with this interpretation into the SSC model, the TI Team gave a weight of 0.8 to fault-slip rates based on geologic data, and a weight of 0.2 to rates based on GPS data.

STAFF EVALUATION

The NRC staff determined that in characterizing the fault sources, the TI Team took appropriate steps to ensure that the results of the SSC capture the center, body, and range of technically defensible information. Based on observations made during the SSHAC workshops and review of the associated documentation, the staff concludes that an appropriate range of resource and proponent experts were engaged in the SSC workshops. The staff also determined that the TI

Team considered alternative data and models in developing and characterizing the fault sources. The staff notes that faults located within at least 400 km from the PVNGS site are considered in the SSC model. The staff concludes that this distance is reasonable for including tectonic features >320 km from the PVNGS site that might contribute significantly to seismic hazard, as recommended in RG 1.208.

The NRC staff observed workshop discussions and PPRP interactions with the TI Team and concludes that the additional field investigations were appropriate to characterize potential Quaternary-aged faults in the PVNGS region. The staff reviewed the results of these additional investigations, including detailed geologic maps, and associated reports by the PPRP. Based on these reviews, the staff concludes that the additional field investigations were conducted acceptably and that potential Quaternary-aged faults have been reasonably identified and characterized in the PVNGS site vicinity. Based on review of the SSHAC documentation, observations at SSHAC workshops, and general knowledge of Arizona geology, the NRC staff determines that potentially significant fault sources have been included in the SSC model.

The NRC staff reviewed the TI Team's rationale for focusing detailed characterization on the 18 most significant faults, and determines that the basis for this rationale is reasonable. The staff also reviewed the SSHAC documentation and workshop presentations and concludes that the SSC model used available information to the extent practicable and correctly captures the center, body, and range of technically defensible information.

The staff reviewed the information in the SSHAC documentation on different interpretations in fault-slip rates based on geologic versus GPS information. The staff notes that some of the apparent differences occur because the TI Team did not fully account for fault sources in Arizona that are not included in the NSHMP (Petersen et al., 2014), but are included in the SSC model. Consideration of these additional fault sources likely would lower the apparent differences in crustal extension rates derived from geologic versus GPS-based data. The staff also determines that differences between geologic and GPS-based rates of crustal extension commonly are reported in other published studies, and that the broader technical community does not have a consensus on how to reconcile these differences. In addition, the NRC staff concurs with the TI Team's observation that these high extension rates suggested by the GPS data are not supported by observed seismicity and geologic features such as faults and folds. Consequently, the NRC staff concludes that the TI Team's approach for weighting the alternative interpretations of the slip-rate data is reasonable.

After the licensee submitted its SHSR to the NRC (Cadogan, 2015a), the licensee determined that some incorrect parameters were used to represent fault characteristics in the SSC model and resulting PSHA calculations. The licensee performed a sensitivity analysis for these errors and determined that using the correct values in the SSC model would decrease the resulting seismic hazard by less than 1 percent. The staff reviewed the licensee's sensitivity analysis and determines that the effect of these errors is small, and that the licensee's conclusion of a less than 1 percent decrease in the corrected seismic hazard is reasonable.

In summary, as a result of this review, the staff concludes that fault sources in the SSC model were developed consistent with applicable guidance and the resulting model captures the center, body, and range of the technically defensible information. The staff therefore concludes that these fault sources are acceptable for use in the SSC model and the resulting PSHA.

3.2 Ground Motion Characterization

The GMC for the PVNGS site consists of a set of ground motion prediction equations (GMPEs) for the median and the aleatory standard deviation (i.e., sigma) for use in conducting the PSHA for the site. Specifically, the models predict the median and standard deviation of five percent damped spectral accelerations and peak ground acceleration for a wide range of earthquake scenarios for WUS reference baserock site conditions. For the GMMs used in the PSHA for PVNGS, the licensee used the models developed by the Southwestern U.S. (SWUS) GMC Project (GeoPentech, 2015), which was conducted as an SSHAC Level 3 study. The SWUS study was designed to develop generic GMMs for several WUS plants that could be adapted for site-specific applications.

3.2.1 SSHAC Level 3 Approach

To develop the GMC for the PVNGS site, the SSHAC TI Team evaluated a suite of previously developed data and models that are relevant to the hazard for WUS sites. In particular, the TI Team evaluated the database and models developed by the NGA-West2 project (Bozorgnia et al., 2014), sponsored by the Pacific Earthquake Engineer Research (PEER) center. The NGA-West2 project developed an extensive ground motion database from shallow crustal earthquakes in tectonically active regions around the world along with an accompanying set of GMPEs. In addition to the NGA-West2 database, the TI Team also evaluated the ground motion database used in Europe (Akkar et al., 2014) and the PEER Arizona database (Kishida et al., 2014). From these databases, the TI Team developed a subset of ground motion data that emphasized strike-slip and normal faulting earthquakes, which are the predominant regional faulting mechanisms for the sources surrounding PVNGS. After developing a suitable database, the TI Team used this database to evaluate a group of recently-published GMPEs that were developed for active tectonic regions. From this group of GMPEs, the TI Team selected a set of input models to use as seed models to develop a set of final weighted GMPEs for the PSHA.

For the SSHAC Level 3 study to develop the SWUS GMC Project, the TI Team conducted three formal workshops and multiple working meetings over a 3-year time period from 2012 to 2014. During Workshop 1, held on March 19–21, 2013, resource experts discussed the data available to inform the development of the GMC models and the TI Team identified the issues that it presumed would have the highest impact on the hazard for the PVNGS site. During Workshop 2, held on October 22–24, 2013, several proponent experts presented their viewpoints regarding the GMPEs under consideration for the GMC. In addition, participants of Workshop 2 discussed the need for including alternative models and interpretations to model the scaling of ground motions from large-magnitude earthquakes (**M**7.0 to **M**8.5). During Workshop 3, held on March 10–12, 2014, the TI Team and PPRP discussed the preliminary set of GMPEs to be used for the PSHA for PVNGS. In addition, the TI Team described its approach for characterizing the potentially unique ground motion path effects for earthquakes from the distant California and Mexico regions.

After Workshop 3, the TI Team continued to refine the GMC models and interact with the PPRP. After reviewing the preliminary SSHAC report, the PPRP provided extensive comments to the TI Team and then reviewed the TI Team's responses. In summary, the PPRP concluded in its endorsement letter (GeoPentech, 2015):

> As summarized in the table above, the PPRP reviewed the TI Team's evaluations of data, models and methods on multiple occasions, and through various means, including written communications, in-person meetings, teleconferences, and review of the project report. The Panel was given adequate opportunity to question the TI Team concerning details of their analysis, and provided feedback verbally and in writing. The TI Team was responsive to the technical input from the Panel. The TI Team's responses included evaluating additional data sets suggested by the Panel, undertaking additional analyses to address specific Panel technical questions, and examining and assessing alternative technical approaches suggested by the Panel.
>
> The PPRP therefore concludes that it has been afforded an adequate basis for technical assessment of the TI Team's evaluations and model integration and finds that the project meets the technical expectations for a SSHAC Level 3 study.

STAFF EVALUATION

Based on observations at the workshops and its review of the workshop proceedings, the NRC staff concludes that the SSHAC workshops were conducted in a manner consistent with applicable NRC guidance. The staff observed at the workshops that the TI Team invited and engaged with resource and proponent experts that represented a wide variety of scientific viewpoints. Based on this information, the staff concludes that the TI Team was able to focus its data collection and analysis activities in order to develop a suitable set of GMPEs tailored specifically to the types of earthquakes that dominate the hazard for the PVNGS site.

To evaluate the effectiveness of the PPRP for the GMC model development, the staff examined the PPRP and TI Team correspondence, including the comment and response logs and the letters exchanged following each of the workshops. The staff also observed the open dialog between the TI Team and PPRP at each of the workshops, which included several significant comments from the PPRP that required appreciable effort from the TI Team to resolve. Based on its observations, the staff concludes that the PPRP actively participated in the workshops and provided an extensive and comprehensive review of the SWUS GMC models and report. In summary, the NRC staff concludes that the PPRP was effective and engaged throughout the GMC SSHAC, and that there were no unresolved PPRP issues at the end of the project.

Based on the staff's review of the SSHAC documentation, observations made at the SSHAC workshops, and knowledge of GMPEs used for active tectonic regions, the staff concludes that the SWUS GMC Project acceptably implemented the SSHAC Level 3 process.

3.2.2 Ground Motion Databases and Prediction Equations

To develop a set of applicable GMPEs for the PVNGS site, the TI Team evaluated ground motion databases developed from earthquake recordings in active tectonic regions as well as the GMPEs developed from these databases. Specifically, the TI Team focused on gathering and evaluating data applicable to the region surrounding the site, which is mainly characterized by a low rate of diffuse seismicity consisting of small to moderate normal and strike-slip earthquakes. The TI Team also evaluated data and GMPEs suitable to characterize the hazard from distant (beyond 200 km) and larger earthquakes (**M**7.0 to **M**8.5) located in Southern California and Mexico, which contribute to the low-frequency hazard at the PVNGS site.

The databases evaluated by the TI Team include the following:

- PEER NGA-West2 database (Ancheta et al., 2014)
- Reference Database of Seismic Ground Motion in Europe (RESOURCE) (Akkar et al., 2014)
- PEER Arizona database (Kishida et al., 2014)
- Taiwan database (Lin et al., 2011)

The TI Team extracted the ground motion records from the normal and strike-slip faulting earthquakes from the two largest databases (i.e., NGA-West2 and RESORCE) to evaluate the suitability of the candidate GMPEs for PVNGS. The TI Team used the smaller PEER Arizona dataset to constrain the travel-path effects from distant California and Mexico earthquakes recorded in central Arizona and also to estimate the local-site attenuation, referred to as kappa (i.e., a measure of energy dissipation in the top 1 to 2 km of the crust). The Taiwan database, consisting of ground motions from **M**4 to **M**6 earthquakes, was used by the TI Team to develop one of the key components of the aleatory variability for the GMMs.

In additional to gathering and evaluating ground motion databases, the TI Team also evaluated 19 recently developed and published GMPEs for shallow crustal earthquakes in active tectonic regions. The six criteria developed and used by the TI Team for its evaluation of the candidate GMPEs are:

- selection of the most recently published GMPEs over earlier versions,
- selection of models developed from shallow crustal earthquakes located in active tectonic regions,
- selection of models suitable for large magnitude and distance ranges,
- exclusion of models developed only for small specific regions,
- exclusion of models that have not been peer reviewed or vetted by the larger scientific community, and

- exclusion of models developed as research tools rather than for engineering applications.

Based on these criteria, the TI Team selected all five of the NGA-West2 GMPEs for use in characterizing the hazard from the distant California and Mexico sources and four of the NGA-West2 GMPEs along with two GMPEs developed from the RESORCE database (Akkar et al., 2014; Bindi et al., 2014) for the regional Arizona sources surrounding the site.

STAFF EVALUATION

Based on observations at the SSHAC workshops, review of the SSHAC report and knowledge of current GMPEs developed for active tectonic regions, the NRC staff determines that the TI Team developed an appropriate set of ground motion databases and gathered and evaluated a suitable range of candidate GMPEs. The staff observed that the TI Team described the available databases in detail during Workshop 1 and appropriately considered input from the PPRP in selecting the final databases and developing the criteria for evaluating the candidate GMPEs. The staff notes that the ground motion databases consist of several thousand earthquake records and cover a wide range of magnitudes and distances. The staff finds that the TI Team appropriately emphasized the normal and strike-slip faulting earthquakes from these databases in order to assess the candidate GMPEs and eventually develop a specific set of GMPEs for the PVNGS region. The staff also concludes that the TI Team appropriately used the local central Arizona ground motion records from California and Mexico earthquakes to develop a unique path term for the final GMPEs.

The NRC staff used its experience in developing and evaluating GMPEs to determine that the TI Team selected an appropriate set of initial candidate GMPEs and that the criteria used by the TI Team to select the final set of input GMPEs are appropriate. Specifically, the staff notes that the criteria used by the TI Team resulted in a set of input GMPEs that have been formally peer reviewed, developed specifically from shallow crustal earthquakes in active tectonic regions, and that are the latest versions of the developers published GMPEs.

In summary, the staff concludes that the TI Team developed a suitable ground motion database and selected an appropriate set of input GMPEs consistent with the fundamental goal of the SSHAC process to objectively evaluate and examine available data and a diverse range of candidate models.

3.2.3 Median Ground Motions

The GMPEs, developed by the TI Team for the hazard characterization of PVNGS, predict spectral accelerations, which are assumed to follow lognormal distributions, for generic WUS baserock conditions for several different spectral frequencies. Specifically, GMPEs predict median spectral accelerations in terms of magnitude, various source-to-site distance measures, rupture dimensions, depth to the top of rupture, and faulting type (i.e., strike-slip, normal, and reverse). The TI Team developed two sets of GMPEs, one specifically for the prediction of median spectral accelerations for the regional Arizona sources, and another set for the distant California and Mexico sources. The TI Team also accounted for potential hanging-wall effects (i.e., increases in ground motion at short distances for sites on the hanging wall side of the rupture) but decided not to incorporate directivity effects (i.e., increases in ground motion for sites located in the direction of rupture propagation) into its median predictions. The TI Team concluded, based on simplified sensitivity analyses, that directivity effects had a very small impact on the final hazard results for this site.

3.2.3.1 Median Ground Motions for Greater Arizona Sources

The objective of the TI Team for the SWUS GMC Project was to capture the center, body, and range of the continuum of ground motion space (i.e., the full range of ground motions estimated over a broad range of magnitudes and distances). Rather than merely attaching weights to existing discrete GMPEs, the TI Team developed a suite of GMPEs that was not limited to existing GMPEs and that fully spans and efficiently samples the range of ground motion space. The TI Team recognized that the characterization and quantification of uncertainties, in particular epistemic uncertainties, is a fundamentally important element of the GMC activity. Previous practice has often consisted of representing the epistemic uncertainty in GMC via weighted branches on a logic tree where the branches are discrete existing GMPEs. To develop this suite of GMPEs, the TI Team followed a multi-step process that included utilization of higher-dimensional visualization tools. The steps of this process are summarized below.

First, the TI Team compiled a selection of current, well-documented candidate GMPEs and defined a subset of the candidate models based on technical defensibility and applicability for use in the PVNGS region (as described in Section 3.2.2). These candidate models were used as "seed" models as the initial step in the process to develop a comprehensive suite of GMPEs for the Greater Arizona Sources. Based on an evaluation of the characteristics of the seed models, the TI Team identified a common functional form for the development of new GMPEs. They assessed prior PSHA results for the PVNGS site (LCI, 2012) to determine a hazard-informed range of magnitudes and distances to be used in the development of the final suite of GMPEs.

The TI Team exercised each of the seed GMPEs over the range of magnitude (**M**5 to **M**7.5) and distance (up to 200 km) values that are relevant to the hazard at the PVNGS site. The common form model was then fit to the spectral acceleration results from each of the six seed GMPEs, resulting in six common form model versions that represent the original seed models.

Based on the fitted values of each of the 11 coefficients in the common form models, the TI Team calculated the mean and variance for each of the coefficients, as well as the covariance among the coefficients. Using the common form model, the mean, and the covariance structure of the coefficients, the team developed a suite of 2,000 new candidate GMPEs in order to span the ground motion space.

This suite of 2,000 candidate GMPEs was then exercised over a specified set of magnitude and distance pairs. For each GMPE, the ground motion values over this set of magnitude and distance pairs was represented by a high-dimensional vector. The TI Team then utilized visualization tools principal component analysis and Sammon's mapping (Sammon, 1969) to project each of the high-dimensional ground motion vectors as a point on the two-dimensional Sammon's map.

Based on an analysis of the projected candidate GMPEs and scaled versions of the seed GMPEs the TI Team identified a range of plausible ground motion space on the Sammon's map, which the team represented as an ellipse. The TI Team subdivided the ellipse into 31 discrete cells and specified a single representative GMPE for each cell. Using several metrics based on consistency with data (i.e., the NGA-West2 PV data set) and the distribution characteristics of the common form models within each cell, the TI Team determined weights for each of the 31 GMPEs. The criteria the TI Team used resulted in a broad range of weighted GMPEs, with some receiving a weight of zero. As such, the result of the Sammon's map approach for the Arizona sources resulted in a suite of about 20 to 25 GMPEs for each of the spectral frequencies. Finally, the TI Team repeated this process for an alternative source-to-site distance parameter, which resulted in a total of about 40 to 50 GMPEs for each of the spectral frequencies.

3.2.3.2 Median Ground Motions for California and Mexico Sources

To develop the GMPEs for the California and Mexico regions (referred to as Regions 1, 2, and 3), the TI Team selected the five NGA-West2 GMPEs, and then added path-specific adjustment factors to take advantage of the available ground-motion data in Arizona from these distant sources. Even though fault sources in California and Mexico are farther than 200 km from the site, they are capable of generating large-magnitude earthquakes (i.e., **M**7 to **M**8.5) and, as such, contribute to the low-frequency hazard (i.e., below about 2 Hz) at PVNGS. Because these earthquakes affect the low-frequency hazard over a limited combination of distances and magnitudes, the TI Team decided that the Sammon's map procedure was not warranted and instead used a simpler approach, which is described below.

Before using the five NGA-West2 GMPEs for these sources, the TI Team evaluated whether the attenuation of ground motion from California to central Arizona is different from the attenuation within California. To evaluate the potential differences in attenuation, the TI Team compared the regional differences in Q (quality factor) in California and Arizona. Specifically, the TI Team computed the average Q for earthquakes recorded at stations in Southern and Central California as well as at stations in Arizona and found that over the relevant distance range (200 to 400 km), the average Q values for California (100 to 300) and Arizona (150 to 350) stations are similar. Because variations in Q over these distances are small, the TI Team concluded that NGA-West2 GMPEs are suitable to predict ground motions for the distant California and Mexico sources.

The TI Team also evaluated the potential differences in attenuation that could result from path effects. Specifically, the TI Team evaluated the differences in the median spectral accelerations from the distant earthquakes in each of the three Regions. A comparison of the median spectral accelerations from earthquakes in these three regions resulted in lower values (about 0.6 natural log units smaller) for Regions 2 and 3 (Baja California and Mexico) compared to Region 1 (Southern California). Based on this result, the TI Team added two alternative branches to the logic tree for the GMPEs for distant sources in California and Mexico. The first branch, which incorporates the path effect differences in median spectral acceleration values, is weighted 0.8 and the alternative branch, which does not include the path effects, is weighted 0.2. In addition to adding these two alternative branches, the TI Team added epistemic uncertainty to the median ground motions in order to account for the limited range of predicted spectral accelerations for earthquakes with greater than **M**7. In the resultant logic tree for the median ground motions, each of the five NGA-West2 GMPEs is augmented by 12 alternative branches that account for path effects and magnitude scaling (as shown in Figure 2-1 of Cadogan, 2015a) resulting in a final set of 60 GMPEs for the California and Mexico sources.

STAFF EVALUATION

Based on review of the SSHAC documentation and knowledge of current GMPEs developed for active tectonic regions, the NRC staff concludes that the TI Team developed an appropriate set of GMPEs in order to characterize the hazard for the PVNGS site. Rather than merely attaching weights to existing GMPEs, the staff notes that the TI Team appropriately expanded the initial set of seed GMPEs to develop two larger sets of GMPEs for the regional Arizona sources and the distant California and Mexico sources.

The staff notes that the complexity of the analysis inherent in the Sammon's mapping approach used by the TI Team was applied for the Arizona sources to address the large range of epistemic uncertainty associated with modeling near-site earthquakes in light of the lack of strong motion records for large earthquakes in Arizona. A more traditional, weighted-GMPE approach was used for the distant large magnitude earthquakes in California and Mexico, where the TI Team concluded that sufficient data exists to model these types of events. The staff concludes that these two approaches, although dissimilar, are reasonable as applied to the two distinct source types (i.e., Arizona sources and distant California/Mexico sources). This is because both approaches produce a broad suite of median models, each of which are appropriately adapted for the particular crustal conditions and source types. The staff finds that this adequately accounts for epistemic uncertainty in each case.

The Sammon's map approach used by the TI Team for the Arizona sources produced a set of GMPEs ranging in size from about 40 to 50 models for each of the spectral frequencies. The staff finds that this large number of GMPEs produced a reasonable distribution of weighted predicted median spectral accelerations for each of the local and regional Arizona earthquakes considered for the hazard evaluation. Similarly, the TI Team developed a set of 60 GMPEs from the initial five NGA-West2 GMPEs for the distant California and Mexico sources. The staff also finds that these 60 GMPEs produced a reasonable distribution of predicted spectral accelerations for the larger and distant magnitude earthquakes considered for the hazard evaluation.

To evaluate the distributions of median spectral accelerations predicted by the two sets of GMPEs, the NRC staff examined the behavior of the models for multiple earthquake magnitude and source-to-site distance combinations. Figure 3.2.3-1 of this assessment shows the distribution of weighted medians produced by the set of GMPEs using the Sammon's map approach for the Arizona sources. Specifically, Figure 3.2.3-1 shows the distribution of weighted median results from the 21 of the 45 GMPEs developed for 10 Hz spectral acceleration from a **M**6 earthquake for source-to-site distances ranging from 1 to 200 km. Shown in the inset to Figure 3.2.3-1 are the cumulative distributions of weighted median values for two vertical slices through the 21 weighted medians at source-to-site distances of 5 km (blue) and 50 km (red). As shown by the two cumulative distributions at 5 km and 50 km, the 21 predicted weighted medians are centered at reasonable values (0.05g for 50 km and 0.50g for

5 km) and cover a suitably wide range of 10 Hz spectral accelerations (0.02g to 0.09g for 50 km and 0.40g to 0.70g for 5 km).

Similarly, Figure 3.2.3-2 of this assessment shows the distribution of weighted medians produced by the set of GMPEs developed by the TI Team for the distant California and Mexico sources. Specifically, Figure 3.2.3-2 shows the distribution of weighted median results from the 60 GMPEs developed for 1 Hz spectral acceleration from a **M**7.5 earthquake for source-to-site distances ranging from 100 to 500 km. Shown in the insert to Figure 3.2.3-2 is the cumulative distribution of weighted median values for a vertical slice through the 60 weighted medians at a source-to-site distance of 250 km. As shown by the cumulative distribution at a distance of 250 km, the 60 predicted weighted medians are centered at reasonable value (0.008g) and cover a suitably wide range of 1 Hz spectral accelerations (0.002g to 0.030g).

The staff used its experience in developing and evaluating GMPEs to determine that the TI Team developed two appropriate sets of GMPEs, which were modified and adapted for the regional Arizona and California and Mexico sources. The staff notes that the modifications and adaptions used by the TI Team resulted in two sets of GMPEs that predict a suitable distribution of median spectral accelerations for each of the earthquake scenarios used to develop the hazard for the PVNGS site.

In summary, as a result of this review, the NRC staff concludes that the TI Team developed two sets of GMPEs adapted specifically for the seismic sources surrounding PVNGS and suitable for use in the PSHA for the site. The staff further concludes that the high-dimensional visualization and sampling through application of Sammon's mapping used by the TI Team for the regional Arizona sources as well as the traditional approach used for the distant and larger magnitude California and Mexico sources are consistent with the intent of the SSHAC Guidelines of capturing the center, body, and range of the technically defensible information of available data, models, and methods.

3.2.4 Ground Motion Variability

In addition to developing GMPEs that predict median ground motions, the TI Team developed models to characterize the aleatory variability about the median ground motions. To develop these models, the TI Team used the ground motion databases and seed GMPEs models described in Section 3.2.2. Because Enclosure 1 to the 50.54(f) letter requests that addressees perform a detailed site response analysis, the TI Team first separated the total aleatory variability into its component pieces in order to remove the repeatable effects of site response. The resulting sigma is referred to as single-station sigma. In order to use the single-station sigma approach, the TI Team captured the site-specific portion of the uncertainty by developing (1) a set of WUS-generic baserock to site-specific baserock ground motion correction factors (referred to as the V_S-kappa correction factors), (2) distributions for the local site response amplification factor, and (3) a distribution for the epistemic uncertainty on single-station sigma. The staff's review of the first two site uncertainty factors is discussed in Section 3.4.

The single-station sigma approach starts with separating the total residual into its between-event and within-event residual components, where the between-event and the within-event residuals have standard deviations τ and φ, respectively. The within-event residual is then further separated into a site term component and a site- and event-corrected residual component with standard deviations φ_{S2S} and φ_{SS}, respectively. The single-station sigma approach then excludes the site term standard deviation φ_{S2S} from the total sigma and instead assigns it as an epistemic uncertainty.

To develop a model for the single-station sigma, the TI Team first constructed models for the between event standard deviation τ and the single-site within-event standard deviation φ_{SS}, assuming both models to be dependent only on magnitude and not source-to-site distance. The TI Team developed the τ model for PVNGS by averaging the τ models of four of the five NGA-West2 models along with the Zhao et al. (2006) models. For the φ_{SS} model, the TI Team used multiple NGA-West2 data sets as well as the European and Taiwan data sets to develop within-event site corrected residuals using recording sites with a minimum of at least three recordings. For the distant larger sources in Regions 1, 2, and 3, the TI Team used the recordings from California and Mexico earthquakes recorded at a group of sites around PVNGS to estimate the repeatable similar path-to-region component of sigma, referred to as φ_{SP-R}.

In addition to developing models for each of the individual components of sigma (τ, φ_{SS}, and φ_{SP-R}), the TI Team develop epistemic uncertainty distributions for each of these components. The TI Team next combined these epistemic uncertainty distributions to develop a final continuous distribution for single-station sigma, which it represented by three discrete points selected at the 5^{th}, 50^{th} and 95^{th} percentiles (low, medium, and high values).

STAFF EVALUATION

Based on review of the SSHAC report and knowledge of current GMPEs developed for active tectonic regions, the NRC staff determined that the TI Team developed an appropriate set of models for the ground motion variability in order to characterize the hazard for the PVNGS site. The staff finds that the TI Team appropriately used several ground motion databases in order to characterize the individual component pieces of the total variability for the single-station sigma approach. The staff notes that the ground motion data sets, described in Section 3.2.2, contain thousands of earthquakes, many of which are recorded at multiple sites. The NRC staff also notes that the TI Team appropriately separated out the stations with at least three recordings in order to estimate the site-term component of the variability. In addition, the staff concludes that the TI Team used an appropriate approach to combine the individual components of sigma into a final distribution for single-station sigma and that this distribution is adequately represented by including three branches in the logic tree for sigma at PVNGS.

To evaluate the ground motion variability about the predicted median spectral accelerations, the NRC staff examined the behavior of the ground motion distributions for multiple earthquake magnitude and distance combinations. Figure 3.2.4-1 of this staff assessment shows the GMPEs for 10 Hz spectral accelerations from a **M**6 earthquake over a distance range of 1 to 200 km. The inset to Figure 3.2.4-1 shows the weighted distributions of 10 Hz spectral accelerations in terms of the median (dots) and single station sigma values for a vertical slice at a distance of 5 km. As shown by the 21 models for this particular scenario earthquake (i.e., **M**6 at a distance of 5 km), the weighted distributions cover a wide range of 10 Hz spectral accelerations from about 0.03g to about 1.5g.

The staff notes that Figure 3.2.4-1 shows the multiple distributions of 10 Hz spectral acceleration using only the middle branch (i.e., median) for single-station sigma. Not shown are the additional distributions of 10 Hz spectral accelerations for the low (5^{th} percentile) and high (95^{th} percentile) values of single-station sigma. In addition, Figure 3.2.4-1 shows only 21 of the 45 GMPEs developed by the TI Team for 10 Hz spectral acceleration for the regional Arizona sources. In total, there are 135 individual weighted distributions (45 medians x 3 sigmas) for the spectral frequency of 10 Hz. Similarly, there are 120 to 150 unique distributions developed by the TI Team for each of the other 21 spectral frequencies. For the California and Mexico sources, the TI Team developed 360 individual weighted distributions (60 medians x 6 sigmas) for each of the spectral acceleration frequencies. The additional three sigmas for the distant sources capture the unique source-to-site path effects from the California and Mexico scenario earthquakes. The staff finds that the TI Team's use of this large number of distributions for each of the spectral frequencies adequately captures the epistemic and aleatory uncertainty in predicted ground motions for PVNGS.

As a result of this review, the NRC staff concludes that the TI Team appropriately modeled the variability in ground motions to develop GMPEs for the PSHA for PVNGS. Based on this conclusion, the staff finds that the resulting GMPEs adequately capture the center, body, and range of the technically defensible information.

3.3 Probabilistic Seismic Hazard Analysis

The SSC TI Team implemented the SSC and GMC logic trees to develop generic-WUS baserock PSHA hazard curves, which then serve as inputs to the site response analysis. Additional uses of the PSHA are to identify the fault and areal seismic sources that have the largest impact on the hazard and to identify the specific magnitude and distance combinations that control the hazard at 10^{-4}, 10^{-5}, and 10^{-6} annual frequencies of exceedance.

3.3.1 Summary of PSHA Implementation and Results

For each of the fault and area sources, discussed in Section 3.1 of this staff assessment, the SSC TI Team developed logic trees in order to define the potential locations, sizes, and rates of future earthquakes. Specific key parameter values captured by each of the source logic trees include (1) maximum magnitude, (2) earthquake rupture mechanism, (3) rupture dip angle, (4) depth to the top of rupture, (5) seismogenic thickness, and (6) recurrence model and rates. Each of these parameters is represented as a node in the logic tree with multiple weighted branches at each node providing alternative parameter values for that element.

The TI Team developed a logic tree for both of the Two-Zone areal source models, as well as for each of the six areal sources included in the Seismotectonic model. The logic tree for each of the areal sources defines a unique set of parameters for future potential earthquakes, primarily based on the characteristics of the known Quaternary faults and historical seismicity within each of the source zones. Because the six-zone Seismotectonic model is weighted more heavily than the Two-Zone alternative model and the site is located within the SBR Seismotectonic zone, the hazard contribution from SBR dominates the 10 Hz hazard and is also a significant contributor to the 1 Hz hazard for PVNGS.

The TI Team characterized each of the individual fault sources as a series of straight-line fault segments, allowing future earthquake ruptures to potentially occur on one or more of the segments. The TI Team implemented the UCERF3 fault model and also developed an alternative layered-fault model for the active plate boundary fault sources such as the San Andreas, San Jacinto, Elsinore, and Cerro Prieto faults. Of these faults, the TI Team determined that only the San Andreas, Cerro Prieto, and San Jacinto faults moderately impact the 1 Hz hazard for PVNGS. The TI Team also developed logic trees for faults in the California/Salton Trough region; however, due to their lower slip rates (generally < 1 mm/yr) and distances from PVNGS (beyond 300 km), the 1 Hz hazard for these faults is negligible. Similarly, the TI Team determined that normal fault sources in Arizona, Nevada, and New Mexico, such as the Sand Tank fault, have very low slip rates and, as such, make a small contribution hazard at PVNGS.

The GMC TI Team developed logic trees for the GMPE median and sigma models for both the regional Arizona sources and the distant California and Mexico sources. The GMC logic tree for the regional Arizona sources includes nodes and branches for each of the different median models, two alternative distance parameters, and multiple hanging-wall effects. For the distant California and Mexico sources, the GMC logic tree includes nodes and branches for each of the five NGA-West2 GMPEs, path term effects, and epistemic uncertainty for large-magnitude scaling. The sigma logic trees include nodes and branches for magnitude dependence, the distribution of epistemic uncertainty in single-station sigma, and the use of either a normal distribution or a mixture model for the final distribution of ground motion residuals.

After implementing the SSC and GMC logic trees in order to develop the site-specific rock hazard curves at PVNGS for each of the seismic sources, the TI Team performed a deaggregation of the hazard for both the low (1 and 2.5 Hz) and high (5 and 10 Hz) frequency spectral accelerations for the 10^{-4}, 10^{-5}, and 10^{-6} mean annual frequencies of exceedance. For the high frequencies, the TI Team determined that local earthquakes with moderate magnitudes (i.e., **M**6.1 to **M**6.3 at distances from 7 to 21 km) dominate the hazard, while for the low frequencies, large distant earthquakes (i.e., **M**7.4 to **M**7.6 at distances around 200 km) dominate the hazard.

3.3.2 Staff Confirmatory Evaluation

To evaluate the PSHA, the NRC staff performed a confirmatory evaluation for the seismic sources that contribute the most to the hazard. The purpose of the staff's evaluation was to evaluate the reasonableness of the 1 and 10 Hz mean hazard results for a few selected seismic sources, and also to evaluate the impact of the key source and ground motion parameters on the final hazard results. For this confirmatory analysis, the NRC staff selected a subset of the branches that focus on the highest weighted components of the logic tree.

The areal sources selected by the staff for its confirmatory evaluation are the SBR, which is the host areal source zone, and the TZ (Transition Zone). These areal zones are two of the six-zone Seismotectonic sources that are significant contributors to both the 1 and 10 Hz total mean hazard for PVNGS. Because the locations of the causative faults within the SBR and TZ are not known, the staff developed a set of virtual faults to simulate earthquake sources in the two areal source zones. Using Hanks and Bakun (2008) magnitude-area scaling relationships, the staff derived the length for each of the virtual faults based on the median maximum magnitude, faulting mechanism, dip angle, and seismogenic thickness as used in the logic tree for each of the sources. For each of the virtual faults in the SBR and TZ, the staff calculated the hazard using a range of earthquake sizes from **M**5 to the median maximum magnitude earthquake which is **M**7.2 for both the SBR and TZ. The staff developed a seismic hazard curve for each of the virtual faults and then summed the results to obtain mean 1 and 10 Hz hazard curves for the SBR and TZ.

Figure 3.3.2-1 of this staff assessment shows the location of the virtual faults for the SBR (blue) and TZ (brown) areal source zones. For the analysis, the staff placed virtual faults more densely around the PVNGS site (red triangle) and more sparsely out to a distance of 250 km. The staff used this placement of virtual faults to adequately capture the entire range of possible source-to-site distances. Shown in Figure 3.3.2-1 are the virtual faults for the normal faulting mechanism, with each fault having a length of about 65 km and a down-dip width of about 20 km. To represent the structural characteristics of the source zones the staff selected a fault orientation randomly between N40°W and N–S for the SBR. For TZ, the staff selected fault orientations randomly between N20°W to N20°E.

Figure 3.3.2-2 of this staff assessment shows the 1 Hz (left) and 10 Hz (right) mean hazard curves for the SBR (blue) and TZ (brown) areal sources. The staff's PSHA confirmatory results are shown by the solid heavy line with the licensee's results shown by the dashed heavy line. To obtain the final confirmatory results, the staff added up the hazard curves for each of the virtual faults (377 for SBR and 83 for TZ). As shown in Figure 3.3.2-2, the staff's confirmatory results closely match the licensee's results for both the 1 and 10 Hz mean hazard curves.

In addition to the SBR and TZ areal source zones, the staff also performed a confirmatory evaluation of the San Andreas Fault, whose nearest approach is about 270 km from PVNGS. For its confirmatory analysis, the staff used representative subsets of the logic trees for the layered model SSC and the GMC for distant California and Mexico sources. The staff's resulting 1 Hz hazard curve for the San Andreas Fault is reasonably consistent with the licensee's result.

In summary, the NRC staff concludes that the SSC TI Team acceptably implemented the SSC and GMC logic trees, in developing the baserock consistent with the guidance specified in Enclosure 1 to the 50.54(f) letter. Through confirmatory analyses for three of the major contributors to the hazard for PVNGS, the NRC staff was able to confirm the TI Team's hazard results. Therefore, the staff concludes that the resulting baserock PSHA hazard curves capture the center, body, and range of the technically defensible information.

3.4 Site Response Evaluation

After completing PSHA calculations for site rock conditions, Attachment 1 to Enclosure 1 of the 50.54(f) letter requests that licensees provide a GMRS developed from the site-specific seismic hazard curves at the control point elevation. To develop site-specific hazard curves at the control point elevation, Attachment 1 requests that licensees perform a site response analysis. The purpose of the site response analysis is to determine the site amplification that will occur because of bedrock ground motions propagating upwards through the soil/rock column to the

surface. The critical parameters that determine what frequencies of ground motion are affected by the upward propagation of bedrock motions are the layering of soil and/or soft rock, the thicknesses of these layers, the shear-wave velocities and low-strain damping of the layers, and the degree to which the shear modulus and damping change with increasing input bedrock amplitude. Detailed site response analyses typically were not performed for many of the older operating plants; therefore, Appendix B of the SPID provides detailed guidance on the development of site-specific amplification factors (including the treatment of uncertainty) for sites that do not have detailed, measured soil and rock parameters to extensive depths.
In addition, the 50.54(f) letter specifies that the subsurface site response model, for both soil and rock sites, should extend to sufficient depth to reach the generic or base rock conditions as defined in the GMMs used in the PSHA. In order to transfer the median ground motions predicted by the GMPEs for WUS generic rock conditions (referred to as the "host" conditions) to the site-specific baserock (referred to as the "target" conditions), the licensee developed a distribution of adjustment factors, which are described in Section 3.4.3.

3.4.1 Site Base Case Profiles

To perform a site response analysis, the licensee developed both shallow and deep stratigraphic models for PVNGS. For each of the profiles, the licensee modeled physical properties, such as the shear-wave velocity (V_S) density, and the thickness of each of the layers. The licensee used the shallow profile to calculate the site amplification factors for development of the control point hazard curves, while the deeper profile was used to develop the host-to-target adjustment factors for the input ground motions.

The licensee stated that the shallow subsurface at the PVNGS site is composed of approximately 105 m of interbedded sands and clays and 26 m of fanglomerate overlying the volcanic rocks that characterize the top of the deep profile. The licensee based its base case profiles on data collected at the time of licensing (APS, 2013), and recently collected downhole and Spectral Analysis of Surface Waves (SASW) data summarized in the SHSR. To capture the epistemic uncertainty in the base case model, the licensee also developed upper and lower base case profiles using a natural log standard deviation that ranged from a value of 0.23 to 0.15, depending on the variation of the observed seismic velocities. Figure 3.4.1-1 of this assessment shows the licensee's three shear-wave velocity profiles for the shallow subsurface.
The licensee stated that the deeper profile, which extends from an average depth of 120 m to 1968 m, represents an upper section of volcanic rocks that transition into Precambrian granitic and metamorphic crystalline basement. To develop the base case profile for the deeper rock layers, the licensee used data presented in the Updated Final Safety Analysist Report (UFSAR) (APS, 2013) as well as a regional seismic refraction profile for Central Arizona (Warren, 1969). To capture the epistemic uncertainty in the base case profile, the licensee developed upper and lower base case profiles using a natural log standard deviation value of 0.35, as recommended in Appendix B of the SPID.

STAFF EVALUATION

The NRC staff determined that the site base-case profiles developed by the licensee are consistent with the information available about the subsurface at the PVNGS site. The licensee collected additional downhole seismic data and performed an SASW survey across the PVNGS site to develop its base case for the shallow profile. Similarly, for the deeper layers, the licensee developed its base case V_S profile using site-specific compressional wave velocities as well as a regional seismic refraction profile for Central Arizona. The licensee also accounted for the epistemic uncertainty in both of the base case profiles by developing upper and lower profiles using the variability observed in the data for the shallow profile and the SPID recommended uncertainty value for the deeper profile.

3.4.2 Dynamic Material Properties

In Section 2.3.2.1 of its SHSR, the licensee stated that no site-specific dynamic material properties were available for soils at the PVNGS site. Therefore, the licensee followed the SPID guidance and assumed the response of the soils could be modeled with varying degrees of nonlinearity. To capture the upper limit of nonlinearity in the sand layers, the license used the EPRI shear modulus and damping soil curves. For the equally plausible, more linear alternative, the license used the Peninsular Range curves. For the clay layers, the licensee assumed that the Vucetic and Dobry (1991) curves were appropriate.

In addition to considering the impact of material damping, the licensee considered the impact of kappa on site response. Kappa is the damping contributed by both intrinsic hysteretic damping, as well as scattering due to wave propagation in heterogeneous material. The licensee estimated both the site-specific or target kappa value as well as the kappa value for the generic WUS baserock or host conditions assumed for the GMPEs. To estimate the target kappa value of 0.033 sec, the licensee used earthquake ground motion recordings at sites near PVNGS, developed as part of the SWUS GMC project (GeoPentech, 2015). To capture the epistemic uncertainty in the target kappa value, the licensee used a natural log standard deviation of 0.5 to determine upper and lower estimates of kappa for the PVNGS site. For the host kappa, the licensee used the average kappa value of 0.041 sec from the input seed GMPEs, which range from 0.037 to 0.045 sec.

STAFF EVALUATION

The NRC staff reviewed the information provided by the licensee in the SHSR and information available in the PVNGS UFSAR (APS, 2013). The NRC staff determined that the dynamic material property curves used by the licensee are consistent with both the geology of the site and the guidance provided in the SPID.

The NRC staff also reviewed the information provided by the licensee and contained in the SWUS GMC report concerning the target and host kappa estimates. The SWUS GMC TI Team used earthquake recordings at about a dozen sites located in Central Arizona and multiple analysis methods to estimate the target kappa value. Based on its review of the data and methods used by the TI Team to determine the site target kappa value, the staff concludes the estimates determined by the licensee are acceptable. In addition, the staff concludes that the TI Teams use of a natural log standard deviation of 0.5 is reasonable, given the limited number of earthquakes and recording sites. To confirm the licensee's host kappa value of 0.041 sec, the staff calculated the kappa values for several of the input seed GMPEs and obtained a similar value (0.040 sec).

3.4.3 Input Spectra

To develop input ground motions for the site response analysis, the licensee used the results of the PSHA deaggregation (described in Section 3.3). Specifically, the licensee used the magnitude and distance pairs from the deaggregation performed by the SWUS GMC TI Team to develop high-frequency and low-frequency input spectra at hazard levels of 10^{-4}, 10^{-5}, and 10^{-6} mean annual frequency of exceedance. The licensee then scaled these input spectra to 11 different PGA amplitudes between 0.01g and 1.5g, resulting in a suite of 22 input ground motion response spectra. Next, the licensee converted these host WUS generic-baserock input spectra to target site-specific input spectra using a set of 9 V_S-kappa conversion factors. To develop the set of 9 V_S-kappa conversion factors, the licensee combined the three target kappa values, the three deeper target base case V_S profiles, as well as the host kappa value and a host V_S profile. The licensee developed the V_S-kappa conversion factors by taking the ratio of the target conditions, in terms of V_S and kappa, divided by the host conditions. The licensee then used these V_S-kappa adjusted input spectra to drive the shallow site profile.

STAFF EVALUATION

To review the input spectra used by the licensee for its site response analysis, the staff performed confirmatory calculations to evaluate the licensee's set of 9 V_S-kappa conversion factors. The method used by the staff to develop confirmatory V_S-kappa conversion factors involves calculating the impedance contrast between the host and target V_S profiles, as well as adjusting the high-frequency decay of the input spectra to account for the difference between the host and target kappa values. Figure 3.4.3-1 of this staff assessment shows that the staff's V_S-kappa conversion factors (solid lines) closely match the licensee's conversion factors (dotted lines). Based on this result, the staff concludes that the licensee adequately took into account the necessary conversion of the host WUS generic ground motions to the target site-specific conditions.

In summary, the NRC staff reviewed the information provided by the licensee in its SHSR related to the development of its input spectra and confirmed that the licensee developed an appropriate suite of input ground motion spectra for its site response analysis.

3.4.4 Site Response Method and Results

In Section 2.3.5 of its SHSR, the licensee described its implementation of the random vibration theory (RVT) approach to perform the site response calculations. Specifically, for each combination of V_S-kappa adjusted input spectra, three base case V_S profiles, and material models (i.e., EPRI or Peninsular curves), the licensee developed 60 random profiles to calculate a median amplification factor and associated log standard deviation. Section 2.3.6 of the SHSR shows the resulting amplification functions and associated uncertainties for the eleven input loading levels for the each base case profile. Following guidance in the SPID, the licensee used a minimum median amplification value of 0.5 in the analysis.

In order to develop probabilistic site-specific control point hazard curves, as requested in Requested Information Item (1) of the 50.54(f) letter, the licensee used Approach 3, which is described in Appendix B of the SPID. The licensee's use of Approach 3 involved computing the site-specific control point elevation hazard curves for a broad range of spectral accelerations by combining the site-specific reference rock hazard curves, determined from the initial PSHA (reviewed in Section 3.3 of this staff assessment), and the amplification functions and associated uncertainties that were determined from the site response analysis.

STAFF EVALUATION

Because Appendix B of the SPID guidance is more focused on the development of site-specific amplification factors for sites located in the CEUS rather than the WUS, it does not provide guidance on the development of V_S-kappa conversion factors needed for the site response input spectra. In a June 24, 2015, RAI to the licensee (NRC, 2015b), the NRC staff requested that the licensee justify its decision to incorporate the 9 V_S-kappa conversion factors into the site response logic tree rather than into the median GMPE logic tree.

In its August 6, 2015, RAI response (Lacal, 2015), the licensee stated that it incorporated the multiple V_S-kappa conversion factors into the site response logic tree for the sake of computational efficiency in the hazard calculations. The licensee justified this decision by showing that the resulting mean hazard and GMRS are the same using either approach. The NRC staff reviewed the licensee's RAI response and determined that the licensee's approach is acceptable on the basis that the resulting mean hazard and GMRS are unaffected. The staff notes that its acceptance of the licensee's implementation of the V_S-kappa correction factors as part of the site response logic tree is based on the outcome of the screening comparison between the GMRS and SSE, which is described in Section 3.5 of this staff assessment. If further plant evaluation in the form of a seismic probabilistic risk analysis had been warranted for the PVNGS, then the licensee would have needed to calculate control point hazard curves for multiple fractiles. The staff notes that the inclusion of the V_S-kappa conversion factors as part of the site response logic tree, rather than as part of the median GMPE logic tree, would have likely affected calculation of the fractile hazard curves.

In summary, the NRC staff reviewed the information provided by the licensee in its SHSR with respect to the development of the site response amplification factors, and concludes that the licensee appropriately implemented the guidance in the SPID. Specifically, the licensee developed site amplification factors for multiple input rock amplitudes while also incorporating multiple soil profiles, kappa values, and soil shear-modulus and damping curves. The staff concludes that the licensee appropriately implemented the site response amplification factors in the development of the control point hazard curves and GMRS for PVNGS.

3.4.5 Staff Confirmatory Site Response Analysis

To evaluate the licensee's site response analysis, the NRC staff performed a confirmatory site response analyses for the PVNGS site. Because the licensee had recently completed extensive geophysical testing of the PVNGS site, the staff adopted the licensee's shallow site velocity profiles for use in its confirmatory analysis. The staff performed 60 randomizations of the site profiles using information provided in the SHSR about the variability of the subsurface. To account for uncertainty in depth-to-baserock, the staff randomized this depth by ±20 percent. Figure 3.4.1-1 shows the site velocity profiles used in staff's confirmatory analysis.

Consistent with Appendix B of the SPID, as well as the approach used by the licensee, the staff used the EPRI soil curves as well as the Peninsular Range shear modulus and damping curves for sand layers. To model a lower limit of nonlinearity, the staff used the peninsular range curves for sands. The staff also adopted the Vucetic and Dobry (1991) curves for the clay layers.

Figure 3.4.5-1 of this assessment shows a comparison of the median and natural log standard deviation for amplification functions derived by the NRC staff and by the licensee, for the base case velocity profile at 1, 5 and 10 Hz spectral frequencies. As shown in Figure 3.4.5-1, the staff and licensee's site response evaluations resulted in similar median amplification factors and associated uncertainties across the range of input spectral accelerations.

In summary, the NRC staff concludes that the licensee's site response analysis was conducted using present-day guidance and methodology, including the NRC-endorsed SPID. The staff performed confirmatory calculations that verified the licensee's amplification factors adequately characterize the site response, including the uncertainty associated with the subsurface material properties, for the PVNGS site.

3.5 Plant Seismic Design Basis and Ground Motion Response Spectrum

3.5.1 Plant Seismic Design Basis

Enclosure 1 of the 50.54(f) letter (NRC, 2012a) requests the licensee provide the SSE ground motion values, as well as the specification of the control point elevation(s), for comparison to the GMRS. For operating power reactors with construction permits issued before 1997, the SSE is the plant licensing basis earthquake and is characterized by (1) a peak ground acceleration (PGA) value that anchors the response spectra at high frequencies (i.e., typically at 20 to 30 Hz for the existing fleet of NPPs); (2) a response spectrum shape that depicts the amplified response at all frequencies below the PGA; and (3) a control point location where the SSE is defined.

In Section 3.1 of its SHSR (Cadogan, 2015a), the licensee described its seismic design bases for PVNGS and states that the SSE is defined as a PGA of 20 percent gravity (i.e., 0.20g). However, the licensee further states that "the seismic analysis of all Seismic Category 1 structures was performed utilizing a Design Spectral Response Curve anchored at a PGA value of 0.25g. A PGA of 0.25g thus constitutes the design value for PVNGS, which bounds the 0.20g site characterization SSE (licensing basis)." In Section 3.2 of its SHSR, the licensee specified that the SSE control point is located at the plant grade foundation level for all units.

The staff reviewed the licensee's description in its SHSR of the SSE for PVNGS. Based on review of the licensing basis contained in Revision 17 of the PVNGS UFSAR (APS, 2013) and supplemental information provided in Cadogan (2015b), the NRC staff determined that the licensee's SSE is a 5 percent damped response spectrum anchored at 0.2g (Figure 3.5.1-1 of this staff assessment). Although the 0.25g response spectrum referenced in the SHSR was used for design of structures, it does not represent the plant's SSE. Therefore, the staff performed its screening evaluation for PVNGS based on a comparison of the GMRS with the plant's licensing basis SSE. Finally, based on its review of the SHSR and the UFSAR (APS, 2013), the NRC staff confirmed that the licensee's control point elevation for the PVNGS SSE is consistent with the guidance provided in the SPID (EPRI, 2012).

3.5.2 Ground Motion Response Spectrum

The GMRS is used to represent the free-field seismic hazard at the top of the soil column. To calculate the GMRS, the licensee first used site-specific rock hazard curves from the PSHA (reviewed in Section 3.3) and the soil amplification functions (reviewed in Section 3.4) to calculate control point hazard curves. The licensee then used these curves to develop uniform hazard response spectra at 10^{-4} and 10^{-5} mean annual frequencies of exceedance, and then computed the GMRS using the criteria in RG 1.208 (NRC, 2007). The resulting horizontal GMRS for the PVNGS site is shown in Figure 3.5.1-1 of this staff assessment.

To review the licensee's GMRS, the staff relied on the results of the reviews documented in Sections 3.1 to 3.4 of this staff assessment. Based on the result of its review, the staff determined that the licensee developed acceptable site-specific rock hazard curves that represented a reasonable implementation of the seismic source and GMMs in a PSHA. The staff also determined in Section 3.4 that the licensee developed acceptable site amplification factors, which it then used to calculate acceptable control-point hazard curves. The staff also determined that the licensee used appropriate criteria in RG 1.208 to calculate the GMRS.

Based on the assessment of the licensee's SHSR and the April 10, 2015, response to the RAI (Cadogan, 2015b), the staff confirms that the licensee used present-day guidance and methodologies outlined in RG 1.208 and the SPID to calculate the horizontal GMRS, as requested in the 50.54(f) letter. Based on the results of its review, the staff concludes that the GMRS determined by the licensee adequately characterizes the reevaluated seismic hazard for the PVNGS site. Therefore, this GMRS is suitable for use in subsequent evaluations and confirmations, as needed, for the response to the 50.54(f) letter (NRC, 2012a) and other actions associated with NTTF recommendations.

4.0 CONCLUSION

The NRC staff reviewed the information provided by the licensee for the reevaluated seismic hazard for the PVNGS site. Based on this review, the staff concludes that the licensee conducted the seismic hazard reevaluation using present-day methodologies and regulatory guidance, it appropriately characterized the site given the information available, and met the intent of the guidance for determining the reevaluated seismic hazard. Based upon the preceding analysis, the NRC staff concludes that the licensee's SHSR provides an acceptable response to Requested Information Items (1) – (3) and (5-7), identified in Enclosure 1 of the 50.54(f) letter.

In reaching this conclusion, the staff determined that the licensee's SHSR screening on the plant's Design Spectral Response Curve was not an acceptable basis for evaluating the plant's SSE against the GMRS, as specified in item (4) of Enclosure 1 of the 50.54(f) letter (NRC, 2012a). Compared to the SSE, the staff determined that the GMRS was approximately 2 percent higher at 1.2 Hz and approximately 10 percent higher at greater than 35 Hz (Figure 3.5.1-1). Based on criteria discussed in NRC (2015c), the staff determined that these small

GMRS exceedances of the SSE were not significant, and that the licensee did not need to complete additional seismic risk evaluations (Item 8), an SFP evaluation (Item 9) or an HF confirmation (Item 4), identified in Enclosure 1 of the 50.54(f) letter. Based upon the preceding analysis, the NRC staff concludes that the licensee responded appropriately to Enclosure 1, of the 50.54(f) letter.

5.0 REFERENCES

Note: ADAMS Accession Nos. refers to documents available through NRC's Agencywide Documents Access and Management System (ADAMS). Publicly-available ADAMS documents may be accessed through http://www.nrc.gov/reading-rm/adams.html.

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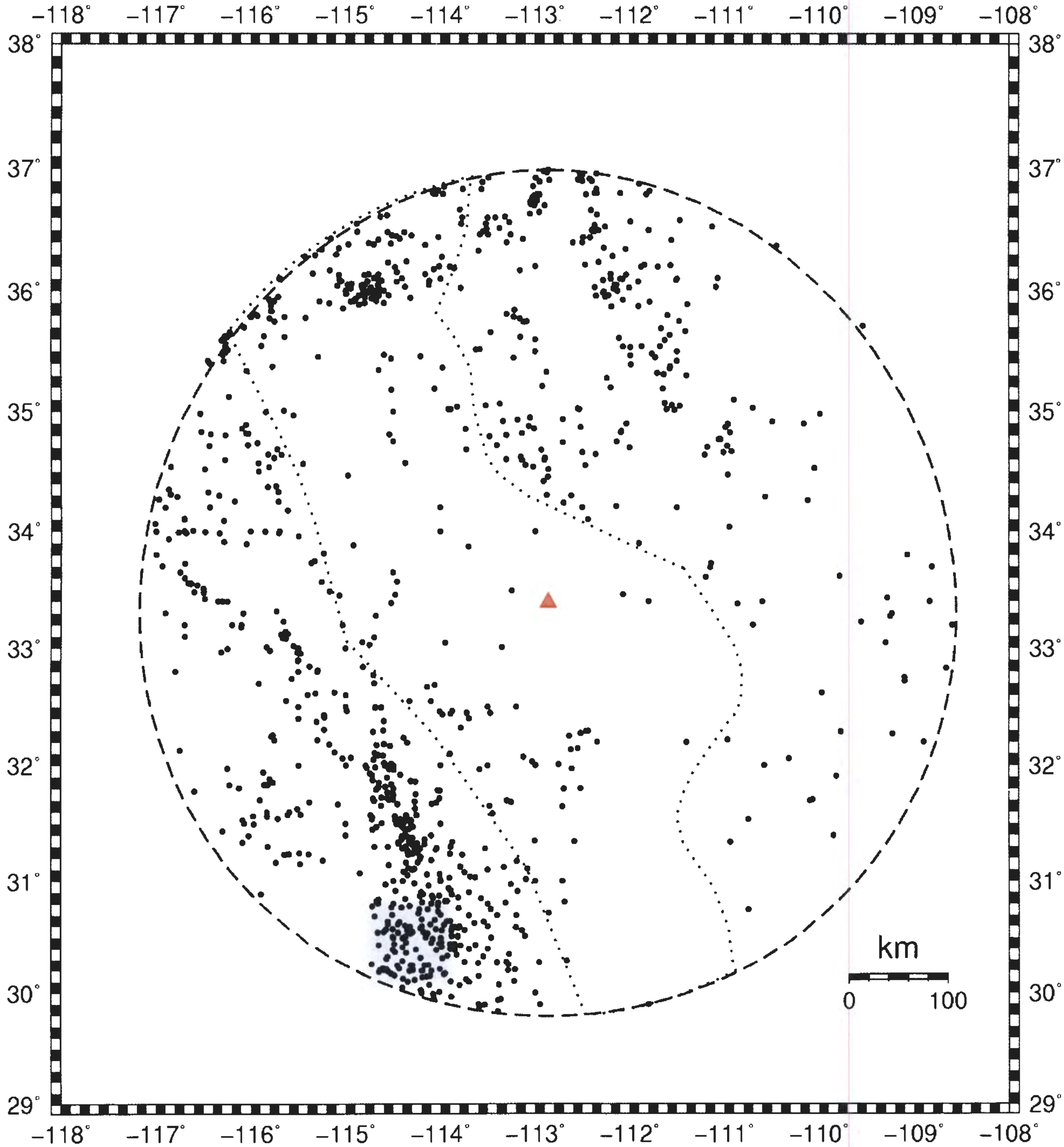

Figure 3.2.1-1. Independent earthquakes (dots) located within 400 km (dashed line) of the PVNGS site (triangle). Boundaries of the Southern Basin and Range seismic source zone shown in dotted lines.

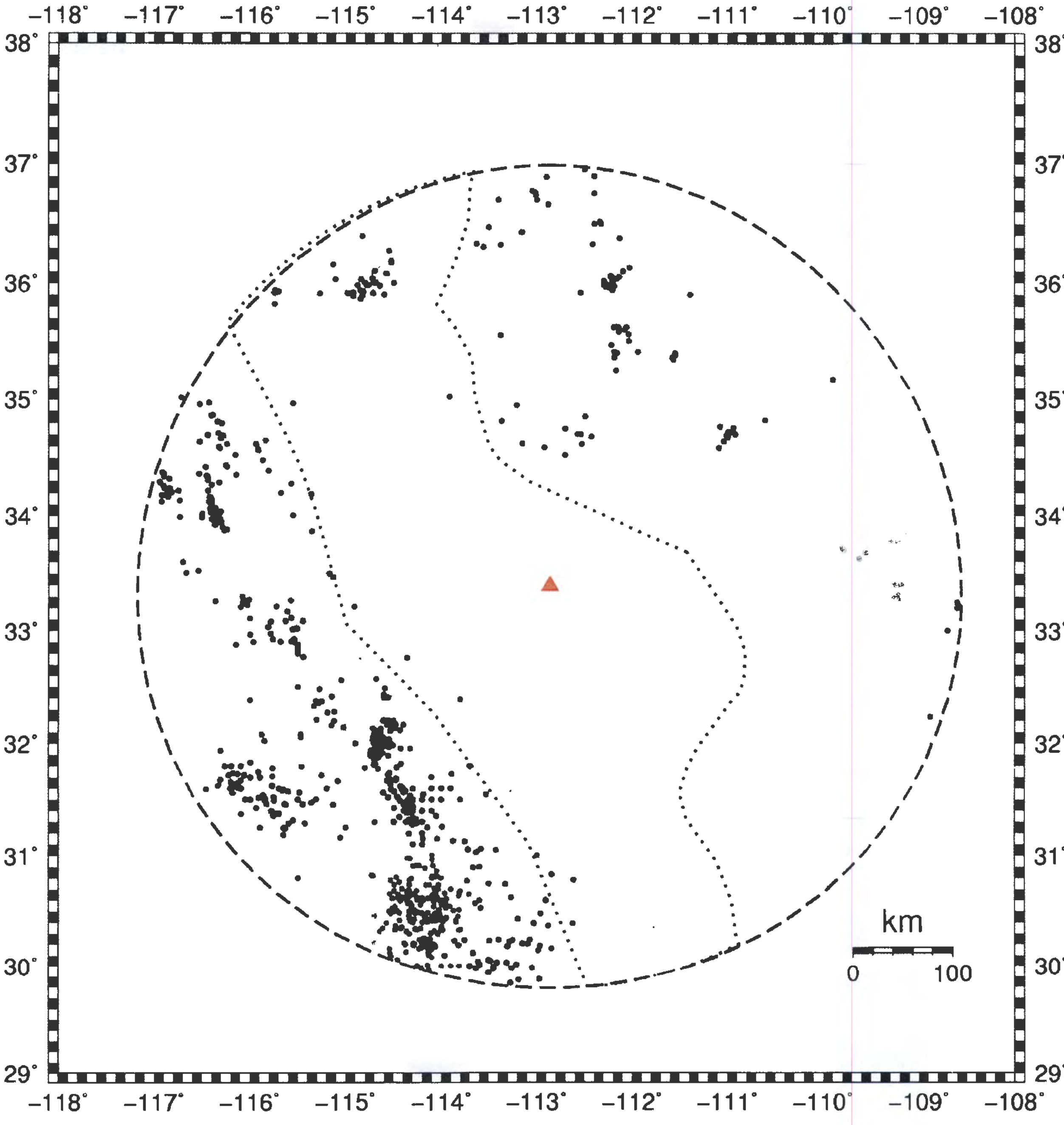

Figure 3.2.1-2. Dependent earthquakes (dots) located within 400 km (dashed line) of the PVNGS site (triangle). Boundaries of the Southern Basin and Range seismic source zone shown in dotted lines.

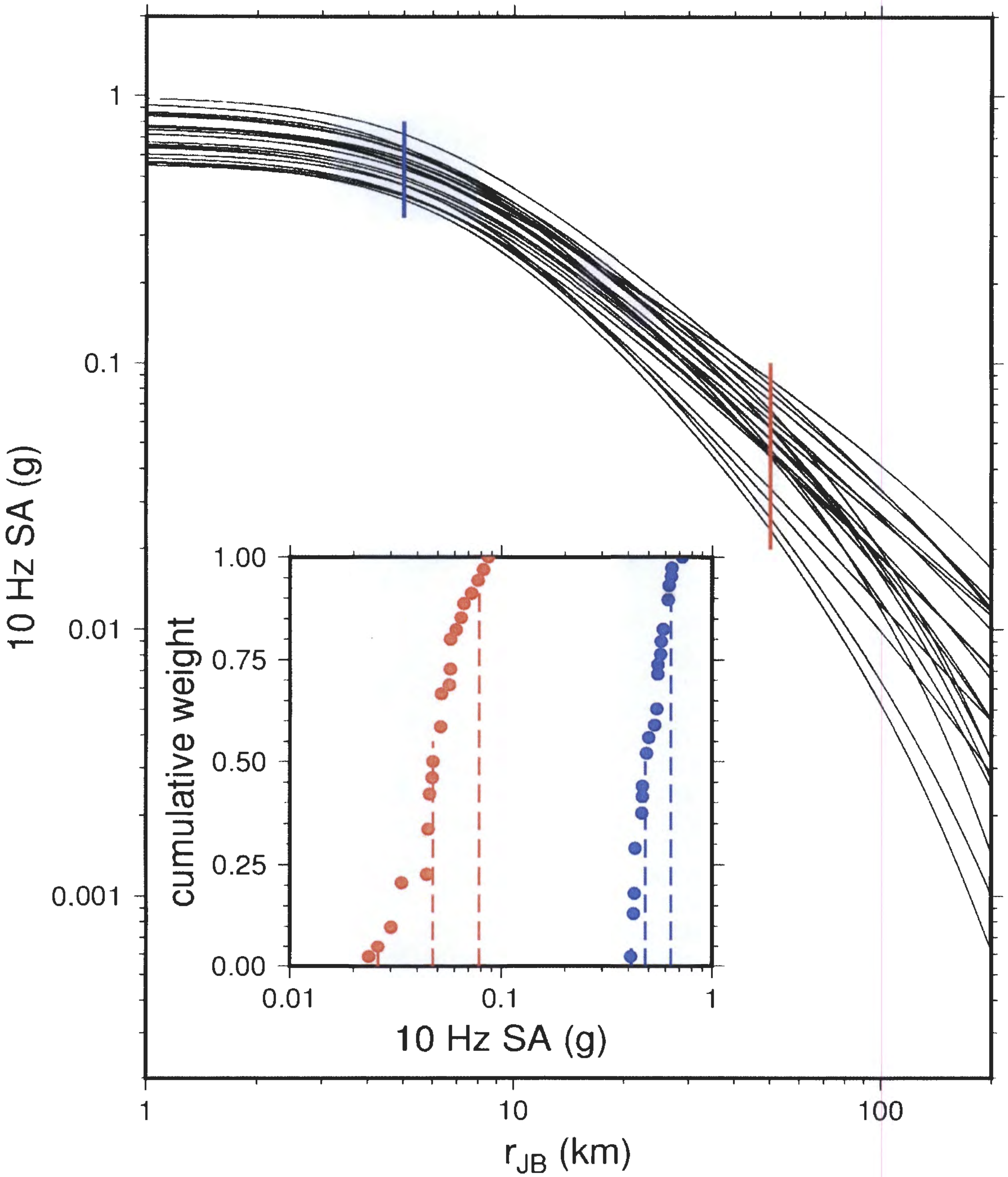

Figure 3.2.3-1. Distribution of weighted median results from the 21 GMPEs developed for a 10 Hz spectral acceleration from a **M**6 earthquake, for source-to-site distances ranging from 1 to 200 km. Inset shows the cumulative distributions of weighted median values for two vertical slices through the 21 weighted medians at source-to-site distances of 5 km (blue) and 50 km (red).

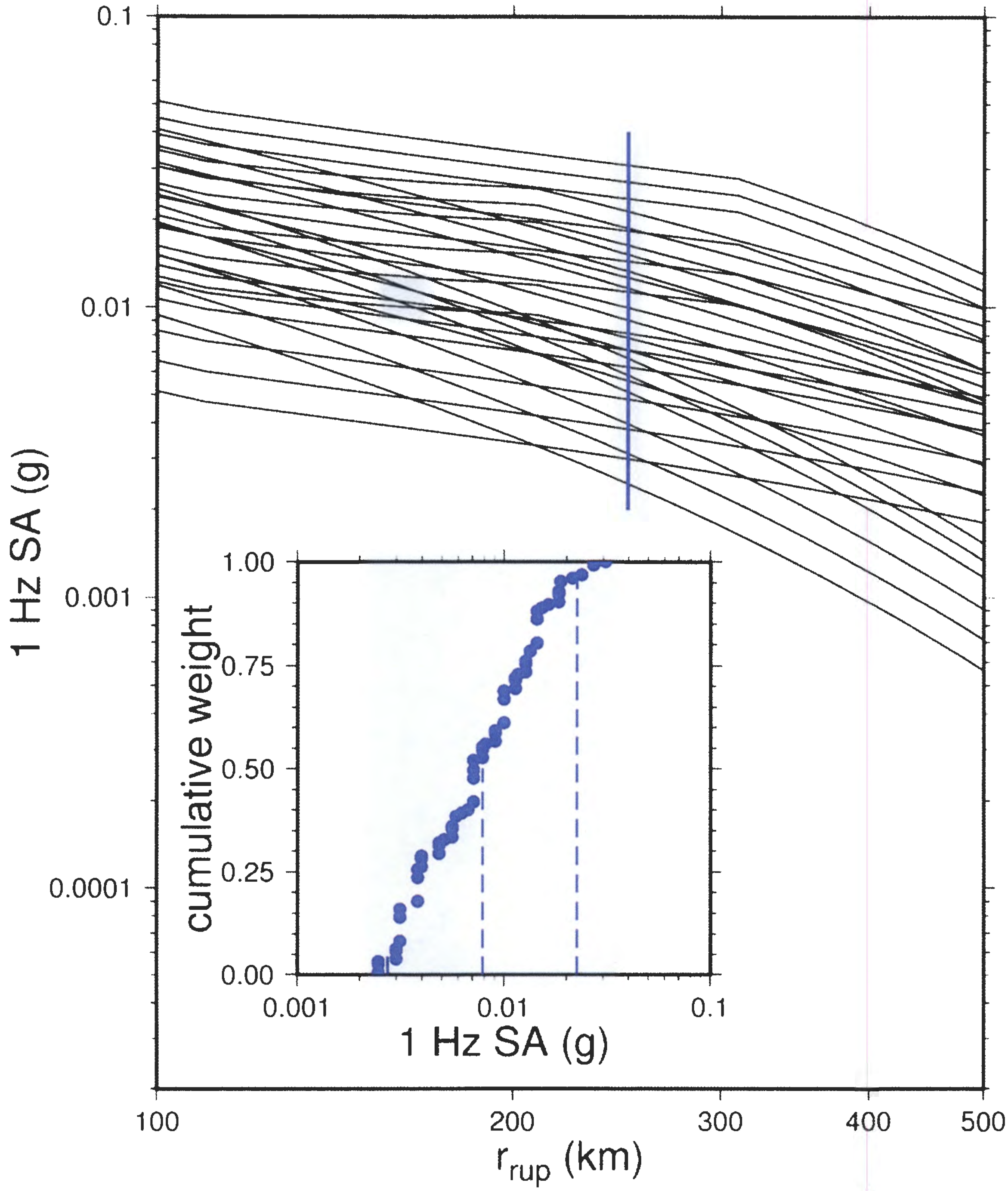

Figure 3.2.3-2. Distribution of weighted median results from the 60 GMPEs developed for a 1 Hz spectral acceleration from a **M**7.5 earthquake, for source-to-site distance ranging from 100 to 500 km, for distant sources in California and Mexico. Inset shows the cumulative distribution of weighted median values for a vertical slice through the 60 weighted medians at a source-to-site distance of 250 km.

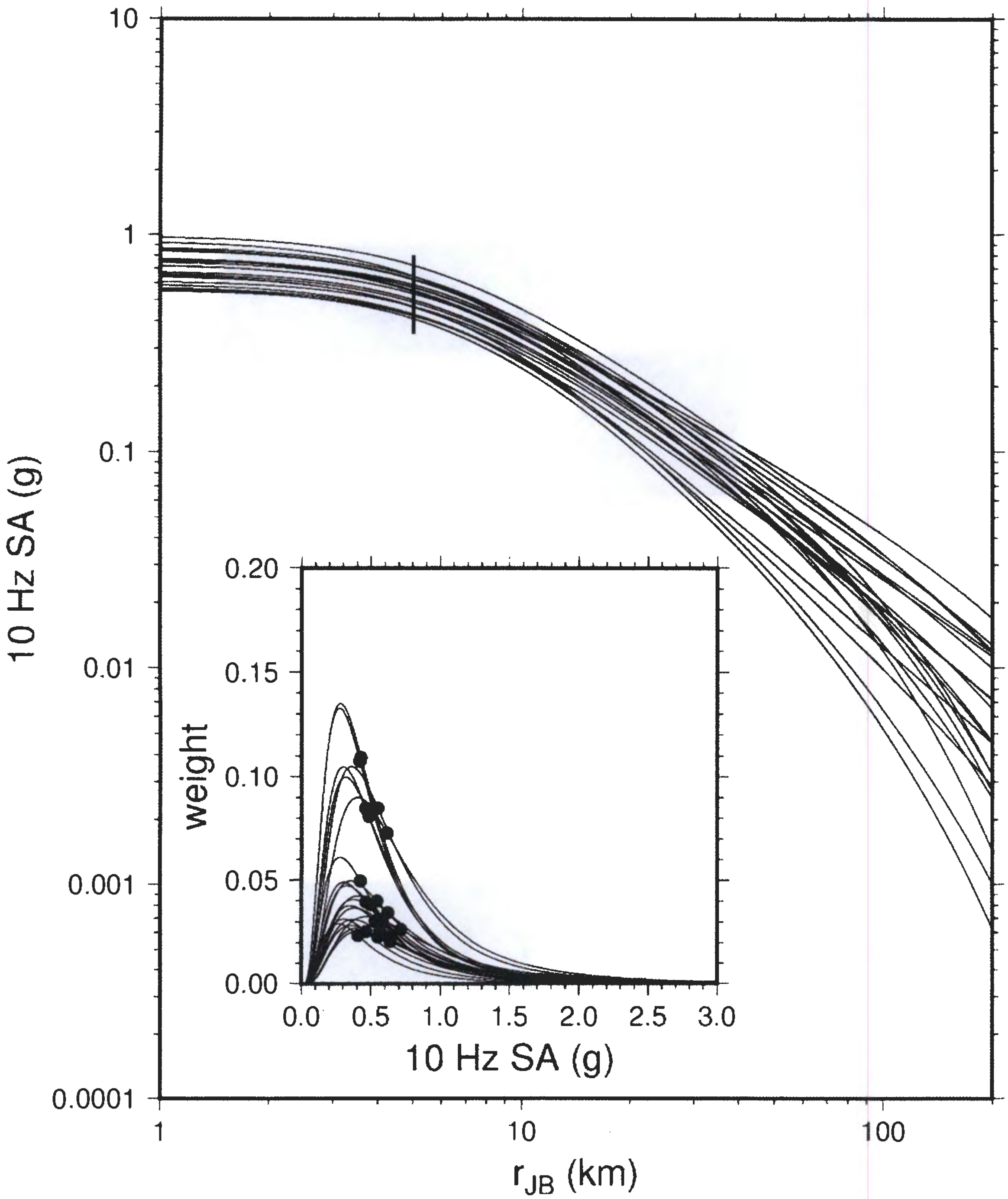

Figure 3.2.4-1. Distribution of GMPE model results as shown previously in Figure 3.2.3-1; however, the inset shows the complete lognormal distributions, defined in terms of their weighted medians (dots) and single-station sigmas, for each of the predicted 10 Hz spectral accelerations from a **M**6 earthquake at a distance of 5 km.

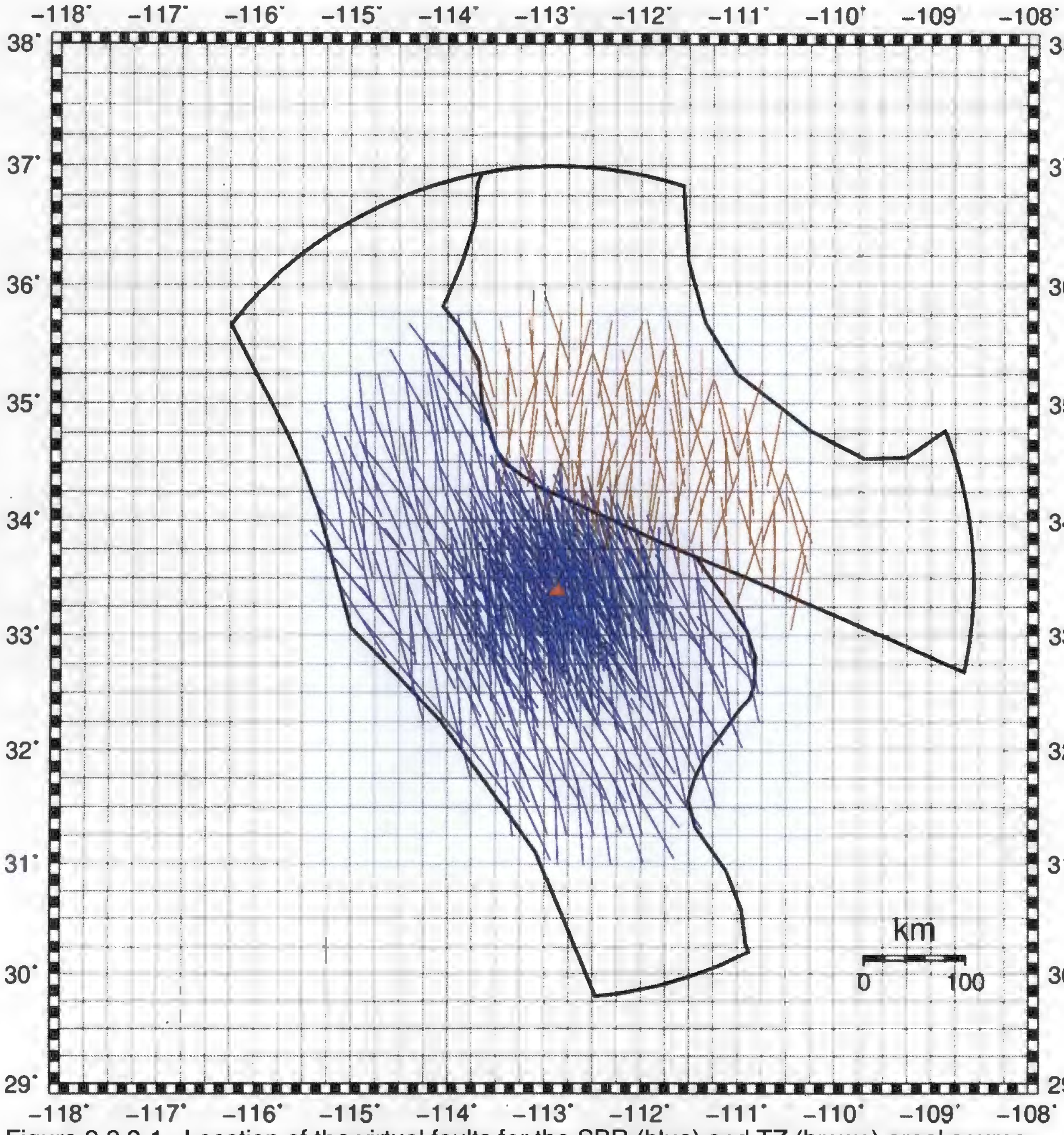

Figure 3.3.2-1. Location of the virtual faults for the SBR (blue) and TZ (brown) areal source zones (outlined in black). For the confirmatory analysis, the staff placed virtual faults more densely around the PVNGS site (red triangle) and more sparsely out to a distance of 250 km.

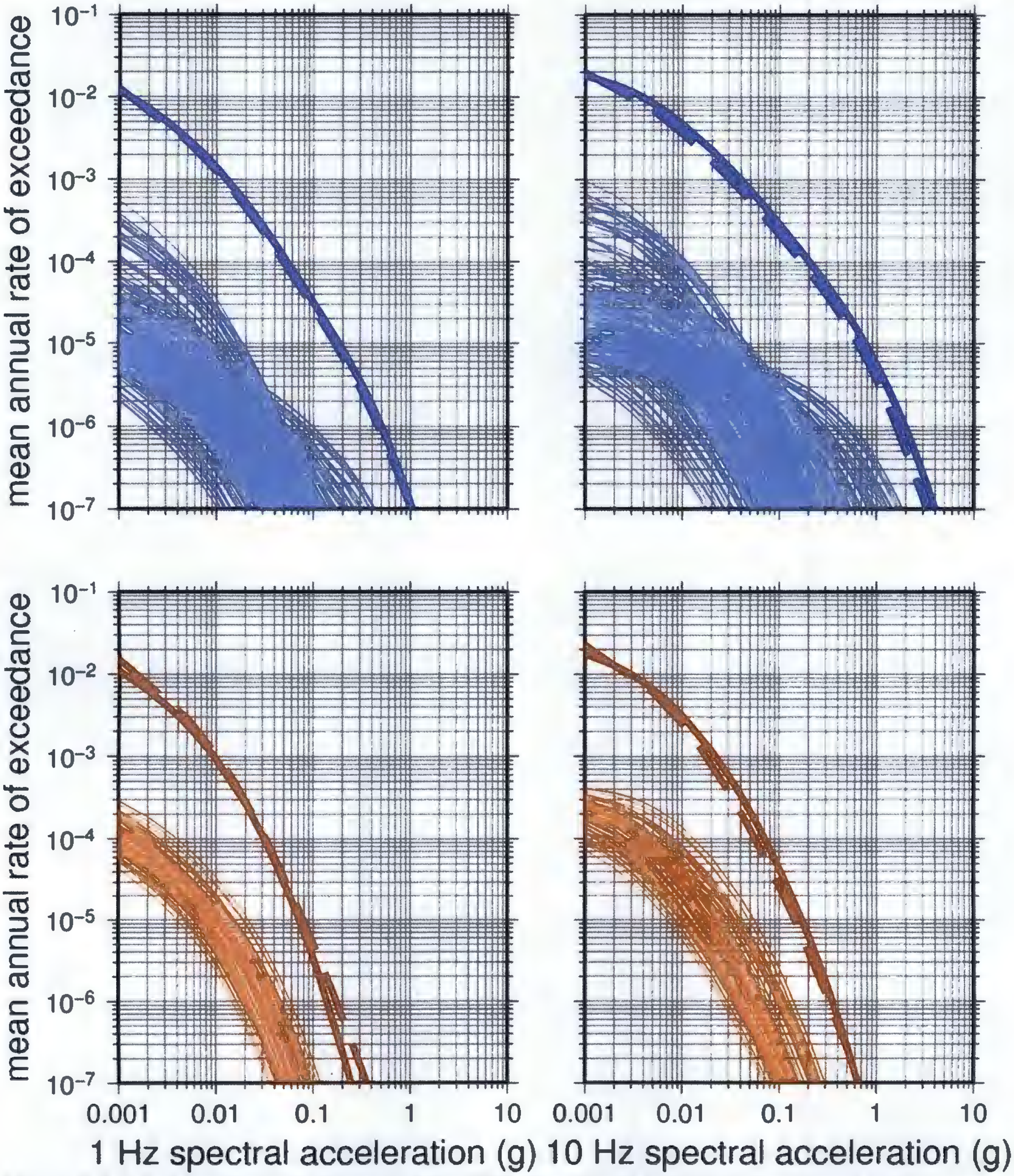

Figure 3.3.2-2. Mean hazard curves for the SBR (blue lines) and TZ (brown lines) areal sources. The staff's PSHA confirmatory analysis results are shown by the solid heavy lines, and the licensee's results are shown by the dashed heavy line.

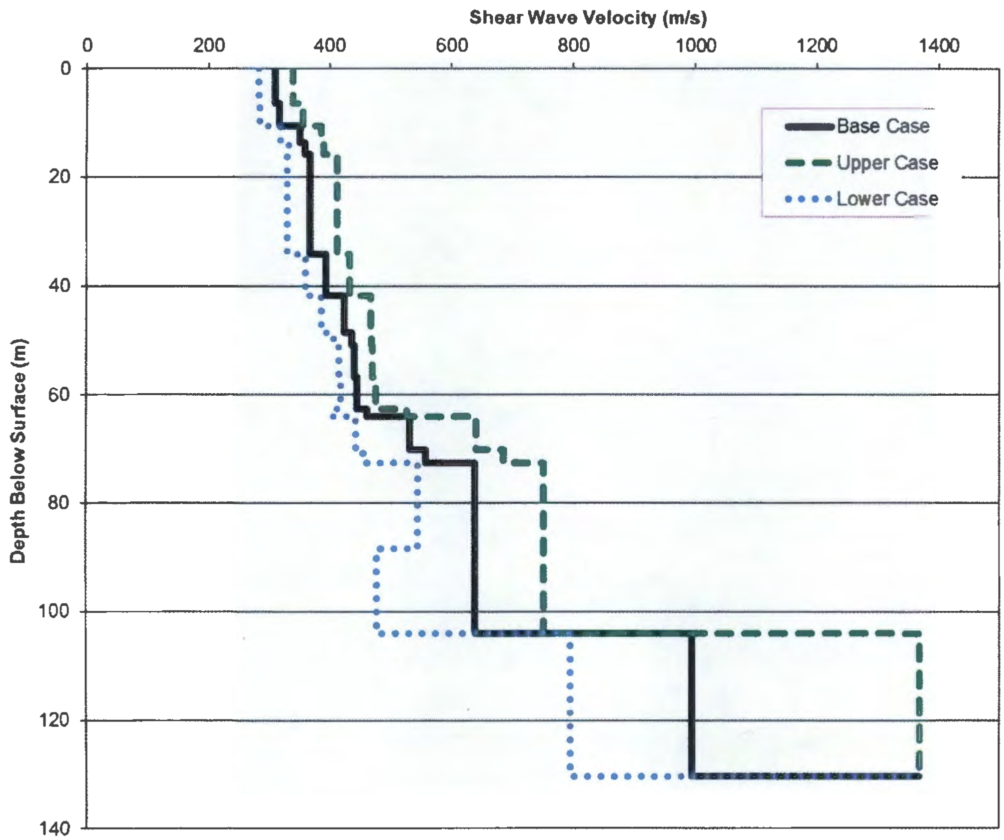

Figure 3.4.1-1. Shallow seismic velocity profiles used by the NRC staff in confirmatory analyses for the PVNGS site.

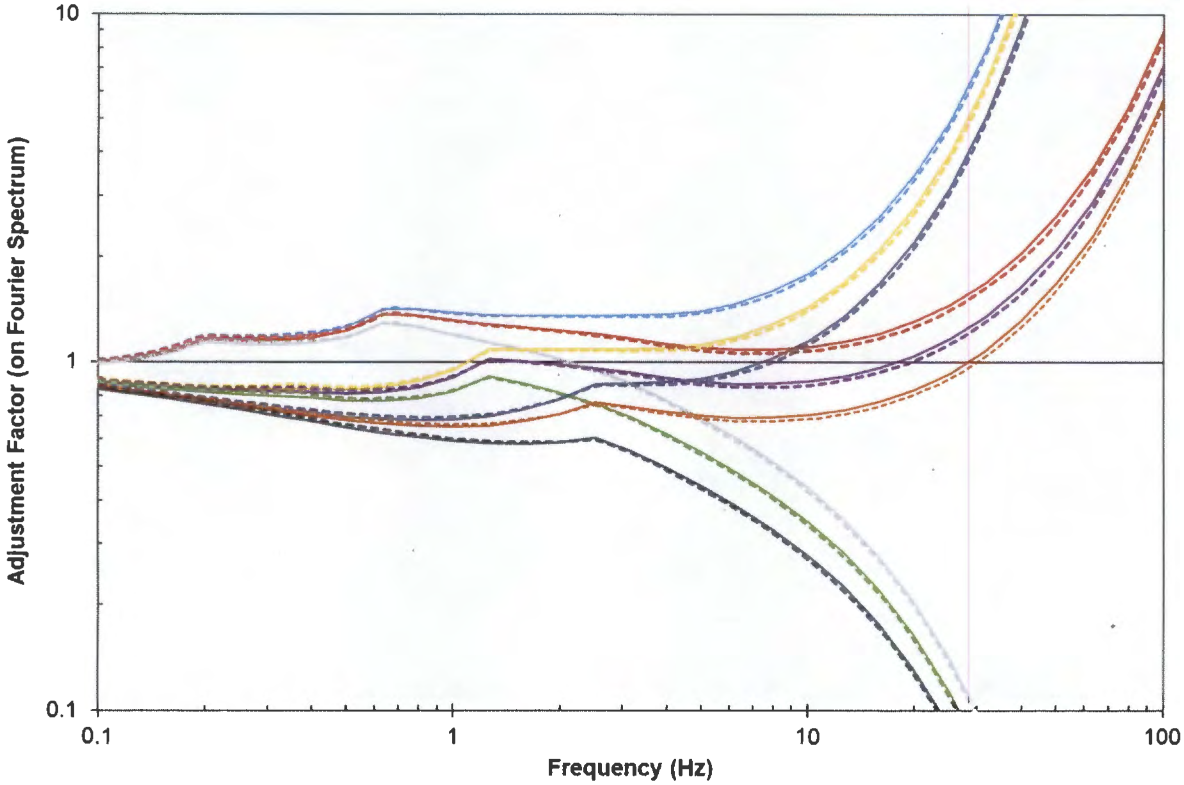

Figure 3.4.3-1. Comparison of PVNGS V_S-kappa factors from the licensee (dotted lines) and NRC staff's confirmatory analyses (solid lines).

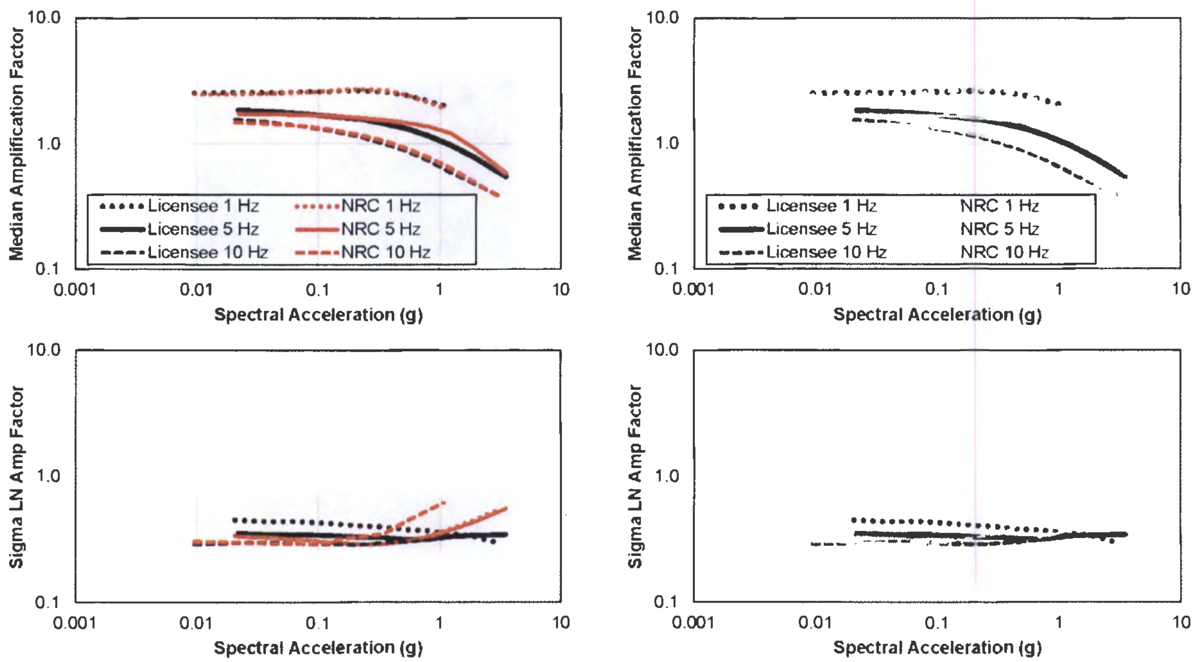

Figure 3.4.5-1. Comparison of the median and natural log standard deviation for amplification functions derived by the NRC staff and by the licensee, for the base case velocity profile at 1, 5, and 10 Hz spectral frequencies.

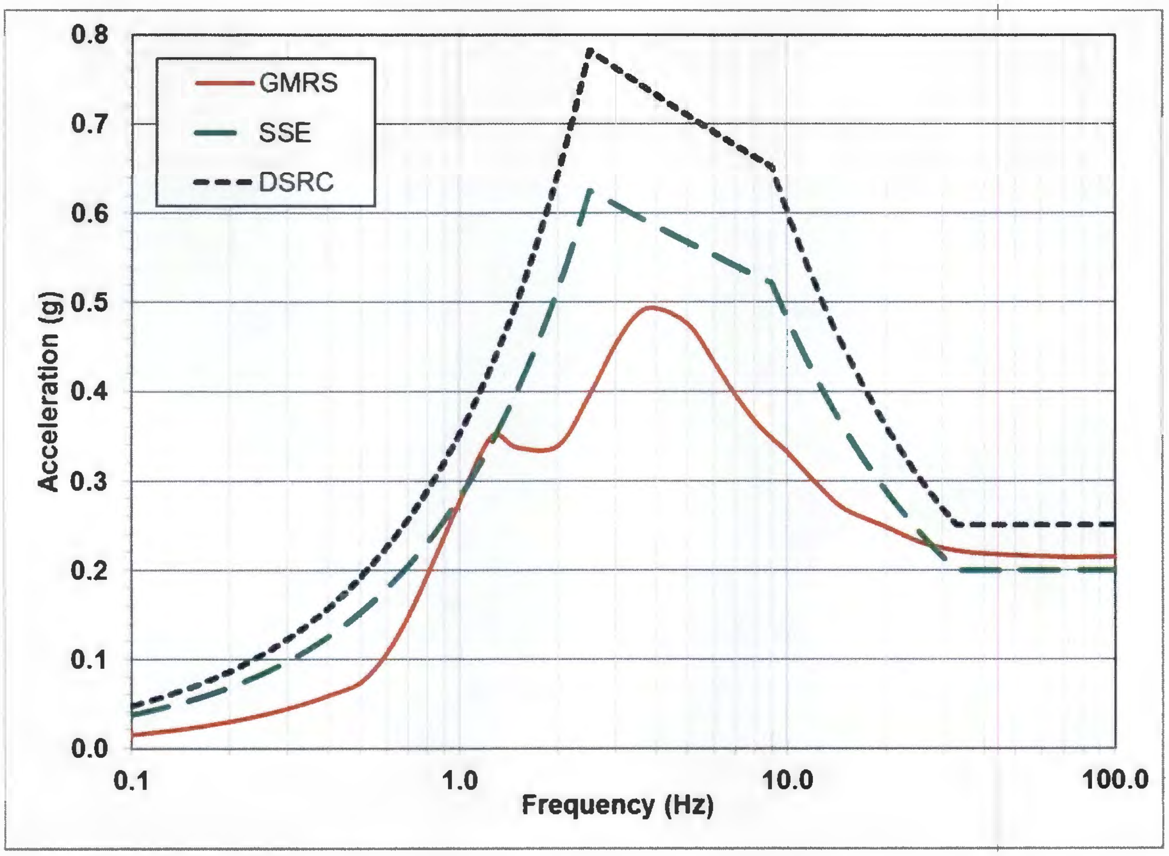

Figure 3.5.1-1. Ground Motion Response Spectrum (GMRS) and Design Spectral Response Curve (DSRC) from SHSR (Cadogan, 2015a). Safe Shutdown Earthquake (SSE) from UFSAR (APS, 2013).

As such, the NRC staff concludes that no further responses or regulatory actions associated with Phase 2 of Near-Term Task Force (NTTF) Recommendation 2.1 "Seismic" are needed for PVNGS. This closes out the NRC's efforts associated with Phase 1 and 2 of NTTF Recommendation 2.1 "Seismic" (CAC Nos. MF5277, MF5278 and MF5279) for PVNGS.

If you have any questions, please contact me at (301) 415-1617 or at Frankie.Vega@nrc.gov.

Sincerely,

/RA/

Frankie Vega, Project Manager
Hazards Management Branch
Japan Lessons-Learned Division
Office of Nuclear Reactor Regulation

Docket Nos. 50-528, 50-529, AND 50-530

Enclosure:
Staff Assessment of Seismic
Hazard Evaluation and Screening Report for PVNGS

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