`UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

November 04, 2016

Mr. Mark E. Reddemann
Chief Executive Officer
Energy Northwest
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P.O. Box 968
Richland, WA 99352

SUBJECT: COLUMBIA GENERATING STATION - 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 (CAC NO. MF5274)

Dear Mr. Reddemann:

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 12, 2015, Energy Northwest (EN, the licensee), responded to this request for Columbia Generating Station (Columbia).

The NRC staff has reviewed the information provided related to the reevaluated seismic hazard for Columbia and, as documented in the enclosed staff assessment, determined that the licensee provided sufficient information in response to Requested Information Items (1) – (3), (5) - (7) and the comparison portion to Item (4), identified in Enclosure 1 of the 50.54(f) letter. Further, the NRC staff concludes that the licensee's reevaluated seismic hazard is suitable for other actions associated with Near-Term Task Force Recommendation 2.1, "Seismic".

Contingent upon the NRC's review and acceptance of EN's seismic risk evaluation, including the high frequency confirmation and spent fuel pool evaluation (i.e., Items 4, 8 and 9) for Columbia, the Seismic Hazard Evaluation identified in Enclosure 1 of the 50.54(f) letter will be completed.

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 No. 50-397

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

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STAFF ASSESSMENT BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO SEISMIC HAZARD AND SCREENING REPORT

COLUMBIA GENERATING STATION

DOCKET NO. 50-397

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, 2011b).[1] In particular, the NRC Near-Term Task Force (NTTF) Recommendation 2.1, and subsequent staff requirements memoranda (SRMs) associated with Commission Papers SECY 11–0124 (NRC, 2011c) and SECY–11–0137 (NRC, 2011d), 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 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 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),

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[1] Issued as an enclosure to Commission Paper SECY-11-0093 (NRC, 2011a).

(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 described in the 50.54(f) letter, if the reevaluated 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 (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, or 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 structures, systems, and components reflect appropriate consideration of the most severe natural phenomena that had been historically reported for the site and surrounding area. The design bases are also to reflect 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, the 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 12, 2015 (Swank, 2015a), Energy Northwest (EN, the licensee) provided its SHSR for the Columbia Generating Station (CGS, Columbia) site. The licensee’s SHSR concluded that the site GMRS exceeds the SSE for the CGS site within the frequency range of 1 Hertz (Hz) to 10 Hz. Therefore, the licensee will perform a risk evaluation, as well as a SFP evaluation. Further, the licensee indicated that it will perform a high frequency confirmation, because the GMRS also exceeds the SSE above 10 Hz.

On May 13, 2015 (NRC, 2015a), and October 27, 2015 (NRC, 2015b), the NRC staff issued letters providing the outcome of its screening and prioritization evaluation for WUS plants. As indicated in the letters, the NRC staff confirmed the licensee's screening results and CGS is expected to conduct a seismic risk evaluation that will be submitted to NRC by March 31, 2019.

On August 18, 2015, the NRC staff requested additional information and clarification on certain elements of the SHSR submittal (NRC, 2015c; 2015d). The licensee provided its response on September 24, 2015 (Swank, 2015b). This additional information is also included in the NRC staff's review of the licensee's SHSR submittal.

3.0 TECHNICAL EVALUATION

The NRC staff evaluated the licensee's submittal to determine if the provided information responded appropriately to Enclosure 1 of the 50.54(f) letter with respect to characterizing the re-evaluated seismic hazard. In addition to an evaluation of the technical information, the NRC staff also determined if the process used to develop the reevaluated seismic hazard was acceptable and consistent with applicable guidance.

3.0.1 Summary of Regional Geology

The CGS site is located east of the Cascade Range in southeastern Washington within the back-arc of the Cascadia Subduction Zone. The Cascadia back-arc developed about 40 million years ago (Ma) in response to subduction of the Juan de Fuca plate beneath northern California, western Oregon, and western Washington. About 18 Ma, continental flood basalts (the Columbia River Basalts, or CRB) erupted in the Pacific Northwest covering about 210,000 kilometer (km)2 of eastern Washington, western Idaho, and northern Nevada (e.g., Reidel et al., 2013). At the CGS site, the CRB ranges in thickness from 2–3 km and comprises four major units, the Saddle Mountain Basalt (6.0–14.5 Ma), Wanapum Basalt (14.5–15.6 Ma), Grande Ronde Basalt (15.6–16.5 Ma), and Imnaha Basalt (16.5–17.5 Ma). Some of the CRB units are massive, indicating formation through rapid or continuous eruptions. However, many CRB units also contain interbeds of fluvial and lacustrine sediments that were deposited onto weathered tops of the lava flows. This CRB-sediment sequence is capped by several hundred meters of alluvium and colluvium that were deposited in sub-basins within the Columbia Plateau.

The CRB erupted onto highly eroded basement rocks, which consist of a series of late Paleozoic and Mesozoic accreted terranes that compose much of western North America. In the vicinity of the CGS, these older rocks form a section about 4 km thick, with crystalline basement encountered at depths ranging from 7.5–9.0 km.

3.0.2 Summary of Local Geology

Folding and faulting due to tectonic deformation is a characteristic of the CGS site vicinity. The CRB lavas and interbedded strata are deformed by a series of generally east-trending, north-verging asymmetric anticlines that were formed by reverse faults. With a few exceptions, the north-verging folds have short, steep, north-dipping fore limbs and broad, shallow, south-dipping back limbs. This folded and faulted terrane is known collectively as the Yakima Fold and Thrust

Belt (YFTB). Deformation of the YFTB extends beyond the Columbia Plateau, and north-south shortening (i.e., compression) is observed to fan westward across the Cascade Range. Geodetic indicators, including Global Positioning System (GPS) measurements, confirm that north-south compressional stresses continue to control tectonic deformation of the YFTB. Seismicity around the CGS site is dominated by small-magnitude reverse and strike-slip earthquakes that occur within the upper 3 km of the CRB, with more diffuse seismicity extending to depths of about 20 km.

Much of the Columbia Plateau in eastern Washington was extensively eroded by the cataclysmic Missoula Floods, which occurred about 14,000 to 30,000 years ago. At the CGS site, the Missoula Floods removed about half of the sedimentary deposits that overlie the CRB. Throughout the Columbia Plateau, the Missoula Floods removed much of the relatively young geologic deposits, which are normally relied on by paleo seismologists to develop estimates of fault slip-rate.

3.0.3 Senior Seismic Hazards Analysis Committee Approach

Consistent with current NRC guidance, the licensee used a SSHAC Level 3 study to develop the SSC and GMC models for the Hanford site (PNNL, 2014). The Hanford SSHAC was conducted as part of the sitewide PSHA of the U.S. Department of Energy's (DOE) Hanford Site in southeastern Washington State, which includes the CGS site. Although the Hanford SSHAC applies to all of the DOE facilities and the CGS on the Hanford site, the focus of the NRC staff's review in this staff assessment is on information relevant to the CGS site.

The SSHAC process was developed as a formal approach that uses expert judgment to evaluate uncertainties in a PSHA for nuclear power plants (Budnitz et al., 1997). The process allows for the consideration of the complete set of seismological, geological, and geophysical data, models, and methods that exists within the larger technical community, which are relevant to the seismic hazard analysis. In the SSHAC process, technical experts evaluate and integrate available data, models, and methods into the PSHA to ensure that the hazard results capture the center, body, and range of technically defensible interpretations (i.e., consider the range of diverse technical interpretations from the larger technical community) (NRC, 2012c).

Site-specific hazard curves and associated seismic engineering inputs (e.g., GMRS or design spectra) are derived from three component studies: 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 (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 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. Section 3.1 of this staff assessment evaluates the SSC, and the GMC is evaluated in Section 3.2. The PSHA is reviewed in Section 3.3. Site response, which is not developed using the SSHAC process, is evaluated in Section 3.4 of this staff assessment.

As requested in NRC (2012a), the licensee conducted a Level 3 SSHAC study for the SSC and GMC using the guidance in NUREG/CR-6372 (Budnitz et al., 1997) and NUREG-2117 (NRC, 2012c). The licensee and the DOE served as project sponsors for the SSHAC, and identified a project technical integrator who was the technical lead for the SSC and GMC. Technical integration teams (TI Teams) assisted the project technical integrator by developing and documenting the SSC and GMC models. The TI Team members served as both evaluator and integrator experts during the SSHAC process.

The SSHAC studies for both the SSC and GMC followed the same general process. The TI Team developed a project plan and began development of a project database. They then 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, which included NRC staff, also attended the workshops, along with Participatory Peer Review Panel (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 in a final project report (PNNL, 2014).

An important part of a Level 3 SSHAC process is a PPRP, which provides peer review and feedback to the TI Teams throughout the evaluation. The PPRP attended workshops and working meetings, reviewed work products, and provided input to the TI Teams throughout SSC and GMC development. The PPRP also provided a formal review of the resulting hazard study (Appendix B, PNNL, 2014). In addition, the project management team at Pacific Northwest National Laboratory (PNNL) developed an electronic library of workshop materials for SSHAC participants, which included workshop summaries, presentations, references, and data.

Additional details on the SSHAC process are discussed and evaluated in the following sections, in the context of technical topics for SSC and GMC development. In each subject area, the reviews identify the most significant technical issues for the PSHA, and discuss how the NRC staff evaluated these issues during the review.

3.1 Seismic Source Characterization

The SSC for the CGS site represents the first stage of a PSHA. The goal is to develop a SSC model for the PSHA based on evaluation of available geological, geophysical, and seismological information. For the SSC, the TI Team considered three types of seismic sources: faults, areal source-zones, and the Cascadia subduction zone. Input parameters to the SSC model for these seismic sources were derived by the TI Team from (1) earthquake records, based on the instrumented and historical seismicity catalogued for the region; (2) geologic evidence of the magnitude, age, and frequency of past seismic events; and (3) geophysical evidence for crustal strain based on GPS measurements.

3.1.1 Assessments of the SSHAC Process for SSC

To develop the SSC for the Hanford site, the TI Team compiled existing information from plant licensing documents, DOE reports for the Hanford site, USGS reports, and published technical information. This compilation helped focus SSHAC Workshop 1 (held July 23–27, 2012) on identifying data needs, which were identified by presentations from resource experts on characteristics (e.g., faults) to be considered in the SSC model. As a result of SSHAC Workshop 1, the TI Team identified the YFTB faults closest to the Hanford site as having the largest potential hazard significance at the Hanford site. Based on the discussions during Workshop 1, the TI Team recognized the need to conduct additional studies to improve the characterization of fault geometries in the subsurface and to develop information on Quaternary (i.e., less than 2.6 Ma) deformation and slip rates of the YFTB faults. Following SSHAC Workshop 1, the TI Team conducted new studies on Quaternary geologic features and high-resolution seismicity relocation analyses.

The SSHAC Workshop 2 (held on December 3–8, 2012), focused on developing models and associated data that were most significant to seismic hazards at the Hanford site. For SSHAC Workshop 2, the TI Team solicited multiple experts for data and model information, including information about data gaps and alternative interpretations to the available information, from which several technical challenges emerged regarding development of SSC models for the PSHA. Key technical challenges included (1) incorporating the full range of defensible conceptual tectonic models into the PSHA; (2) considering implications of the tectonic models in framing the bounds for, and setting fault parameters in, the SSC model; and (3) accurately assessing maximum magnitudes with consideration for the magnitude distribution function and recurrence models in light of data uncertainties and recent scientific studies.

At SSHAC Workshop 3 (held November 11–15, 2013), the TI Team presented the preliminary SSC model with an emphasis on obtaining feedback from the PPRP. The TI Team described the technical bases for the models to allow for a reasoned discussion of the constraints interpreted from the available data. The main topics of discussion for the SSC model focused on the tectonic environment, seismic sources, earthquake catalog, and recurrence models. Much of the interaction between the PPRP and TI Team centered on the basis for developing SSC logic trees and associated weighting schemes, including consideration of alternative models and data uncertainties. The PPRP also used the hazard sensitivity analyses to focus the TI Team's attention on further refining data and models that had the greatest potential contribution to the resulting PSHA at the Hanford site.

STAFF EVALUATION

Based on observations made during the SSHAC workshops and review of the SSHAC documentation, the NRC staff determined that the licensee conducted the SSHAC workshops in a manner that is consistent with applicable NRC guidance. In addition, the NRC staff did not find significant departures from the guidance in the approach used by the TI Team to develop the SSC model. Due to the potential for anchoring to previous models, the TI Team addressed the potential for cognitive bias during each workshop. The PPRP also discussed sensitivity to cognitive bias as part of the SSHAC process and addressed this in their review. An important component of the SSHAC process is complete documentation. Based on its review, the NRC

staff concludes that the SSHAC documentation (PNNL, 2014) provides an acceptably complete record of the approach used to develop the SSC model. Based on observations made during the SSHAC workshops and review of the SSHAC documentation, the NRC staff also concludes that a reasonable range of resource and proponent experts were engaged in the SSHAC workshops, and that a broad range of alternative data and models were considered. The NRC staff used these observations and their knowledge of the geology and seismology of the Hanford site region to conclude that the TI Team took appropriate steps to ensure that the resulting SSC model captures the center, body, and range of the 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 the SSC model development, the NRC staff reviewed the PPRP and TI Team correspondence, including comment and response logs, and observed workshop interactions. The NRC staff 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. The NRC staff also observed that a PPRP member participated in the Hanford geology field trip, which further demonstrated the PPRP engagement with the TI Team on technical issues. The NRC staff 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 NRC staff's review of SSHAC documentation, observations made at SSHAC workshops, and knowledge of the geological and seismological characteristics of the Hanford region, the NRC staff concludes that the licensee acceptably implemented a SSHAC Level 3 process to develop the SSC model.

3.1.2 Seismicity Catalog

Chapter 6 of the PNNL report (PNNL, 2014) describes the process the TI Team used to develop earthquake catalogs for seismicity associated with both local crustal sources and distant sources in the Cascadia subduction zone. The TI Team compiled earthquake information from both historical and instrumental records that spanned the timeframe from November 1866 to April 2013. These records included regional and continental-scale earthquake catalogs, scientific literature, and pre-existing earthquake catalog compilations (e.g., Jack Benjamin & Associates (JBA) et al., 2012; Geomatrix, 1995). The TI Team combined the information from these sources and developed two catalogs, one for the distant Cascadia subduction zone and one for the continental crust beneath the CGS site region. The process of compiling the two earthquake catalogs used by the TI Team was similar to the process described in NRC (2012b) for the central and eastern United States.

The majority of the earthquake records used by the TI Team were obtained from the Hanford, Pacific Northwest Seismic Network, or United States Geological Survey (USGS) Advanced National Seismic System (ANSS) catalogs, which recorded earthquakes magnitudes in either duration magnitude (M_D) or coda magnitude (M_C). The TI Team converted magnitudes to a uniform moment magnitude (**M**) using the methodology recommended in NRC (2012b). To identify independent events and remove aftershocks and duplicate events from their catalogs,

the TI Team used four declustering techniques (Gardner and Knopoff 1974; Grünthal 1985; Uhrhammer 1986; EPRI, 1988). In addition, the TI Team used two approaches to assess catalog completeness: the Stepp Method (Stepp, 1972) and a probability of detection methodology by Veneziano and Van Dyck (1985).

STAFF EVALUATION

Based on observations at the SSHAC workshop meetings and general knowledge of seismology in the Hanford region, the NRC staff concludes that the TI Team adequately developed the two earthquake catalogs. The staff determined that the TI Team conducted their assessment using appropriate regional and site-specific earthquake records, and developed these composite earthquake catalogs consistent with the methods described in NRC (2012b). In addition, the TI Team's use of NRC (2012b) methods is appropriate because these methods were specifically designed to construct composite records of past earthquakes that can be used to derive the input recurrence parameters needed for seismic sources in a PSHA logic tree.

To review the completeness of the Hanford earthquake catalogs, the NRC staff developed an earthquake catalog from data in the USGS ANSS earthquake catalog covering the time period from January 1700 to May 2015. This catalog contains both local crustal earthquakes and Cascadia subduction zone earthquakes. Through comparison to this catalog, the staff confirmed that the magnitude of completeness and magnitude-recurrence relationships were reasonable in the Hanford earthquake catalogs. Although some additional earthquakes occurred between April 2013 and May 2015, the NRC staff determined that these additional earthquakes are small magnitude events and located far from the Hanford site. The NRC staff concludes that incorporating these additional earthquakes into the Hanford catalog would not significantly affect the PSHA calculations.

To confirm that the earthquake declustering analysis was reasonable, the NRC staff obtained the TI Team's unprocessed earthquake catalog for local crustal sources as it existed prior to the declustering analysis. The NRC staff performed a confirmatory declustering analysis on the Hanford local sources catalog using the Gardner and Knopoff (1974) declustering algorithm, which also was one of the methods used by the TI Team. Figure 3.1-1 of this staff assessment shows the locations of the independent earthquakes and Figure 3.1-2 shows the locations of the dependent earthquakes (e.g., aftershocks and foreshocks). Using these analyses, the staff determined there are 531 dependent earthquakes out of 2,384 total earthquakes in the catalog. This result is reasonably similar to the 523 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, based on the NRC staff's confirmatory analysis and review of the TI Team's methodology described in Chapter 6 of the PNNL Report (PNNL, 2014), the NRC staff concludes that the TI Team developed acceptably complete earthquake catalogs for the region surrounding the Hanford site, which are appropriate for use in developing recurrence and magnitude parameters used to populate the PSHA logic tree. Therefore, the NRC staff concludes that the earthquake catalog is acceptable for use in the SSC model and resulting PSHA.

3.1.3 Fault Sources

The TI Team identified twenty Quaternary fault sources as having the potential to contribute to the seismic hazard at the Hanford site. Nineteen of these are part of the YFTB faults (Figure 3.1-3 of this staff assessment). The 20th is the Seattle fault, which is located more than 200 km west of the Hanford site in the Puget Lowlands. It is a well-characterized Quaternary fault and is assessed as having the highest slip rate of all the faults in the Puget Lowlands (JBA et al., 2012). Sensitivity analyses conducted by the TI Team showed that the Seattle fault does not contribute significantly to the hazard because it is so distant from the site. The TI Team included the Seattle fault in their analysis, using the characterization from JBA et al. (2012), to document the limited contribution these Puget Lowland faults make to the hazard and to justify their decision to exclude the other faults from the Puget Lowlands from the Hanford PSHA.

The TI Team based its assessments of seismic potential of the faults on presence of: (1) geologic evidence for active deformation within the contemporary tectonic regime; (2) evidence that the fault could produce an earthquake with **M**>5; and (3) information indicating that the fault generated seismicity above the rate calculated for the areal seismic sources. The TI Team assumed that evidence of active deformation of Quaternary geomorphic surfaces and deposits or evidence for deformation of CRB lavas were sufficient to indicate the potential for continued seismicity within the contemporary tectonic stress regime. These criteria were used to differentiate the 19 YFTB faults included in the SSC model from all other mapped faults in the YFTB.

The SSC model for fault sources is based on constructing a logic tree for each fault source, which is a standard method to account for a fault source parameters and associated uncertainties in seismic hazard calculations. Nodes of the logic tree account for faulting characteristics such as the three-dimensional fault geometry (including fault segments), style of faulting (i.e., reverse, oblique, and strike-slip), slip rate for each fault segment, characteristic magnitude (M_{CHAR}) and maximum magnitude (M_{MAX}) for each fault segment, and earthquake recurrence for each fault source. Branches at each of these nodes account for the epistemic uncertainties associated with alternative interpretations or statistical distributions of these fault parameters.

An important consideration in the characterization of these fault sources in the YFTB is the nature of the faults in the subsurface. Two alternative geologic models have been proposed within the geologic literature to explain the observed deformation of YFTB (e.g., Zachariasen et al. 2006; Chamness et al., 2012). The most widely accepted interpretation is the thick-skinned model, in which the reverse and thrust faults of the YFTB are considered to extend as single fault planes from the surface all the way to the base of the seismogenic crust (below this depth, the seismologists consider the crust is too ductile for earthquakes to occur). The alternative interpretation is the thin-skinned model, in which the YFTB faults gradually become sub-horizontal at an intermediate depth and terminate within one or more horizontal detachments at the base of the CRB or within other weak zones lower down in the crust. Other unseen faults may exist deeper in the crust beneath the detachments, but these faults are only partially coupled (or completely uncoupled) from the faults observed at the surface. Some earlier PSHAs for the Hanford region (Geomatrix, 1996; JBA et al., 2012) included both thin- and thick-skinned fault models, with model weights justified by interpretations of research available at

those times. For the Hanford PSHA, the TI Team evaluated the latest technical information and reached the conclusion that a thin-skinned model was not justified for the seismogenic sources under consideration. As discussed in Subsection 3.1.3.3 of this staff assessment, the TI Team based the YFTB characteristics exclusively on the thick-skinned model and did not consider the thin-skinned model as credible.

The NRC staff's review of the fault sources is organized into four subsections based on the overall framework of the SSC logic tree: (1) three-dimensional fault geometries and faulting styles; (2) fault slip; (3) slip rates; and (4) $M_{CHAR,}$ $M_{MAX,}$ and earthquake recurrence. The NRC staff assessment evaluates the potential implications of the TI Team's exclusion of the thin-skinned model in favor of the thick-skinned model based on a confirmatory analysis using the staff's PSHA model. The details of the NRC staff's PSHA confirmatory model is discussed in Section 3.3.3 of this staff assessment.

3.1.3.1 Fault Source Geometries

The geometric parameters of fault sources are important because they form the basis from which the TI Team derived fault-slip, slip rate, and the M_{CHAR} and M_{MAX} for each fault source. Fault lengths (i.e., surface trace lengths of the fault) were derived by the TI Team from the topographic expressions of the associated YFTB folds. The TI Team derived the down-dip width (i.e., measured extent of the fault plane from the surface to the base of the seismogenic crust) based on variations in fault dip and three different interpretations of the depth to the base of the seismogenic crust (13 km, 16 km, and 20 km deep). The TI Team associated deeper seismogenic thickness values with steeper fault dips (i.e., Figure 8.75 of PNNL, 2014) and calculated a range of dips for each fault source using a range of possible geometrical relationships that were consistent with the observed features of the resulting YFTB folds, especially the medial extent of the back limb on the surface fold.

The TI Team assessed the style of faulting for each fault source using fault-specific geologic evidence and regional geological and geophysical data, and by considering the tectonic stress regime and other strain indicators. Based on these results, the TI Team determined that the dominant faulting style is reverse, although some of the fault segments include components of both strike-slip and reverse faulting (designated as oblique slip). The SSC model fault tree includes branches for each fault segment that incorporates the detailed assessment of faulting style. Four of the nineteen YFTB faults were identified as strike-slip (Arlington, Luna Butte, Laurel, and Maupin faults). All four were characterized by the TI Team as northwest trending strike-slip or wrench faults. The TI Team considered two alternative models for these faults. One model assumes that the faults are independent reactivated basement faults, and thus are seismogenic. The second model assumes the faults are tear faults or secondary features associated with deformation of the folds, and thus nonseismogenic. Both models were included in the SSC model, but the nonseismogenic model [weight of 0.6] was favored slightly by the TI Team.

STAFF EVALUATION

Based on a review of the PNNL report (PNNL, 2014), observations at SSHAC workshop meetings and general knowledge of geology in the Hanford region, the NRC staff concludes that

the TI Team adequately defined the fault source geometries. The NRC staff confirmed that the fault lengths in the SSC model were appropriate by comparing the length of these fault traces to fault lengths in the USGS Quaternary Fault and Fold Database for the United States (USGS, 2006) and topographic indicators. As shown in Figure 3.1-3 of this staff assessment, the NRC staff used geographic information system (GIS) software to create an independent fault-trace map. The NRC staff also used the GIS to create a simplified version of the CGS fault-trace geometry for use in other confirmatory calculations (Figure 3.1-3 of this assessment). The simplified fault lengths used in the NRC staff's calculations were similar to the lengths specified in (PNNL, 2014). The NRC staff determines that the range of values for the depth of faulting used by the TI Team (i.e., 13 km, 16 km, and 20 km) is appropriate and supported by the earthquake depths in the high-resolution hypocenter relocation analyses (Appendix F, PNNL, 2014).

The NRC staff evaluated the fault widths developed by the TI Team and finds them to be acceptable. The range in fault widths is consistent with the various interpretations of fault dip at the surface and the extent of the faults in the subsurface based on the TI Team's three assumed thicknesses of the seismogenic crust. For example, the NRC staff extracted topographic profiles across the Saddle Mountain fault (Figure 3.1-3 of this assessment) and obtained maximum fault-width measurements similar to those proposed by the TI Team.

The NRC staff also evaluated the style of faulting by reviewing the information in the PNNL report (PNNL, 2014), prior PSHA studies (e.g., JBA et al., 2012), and the scientific literature (e.g., McCaffrey et al., 2007). The NRC staff compared the faulting styles with those reported in the USGS Quaternary fault and fold database for the United States (USGS, 2006). Based on this review, the NRC staff concludes that the TI Team adequately characterized the style of faulting for the faults included in the SSC model. The NRC staff also concludes that the geologic evidence cited in (PNNL, 2014) describing the four northwest-trending strike-slip faults as wrench faults or as tear faults that accommodate differential motion associated with folding is consistent with similar features observed in many fold and thrust belts worldwide (e.g., Rich, 1934; Mitra, 1988) and that the uncertainty in the nature and seismic potential of these faults is properly accounted for in the SSC model.

In summary, based on the result of the confirmatory analyses and review of applicable information, the NRC staff concludes that the licensee acceptably characterized the fault source geometries and faulting styles in the SSC model.

3.1.3.2 Fault Slip

The TI Team determined the fault slip for each of the 19 YFTB fault sources using a simple trigonometric relationship that relates net fault slip to the vertical component of fault offset, fault dip, and the relative proportion of dip-slip motion on the fault to total fault slip considering the potential for strike-slip or oblique-slip motion.

To determine the vertical component of fault offset, the TI Team first measured the topographic relief across the crests of the fault-cored folds. For these measurements, the TI Team anchored the ends of the topographic profiles within a common stratigraphic horizon in the CRB. The TI Team determined through field investigations that there was minimal erosion of the folded

basalts, and thus, that the measured topographic relief effectively quantifies the structural relief of the folds produced by faulting. Using this approach, the TI Team quantified the vertical component of total fault slip that occurred since the fault became active between 6–10 Ma, not the amount of fault slip that has occurred only in the Quaternary. The sole exception to this analysis approach was at Rattlesnake Mountain, where the TI Team was able to measure the vertical offset of Quaternary-aged material that was offset by the Rattlesnake Mountain fault.

To determine fault dip in the subsurface, the TI Team assumed a simple kinematic model that relates fault dip to the three-dimensional geometry of the folds at the surface. In this kinematic model, the folds observed at the surface developed in the hanging wall of a blind or emergent reverse fault. These faults are assumed to extend as planar surfaces to the base of the seismogenic crust. The model also assumes that the medial extent of the fold's back limb is related to fault dip, in which broad back-limbs indicate shallow-dipping reverse faults and narrow back limbs indicate steep-dipping reverse faults. In this model, the TI Team also interpreted the reverse faults to intersect the base of the seismogenic crust along a line parallel to and directly beneath the hinge of the back limb fold (i.e., the inflection point where the basalt beds are essentially horizontal). Because the TI Team derived three alterative interpretations for the thickness of the seismogenic crust (13 km, 16 km, and 20 km deep), its approach resulted in three different fault dips for each YFTB fault. Thus, in the TI Team's approach, the 16 km and 20 km depths of the seismogenic crust yield progressively steeper fault dips compared to a 13 km depth (see Figure 8.75 of PNNL, 2014). The TI Team then added additional epistemic uncertainty to the analysis by including varied interpretations of the location of the back limb syncline hinge relative to the fault (see Figure 8.77 of PNNL, 2014).

Because several of the YFTB fault sources include segments with strike-slip or oblique motion, the TI Team also multiplied the amount of dip slip by a net-slip factor. For pure reverse motion, this net slip factor was 1.0. For oblique slip, this net slip factor was 1.4. For strike-slip motion, this factor was either 2.2 [0.5] or 5.0 [0.5]. According to the TI Team, these net-slip factors are based on the components of lateral to dip slip that are commonly used in seismic hazard analyses to account for the relative contributions of reverse, oblique, and strike-slip faulting.

STAFF EVALUATION

Based on a review of the PNNL report (PNNL, 2014), observations at SSHAC workshop meetings and the field trip, and general knowledge of geology in the Hanford region, the NRC staff concludes that the TI Team's approach to develop vertical fault offsets based on the use of topographic relief as a proxy for structural relief is appropriate. In Figures 8.69 and 8.70 of the PNNL report (PNNL, 2014), the TI Team identified several CRB stratigraphic horizons from well log data for boreholes drilled on both the hanging wall and footwall sides of the Saddle Mountain fault. The NRC staff review found that the CRB stratigraphy is preserved across the Saddle Mountain anticline, and thus, the staff concludes that the TI Team's approach in using topographic relief of this fold to quantify the vertical component of fault offset is acceptable.

The NRC staff confirmed the use of topographic relief as a proxy for structural relief based on the information provided in Figures 8.69 and 8.70 of the PNNL report (PNNL, 2014).

Because the TI Team developed only a thick-skin faulting model, in which the fault surfaces were extended to the base of the seismogenic crust as fault planes, the NRC staff's review focused on the technical bases for the thick-skin model and the hazard implications for excluding alternative subsurface fault geometries, like those that would arise from a thin-skinned interpretation. In Question 2 of the letter dated August 18, 2015 (NRC, 2015c), the NRC staff asked the licensee to provide additional information relating the subsurface geometry of faults in the YFTB to their surficial topographic expression. In the response dated September 24, 2015 (Swank, 2015b), the TI Team explained that the surficial topographic expression of fault-generated folds was based on an elastic dislocation model for moderate-to-steeply dipping faults in the Syrian Arc fold belt in Israel (WLA, 2000; Figure 8.76, PNNL, 2014). This study was conducted as part of the site characterization for the Shivta nuclear power plant in Israel. According to the TI Team response, this study also used net slip values estimated from topographic relief to adequately reproduce the observed regional topography. After reviewing the WLA (2000) report, the NRC staff determined that the TI Team had provided sufficient information to justify use of the elastic dislocation model to interpret subsurface fault geometries, and that the TI Team's thick-skinned, elastic-dislocation model was a reasonable interpretation of the kinematics that created the YFTB.

However, to confirm that the TI Team's faulting model adequately captures the appropriate range of uncertainty, the NRC staff conducted two confirmatory calculations based on alterative interpretations of the subsurface geometry of faults in the YFTB. The goal of these confirmatory studies was to evaluate whether the range of epistemic uncertainty included in the TI Team's SSC was sufficient to ensure that the resulting hazard captured the center, body, and range of technically defensible interpretations.

In the first alternative, the NRC staff used Coulomb elastic dislocation modeling software (Lin and Stein, 2004; Toda et al., 2005) to calculate the expected topographic relief of Saddle Mountain based on the TI Team's fault slip values for the Saddle Mountain fault, as given in Appendix D of PNNL (2014). Results of this calculation showed that the Coulomb elastic dislocation model's calculated topographic relief of Saddle Mountain is less than the observed topographic relief (Figure 3.1-4a of this staff assessment). To reproduce the topography of Saddle Mountain using the Coulomb dislocation model the NRC staff had to increase the amount of slip by 30 to 50 percent (Figure 3.1-4b of this staff assessment). The NRC staff recognizes that its elastic dislocation model does not account for elastoplastic deformation and, therefore, is a simplified representation of the topographic relief produced by fault slip. Nevertheless, results from the staff's Coulomb elastic dislocation modeling suggest that the ranges of these faulting parameters (e.g., fault dip or fault slip) in the SSC model (PNNL, 2014) may be too narrow.

To evaluate the significance of these modeling results on the PSHA, the staff conducted a sensitivity analysis using the PSHA confirmatory model that is discussed in Section 3.3.3 of this staff assessment. In this sensitivity analysis, the staff modified the faulting parameters for Yakima Ridge, Umtanum Ridge, Rattlesnake Mountain, and Saddle Mountain fault sources (Figure 3.1-3 of this staff assessment) to calculate the effect on baserock hazard at the CGS

site. The staff's sensitivity analysis shows that these parameter changes to the YFTB faults did not significantly affect the PSHA at 1 Hz and 10 Hz for 10^{-4} and 10^{-5} annual exceedance frequencies. Therefore, the NRC staff concludes that the current epistemic uncertainty in the TI Team's model is acceptable.

In the second alternative, the NRC staff evaluated the potential significance of including the thin-skinned fault model in the SSC model using similar weights to the thick-skinned and thin-skinned models that were applied in a recent SSC model for the Hanford site (i.e., JBA et al, 2012). For this evaluation, the staff conducted a confirmatory analysis using the staff's PSHA model that is discussed in Section 3.3.3 of this staff assessment. The NRC staff calculated the fault areas for the YFTB faults using the dip angles from (PNNL, 2014) for 8 km depths representing a thin-skinned model, and 16 km depths for a thick-skinned model, and incorporated these alternatives into the logic tree. The staff's sensitivity analyses showed that including the thin-skinned model into the SSC with weights similar to those applied in JBA et al. (2012) did not significantly affect the PSHA at 1 Hz and 10 Hz for 10^{-4} and 10^{-5} annual exceedance frequencies. The NRC staff concludes that incorporation of the thin-skinned tectonic model, as was done in (JBA et al., 2012), would therefore not significantly affect the results of the Hanford PSHA.

In summary, based on the result of the NRC staff's confirmatory analyses and review of applicable information, the NRC staff concludes that the licensee acceptably characterized the net slip of the faults sources in the SSC model.

3.1.3.3 Slip Rate

In the SSC model, the TI Team calculated fault slip rates based on the long-term average slip rates (PNNL, 2014). As described in the Section 3.1.3.2, the TI Team determined the net slip for each fault including a range of uncertainty. In the analysis, the TI Team calculated the slip rate for each fault source by dividing the fault's net slip by the geologic age at which the faulting began. As described in the PNNL report (PNNL, 2014), CRB lavas and overlying sediments of the Ringold Formation dip less relative to the dip of the underlying CRB lavas (e.g., an angular unconformity). This difference in bedding dip indicates that deposition of the Ringold Formation occurred after the basalts already started to tilt in response to the growth of the Saddle Mountain Anticline. This stratigraphic relationship was interpreted by the TI Team to indicate that faulting in the YFTB began before deposition of the Ringold Formation. The geologic age of the Ringold Formation is thought to be between 4 and 9 Ma (e.g., Lindsey and Gaylord, 1990). Based on this observation, the TI Team used end-member ages of 6 Ma and 10 Ma to define the onset of YFTB faulting. These two alternatives were given equal weight by the TI Teams in the SSC model and used to develop two sets of fault slip-rates.

At Rattlesnake Mountain, the TI Team identified a broad coalescing alluvial fan (bajada) that is offset by the Rattlesnake Mountain fault. The TI Team estimated the age of the bajada as 425–600 ka, based on thorium/uranium radiogenic analysis of the carbonate rinds on sedimentary clasts and on magnetic polarity of the sediments (Baker et al., 1991). Using this age and measured vertical separation of the bajada, the TI Team determined an average slip rate for the Rattlesnake Mountain fault of 0.05 mm/yr. The TI Team also determined the average long-term slip rate of this fault at 0.06 mm/yr based on the offset CRB lavas. As summarized in the

analyses provided in Appendix E of the PNNL report (PNNL, 2014), the TI Team documented similar agreement in the Quaternary and long-term slip rates for the Manastash and Umtanum faults.

STAFF EVALUATION

The NRC staff reviewed the information in the PNNL report (PNNL, 2014) and observed all SSHAC workshops and determines that the TI Team adequately considered an appropriate range of information associated with characterization of slip rates on the 19 fault sources in the YFTB. The NRC staff also reviewed the conclusions presented in the PPRP's final letter report and notes that the PPRP accepted the TI Team's characterization of fault sources.

On September 17, 2013, the NRC staff accompanied the TI Team on a geologic field trip to gain a better understanding of the geologic data used to assess fault geometry, timing of most recent faulting, and slip rates for individual fault sources. The NRC staff confirmed field observations at the Saddle and Rattlesnake Mountains, as well as other sites used by the TI Team to develop the Quaternary ages based on radiogenic dates and the degree of calcification of carbonate rinds on sedimentary clasts (Paces, 2014). At the Saddle Mountain location, the NRC staff observed fault offset marked by displacement of CRB basalt units and the angular unconformity between the tilted basalts and overlying Ringold Formation.

Based on review of the information provided in the PNNL report (PNNL, 2014) and the observations made during the field trip, staff concludes the TI Team developed appropriate estimates of fault slip for the fault sources in the SSC model. During the course of its review, the NRC staff also reviewed a new geologic publication by Casale and Pratt (Casale and Pratt, 2015), who used seismic reflection data to interpret YFTB faults in the subsurface in terms of a thin-skinned fault model. In their paper, Casale and Pratt (2015) indicated that their model would result in relatively high slip rates on these faults. In a letter dated August 18, 2015 (NRC, 2015c), the NRC staff asked the licensee to discuss the potential significance of any new information in Casale and Pratt (2015) that was not considered in the SSHAC process for the SSC model. In its response (Swank, 2015b), the licensee stated that the TI Team did not consider the thin-skinned fault model of Casale and Pratt (2015) to be technically defensible, based on its evaluation of the structural relationships and timing of fault slip presented in the paper. Although the NRC staff determined that some aspects of Casale and Pratt (2015) were technically defensible, the staff also note that the higher slip rate proposed by Casale and Pratt (2015) is based on an assumed geologic age for the onset of faulting at 3.5 Ma, which is inconsistent with the 6–10 Ma age for the onset of faulting as indicated by the unconformity observed at Saddle Mountain. The NRC staff's independent confirmatory analysis described in Section 3.1.3.2 of this assessment showed that inclusion of the thin-skinned model in the SSC model, in a manner similar to JBA et al. (2012), did not significantly affect the hazard results. Consequently, the NRC staff concludes that the TI Team's exclusion of a thin-skinned model from the SSC model was reasonable.

In summary, based on the result of the NRC staff's confirmatory analyses and review of applicable information, the NRC staff concludes that the licensee acceptably characterized the slip rates of the faults sources in the SSC model.

3.1.3.4 Earthquake Recurrence

The TI Team evaluated two alternative models to assess the recurrence of earthquakes on the fault sources, one based on the slip-rate approach and one based on the recurrence-interval approach. The slip-rate approach combines information about fault slip with the seismic moment rate and M_{CHAR} and M_{MAX} of future earthquakes on the fault source to develop a recurrence relationship. The recurrence-interval approach uses information about the average slip per past earthquake and the average interval between past earthquakes to determine earthquake recurrence. Because the recurrence-interval approach requires a reliable record of paleo-earthquakes from the Quaternary geologic record, the TI Team could only evaluate the potential use of the recurrence interval approach for three fault sources in the YFTB (i.e., Ahtanum-Rattlesnake Hills, Toppenish, and Rattles of the Rattlesnake-Wallula alignment or RAW). However, even for these three sources, the TI Team concluded that the information needed to identify paleo-earthquakes was highly uncertain, such that, for these three sources, it assigned low weights to the recurrence interval approach [0.30-0.05]. As a result, the slip-rate approach was the dominant approach used by the TI Team for all YFTB fault sources in the hazard analysis.

The TI Team considered four alternative magnitude-frequency distributions to define the recurrence relationships for future earthquakes on the YFTB fault sources, the truncated exponential (Gutenberg and Richter, 1956); characteristic (Youngs and Coppersmith, 1985); maximum moment (Wesnousky, 1986); and Wooddell, Abrahamson, Acevedo-Cabrera, and Youngs (WAACY) models (2014). The TI Team analyzed the rate of small earthquakes associated with each of the YFTB faults, and from this comparison, showed that the characteristic model provided the best fit to the earthquake data (see Figure 8.96 of PNNL, 2014). Based on this analysis and analysis of Hecker et al., (Hecker et al., 2013), the TI Team selected the characteristic model. In addition, the TI Team noted that the because the WAACY model was developed to account for large strike-slip faults that could link with nearby strike-slip faults to produce very large magnitude earthquakes, and that the YFTB does not contain such faults, it was not needed to characterized the fault sources.

The characteristic model uses slip rate and an estimate of the magnitude of M_{CHAR} to derive the recurrence curves for each fault source. In this model, M_{MAX} is defined to be 0.25 magnitude units larger than M_{CHAR} and is the largest earthquake that can occur given the area of the fault surface. To determine the magnitude of the M_{CHAR} for the YFTB fault sources, the TI Team relied on four published scaling relationships that relate the rupture length or rupture area to magnitude: Wells and Coppersmith (1994), Wesnousky (2008), Hanks and Bakun (2008), and Stirling et al., (2008). Based on the results of these four scaling relationships and the relative weights assigned them in the logic tree, the TI Team developed probability distributions of the characteristic magnitude for each fault source (see Figure 8.92 of PNNL, 2014).

STAFF ASSESSMENT

The NRC staff reviewed the information in (PNNL, 2014) and observed all SSHAC workshops, and determined that the TI Team adequately considered an appropriate range of information to characterize maximum magnitude earthquakes and develop earthquake recurrence models for the 19 fault sources in the YFTB. The NRC staff agree that the slip rate approach, as

implemented by the TI Team and which is based largely on long-term slip rate estimates from the structural relief of the YFTB folds, is appropriate and that there is insufficient paleoseismic and paleo-earthquake data to apply the recurrence-interval approach. The slip-rate approach is standard practice in seismic hazard analyses for sites without a well-developed earthquake chronology. Moreover, that NRC staff note that both the long-term and Quaternary slip rates for a fault source are similar in the few cases where these comparisons could be made by the TI Team (e.g., Rattlesnake Mountain). This similarity in rates further supports the NRC staff's conclusion that the slip-rate approach is acceptable.

The NRC staff also reviewed the information provided in the PNNL report (PNNL, 2014) supporting the TI Teams adoption of only the characteristic magnitude-frequency distribution. The characteristic model is a well-established option to describe the magnitude-frequency relationship for large and active faults (e.g., Bakun and McEvilly, 1984; Schwartz and Coppersmith, 1984), but this concept is not universally accepted by all researchers (e.g., Parsons and Geist, 2009). The NRC staff recognizes that the TI Team's use of the characteristic model, using the slip-rate and maximum magnitude inputs described in Sections 8.4.3.6 and 8.4.3.8 of the PNNL report (PNNL, 2014), results in magnitude recurrence rates that are higher than the observed rates of earthquake occurrence within the area about each fault (shown in Figure 8.96 of PNNL, 2014). Based on these comparisons, the NRC staff concludes that the characteristic magnitude-frequency distribution was appropriate for use in the PSHA.

To evaluate the TI Team's determination of M_{CHAR}, the NRC staff conduced a confirmatory analysis. In this confirmatory analysis, the NRC staff recomputed the range of fault areas for each fault source in the YFTB based on the maximum fault lengths and the variable interpretations of the subsurface fault geometry. Using these fault lengths and fault areas, the NRC staff then computed M_{CHAR} for each fault source and compared them to the distributions of M_{CHAR} provided in Figure 8.92 of the PNNL report (PNNL, 2014). In all cases, the NRC staff's results compared reasonably to the TI team's results. On the basis of this confirmatory assessment, the NRC staff concludes that the TI Team's determination of M_{CHAR} is adequate.

In summary, based on the result of the NRC staff's confirmatory analyses and review of applicable information, the NRC staff concludes that the licensee acceptably characterized earthquake recurrence for the faults sources in the SSC model.

3.1.4 Areal Source-Zones

To account for potential seismic hazards from unrecognized faults and background seismicity, the TI Team included four areal seismic source zones: Zone B, Zone C, Zone D and the YFTB (inset, Figure 3.1-3 of this staff assessment) in the SSC model. The TI Team developed the boundaries of these areal source zones to account for differences in (1) earthquake recurrence rate; (2) maximum earthquake magnitude (M_{MAX}); and (3) expected future earthquake characteristics (e.g., style of faulting, rupture orientation, and seismogenic thickness). Because of their distance from the Hanford site, the TI Team did not identify and characterize individual faults within Zones B, C, and D; however the YFTB source zone, which includes the Hanford site, encompasses the individual YFTB faults described and evaluated in Section 3.1.3 of this staff assessment. To model the occurrence of future earthquakes within the areal source zones, the TI Team used "virtual faults" that were randomly located within each of the zones.

The earthquakes on these virtual faults are modeled by their style of faulting, three-dimensional rupture geometry, magnitude-dependent rupture dimensions, and recurrence rates and parameters based on the earthquake catalog for each of the zones.

To develop the boundaries of the areal source zones, the TI Team primarily used the source-zone boundaries previously developed in JBA et al. (2012). In particular, the TI Team defined the eastern boundary of the YFTB using deep crustal structures (Figure 8.33, PNNL, 2014) and positioned the western boundary of the YFTB source-zone to include the westernmost topographic expression of the YFTB faults and the boundary with the Cascades tectonic province. The northern boundary of the YFTB was placed by the TI Team to coincide with the deeper crustal boundary identified in McCaffrey et al. (McCaffrey et al., 2007). The TI Team placed the boundary between the YFTB and Zone D in order to encompass a region of lower seismicity rates that occur south of the Columbia Hills within Zone D. The boundary between the YFTB Zone and Zone D was also drawn so that a collection of north-northwest-trending faults remained within the YFTB source zone (Figures 8.28 and 8.33, PNNL, 2014).

The TI Team used both uniform and smoothed seismicity grids to represent the spatial density of earthquake occurrences and the distribution of earthquake recurrence within the areal source zones. Because the TI Team observed that changes in tectonics, geology, and seismicity across source-zone boundaries were not sharply defined, the TI Team used “leaky source-zone boundaries,” which allows ruptures beginning within a source zone to propagate into adjacent source zones. In addition, the TI Team used the truncated exponential (Gutenberg and Richter, 1956) magnitude frequency distribution to define the recurrence relationships for future earthquakes within the areal source zones.

The TI Team used earthquake focal mechanism information, as well as the tectonic environment of the Hanford site region, to define the style of faulting, seismogenic thickness, and orientation of ruptures for each source zone. The TI Team estimated M_{MAX} using the largest observed magnitude earthquake within each source zone, and also by considering M_{MAX} calculated from fault-source dimensions. For example, the 1872 Lake Chelan earthquake (**M**6.5–7.0) was used to define M_{MAX} in Zone B. However, the largest magnitude earthquake recorded for the YFTB source-zone is only **M**4.8, which the TI Team determined was too small to reliably characterize M_{MAX}. Consequently, the TI Team used the lower part of the M_{MAX} distribution that was developed for the YFTB faults (i.e., **M**6.5) to define the M_{MAX} for the YFTB source-zone. The upper part of the M_{MAX} distribution for the YFTB source-zone is smaller (i.e., **M**7) than used for the other source zones (i.e., **M**7.5), because large faults already are considered as separate seismic sources for the YFTB source-zone.

STAFF EVALUATION

Based on its review of the information in the PNNL report (PNNL, 2014), the NRC staff concludes that the TI Team adequately accounted for the potential seismic hazard from unrecognized faults through its development of the four areal source zones in the SSC model. The staff also concludes that the TI Team adequately characterized the uncertainty in the location, magnitude, and recurrence rate of earthquakes within the areal source zones by using randomly located virtual faults and developing a range of maximum magnitudes, faulting styles, rupture geometries, and recurrence parameters.

To evaluate the boundaries for the four source zones, the NRC staff examined seismicity maps of the region surrounding the Hanford site, focusing in particular on seismicity that occurred between April 2013 and June 2015 (subsequent to the data considered by the TI Team) within 320 km of the Hanford site. The staff also considered information in JBA et al. (2012), McCaffrey et al. (2007), and gravity data from Blakely et al. (2013), which relates seismicity patterns to deep crustal structures. Based on its review of the regional seismicity relative to the source-zone boundaries, the staff notes that the western boundaries of Zone B and the YFTB source-zone exclude seismicity associated with volcanic activity in the Cascade Range (Figure 8.42, PNNL, 2014). However, the NRC staff notes that the small-magnitude earthquakes in the Cascade Range are sufficiently distant (beyond 200 km) from the Hanford site such that they would not significantly affect the seismic hazard. In addition, the NRC staff concludes that alterations to the source-zone boundaries, such as expanding Zone C to the east, would only dilute the seismicity rates in the respective source zone. Based on this information, the NRC staff concludes that the source-zone boundaries in the SSC model are reasonable and acceptable for use in the Hanford PSHA.

With respect to the M_{MAX} distribution for the YFTB source zone, the staff concurs with the TI Team's decision to use a lower set of M_{MAX} values, because the larger M_{MAX} values for the fault sources within YFTB are included in the SSC model. Regarding the M_{MAX} distribution for areal source zones B, C, and D, the staff notes that the M_{MAX} distribution is more heavily weighted towards the lower values (**M**6.5 [0.2], **M**6.75 [0.5], **M**7.0 [0.2], **M**7.25 [0.09], and **M**7.5 [0.01]). Based on review of the PNNL report (PNNL, 2014), the NRC staff determined that the TI Team's rationale for this weighting of the M_{MAX} distributions for these four zones was not clear. In particular, the staff notes that source zone B encompasses the location of the 1872 Lake Chelan earthquake, which may have been larger than **M**7. Therefore, in a letter dated August 18, 2015 (NRC, 2015c), the NRC staff asked the licensee to provide additional detail regarding its basis for the lower weights of M_{MAX} values of 7.25 [0.09] and 7.5 [0.01] and, in general, whether this distribution of M_{MAX} adequately captures the potential for large earthquakes in source zone B. The licensee responded to the NRC staff's request in a letter dated September 24, 2015 (Swank, 2015b) providing justification for use of its M_{MAX} distribution for source zone B. In its response, the licensee cited the study of Bakun et al. (2002), which used intensity data from the 1872 Lake Chelan earthquake as well as more recent smaller earthquakes to justify a postulated magnitude range of **M**6.5 to **M**7.0 for this large historical earthquake. Based on this postulated magnitude range, the licensee concluded that its M_{MAX} distribution for source zone B adequately captures the largest historical earthquake within the zone. In addition, the licensee stated that due to the large source-to-site distances (beyond 100 km) and low recurrence rate for earthquakes within source zone B, increasing the weighting for M_{MAX} values of 7.25 and 7.5 relative to lower M_{MAX} values would not increase the hazard at the Hanford site. Based on the uncertainty regarding the magnitude of the 1872 Lake Chelan earthquake and the overall limited impact on the hazard from source zone B at the Hanford site, the staff concludes that revising the weighting of the M_{MAX} values is not necessary.

In summary, based on its review and evaluation of applicable information, including supplemental information in Swank (2015b), the NRC staff concludes that the licensee acceptably developed areal source zones for use in the SSC model.

3.1.5 Cascadia Subduction Zone Sources

Preliminary sensitivity studies conducted by the TI Team showed that earthquakes from the Cascadia Subduction Zone make a moderate contribution to the seismic hazard at the Hanford site for lower frequency (i.e., 1 Hz and below) ground motions. As such, the TI Team included Cascadia Subduction Zone sources in the SSC model. Rather than develop a new SSC model for the Cascadia Subduction Zone, the TI Team used the recently completed SSHAC Level 3 model in BC Hydro (BC Hydro, 2012). The BC Hydro SSC model represents the Cascadia Subduction Zone as two distinct seismogenic sources: (1) an "intraslab source" within the down-going Juan de Fuca plate (i.e., slab), which is modeled as an aerial source-zone; and (2) a "plate interface source" located at the interface between the Juan de Fuca and North America plates, which is modeled as a fault source (Figure 3.1-5 of this staff assessment). After review of BC Hydro SSC model for the Cascadia Subduction Zone with respect to the Hanford site, the TI Team determined that two important components of the model needed to be updated.

For characterization of the intraslab source zone, the TI Team interpreted plate geometry based on the seismic, geophysical, and geodetic data reported by McCrory et al. (McCrory et al., 2006). The TI Team determined that the parameter of primary significance was maximum depth of the plate beneath the Hanford site, which defines the closest approach of the intraslab source-zone to the site. Seismicity data in McCrory et al. (McCrory et al., 2006) indicates the seismogenic plate only extends to depths of approximately 60 km at the latitude of the Hanford site. To allow for the possibility that the seismogenic plate might be deeper at the latitude of the site, the TI Team modified the weighted depth distribution for the intraslab source-zone based on seismicity patterns north and south of this latitude, to: 80 km [0.2]; 90 km [0.2]; and 100 km [0.6], which effectively extends the intraslab source zone closer to the Hanford site.

For the plate interface source, the TI Team determined that the most significant parameter was the location of the easternmost extent of the plate interface, which defines the closest approach of that source to the Hanford site. The TI Team judged that the three alternative locations (i.e., Locations A, B, and C in BC Hydro, 2012) for the landward down-dip extent of the plate interface source were still appropriate. Nevertheless, the TI Team adjusted the weights of the three potential locations used in the BC Hydro model (BC Hydro, 2012), so that the weights are consistent with more recent interpretations that considered earthquakes in the area of non-volcanic episodic tremor and slip.

STAFF EVALUATION

For both the Cascadia intraslab and interface source zones, the NRC staff reviewed the relevant information from the BC Hydro SSC model (BC Hydro, 2012) as well as the PNNL report (PNNL, 2014) in order to evaluate key source characteristics and parameters such as location, geometry, MMAX, and recurrence rates. In particular, the NRC staff focused its review on the TI Team's assessment of the continued relevance of the BC Hydro model for the Hanford site. Based on its review of this information, the NRC staff concludes that the TI Team's use of the BC Hydro model (BC Hydro, 2012) provides a reasonable characterization of the magnitudes, rates, and geometries of the intraslab and interface sources, which is reasonably consistent with published information and interpretations. Therefore, the staff concludes that the Cascadia subduction zone is characterized appropriately for use in the SSC model.

For the intraslab source zone, the NRC staff concurs with the TI Team's focus on the closest approach of the slab to the Hanford site and its decision to update the depth parameters in the SSC model, because these factors affect the seismic hazard significantly. In addition for the plate interface source, the NRC staff concurs with the TI Team's decision to increase the weighting on the easternmost landward extent of the plate interface source, which likewise defines the closest approach of that source to the Hanford site and, thus, is conservative.

To confirm the relatively small contribution of Cascadia Subduction Zone seismicity to the Hanford hazard, the NRC staff performed a simplified, deterministic calculation to evaluate the potential ground motion at the Hanford site from an **M**9.1 earthquake occurring on the plate interface source. The NRC staff used the GMC model in PNNL (2014) for the Cascadia Subduction Zone to calculate 84th percentile response spectra for a **M**9.1 earthquake occurring on the subduction interface, at distances of 325 km and 350 km from the Hanford site. As shown in Figure 3.1-6 of this staff assessment, the calculated 84th percentile response spectra for this large earthquake scenario are significantly lower than both the SSE and operating basis earthquake for CGS. Thus, the deterministic scenarios considered by the NRC staff show that Cascadia Subduction Zone earthquakes would result in acceptably small ground motions at the CGS site.

In summary, the NRC staff concludes that the TI Team adequately considered an appropriate range of information associated with characterization of the Cascadia intraslab source zone and the plate interface source. The NRC staff concludes that the SSC model adequately accounts for potential seismicity related to the Cascadia Subduction Zone in the assessment of seismic hazards at the Hanford site.

3.2 Ground Motion Characterization

The GMC models, developed as part of the Hanford PSHA (PNNL, 2014), characterize median ground motions and their associated aleatory variability (sigma) for both shallow crustal and subduction zone earthquakes. Specifically, the GMC models consist of two suites of ground motion prediction equations (GMPEs) for five percent damped horizontal spectral accelerations for 20 oscillator frequencies between 0.1 Hz and 100 Hz. Due to the limited number of strong ground motion earthquake recordings in the region, the TI Team used existing GMPEs developed from ground motion datasets in more seismically active regions as the "backbone" models for the GMC. Because these GMPEs were developed from extensive ground motion datasets, the TI Team determined they are suitable for characterizing the ground motions for the entire range of magnitudes and distances required by the seismic sources in the Hanford SSC.

In general, past hazard studies have treated eastern Washington as an active crustal region. However, the TI Team concluded that the region around the Hanford site has some elements of a stable continental region given its distance from the plate boundary and its low seismic activity rates. As such, in order to use active-source GMPEs for the Hanford PSHA, the TI Team developed an extensive set of "host-to-target" adjustment factors that take into account differences between the host (i.e., seismically active regions such as California) and target (i.e., eastern Washington) regions in terms of earthquake source properties, regional path characteristics, and site conditions. For both the shallow crustal and subduction zone earthquakes, the TI Team adjusted the GMPEs to characterize the hazard at the baserock

horizon for the Hanford site (i.e., the top of the Wanapum Basalt in the CRB). These baserock-elevation ground motions were used by the licensee as input motions for its site response analysis for the CGS site.

To develop the GMC model, the TI Team evaluated a suite of data and models that are relevant to the hazard for the Hanford site. In particular, the TI Team evaluated (1) recently developed GMPEs for both crustal and subduction earthquakes; (2) regional data to assess the applicability of the GMPEs; and (3) near-surface geological and geophysical data gathered at the Hanford site to develop adjustment factors for the GMPEs. To evaluate the available GMPEs, the TI Team developed a set of objective criteria based on its assessment of best practices in ground motion modeling and also considered the predominant earthquake source mechanisms for the region surrounding the Hanford site. In order to assess the applicability of the GMPEs and adjust the models for the local site conditions, the TI Team developed a database of ground motion recordings from the area. For the crustal earthquakes, the TI Team selected four of the five NGA-West2 GMPEs (Bozorgnia et al., 2014), and for the subduction-zone earthquakes, the TI Team used a modified version of the GMPE developed for the BC Hydro project (BC Hydro, 2012) for its backbone model. In order to capture the epistemic uncertainty in both the predicted median ground motions and the host-to-target adjustment factors, the TI Team then expanded these backbone GMPEs into multiple sets of GMPEs. The TI Team also developed multiple models to capture the epistemic uncertainty in the aleatory variability about the predicted median ground motions.

3.2.1 Assessment of the SSHAC Process for GMC

To develop the GMC for the Hanford site, the TI Team implemented the SSHAC Level 3 process by first evaluating available data, methods, and models of relevance to the characterization of ground shaking at the Hanford site. The TI Team then used its evaluation of these data and models to construct logic trees for the median ground motions and their associated variability for the GMC models.

For the Hanford SSHAC Level 3 PSHA, the GMC TI Team conducted three formal workshops and multiple working meetings over a three-year time period from 2012 to 2014. During Workshop 1 (held on July 23–27, 2012), the TI Team identified the ground motion issues of highest significance for the Hanford PSHA and resource experts described the available ground motion databases and models. During Workshop 2 (held on December 3–8, 2012), several proponent experts presented their viewpoints regarding the ground motion databases and models under consideration for the GMC. In addition, participants at Workshop 2 discussed approaches for adapting existing GMPEs for use at the Hanford site. During Workshop 3 (held on November 11–15, 2013), the TI Team described its preliminary GMC models and hazard sensitivity analyses in order to get feedback from the PPRP.

After Workshop 3, the TI Team continued to refine the GMC model 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 closure letter (PNNL, 2014):

> The Panel concludes that its ongoing review and feedback interactions with the TI Teams during the conduct of the HSW [Hanford Site Wide] PSHA project activities fully met the expectations for a SSHAC Level 3 study. From the presentation of the plans for conducting the HSW PSHA at the outset of the project to the completion of the HSW PSHA report, the TI Teams provided multiple and effective communications to the PPRP. Conference calls and written communications allowed the PPRP to fully understand the technical support for the TI Teams' assessments. The TI Team provided written responses to PPRP comments documenting that all comments had been adequately considered during the conduct of the work and its documentation. On the basis of the PPRP's review of the HSW PSHA, the Panel concludes that both the process and technical aspects of the assessment fully meet accepted guidance and current expectations for a SSHAC Level 3 study.

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Based on observations at the workshops and review of the workshop proceedings, the NRC staff concludes that the SSHAC workshops were conducted in a manner consistent with applicable NRC guidance. In addition, the NRC staff did not find significant departures from the guidance in the approach used by the TI Team to develop the GMC models. At the workshops, the staff observed 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 GMC models tailored specifically to the types of earthquakes that dominate the hazard and upper crustal conditions for the CGS 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 GMC models and PSHA report. In summary, the NRC staff concludes that the PPRP was effective and engaged throughout the SSHAC Level 3 PSHA, and that there were no unresolved PPRP issues at the end of the project.

An important component of the SSHAC process is complete documentation. Based on its review, the NRC staff concludes that the SSHAC documentation (PNNL, 2014) provides an acceptably complete record of the approach used to develop the GMC model.

In summary, 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 GMC portion of the Hanford PSHA acceptably implemented the SSHAC Level 3 process.

3.2.2 Ground Motion Databases

In order to verify the applicability and adjust the backbone GMPEs for the Hanford PSHA, the TI Team gathered and evaluated ground motion recordings from multiple sources. Specifically, the TI Team collected local and regional ground motion data in order to (1) assess the GMPEs developed for the shallow crustal sources; (2) estimate kappa (i.e., a measure of energy dissipation in the top 1-to-2 km of the crust) for the Hanford site; and (3) determine whether to incorporate potential basin effects on the ground motions. These local and regional recordings include the strong-motion data from the five strong-motion recording stations located near the Hanford site as well as the data from numerous Incorporated Research Institutions for Seismology projects conducted in the region. To evaluate potential subduction-zone GMPEs, the TI Team used the database developed by the BC Hydro project (BC Hydro, 2012), augmented by more recent data.

In addition to gathering ground motion recordings, the TI Team also developed profiles of shear-wave velocity (V_S), density, and damping for the five recording stations near the Hanford site. The TI Team also compared values of the quality factor Q (i.e., a measure of energy loss of earthquake waves due to anelastic attenuation) for sites in Washington and California, finding moderately higher crustal Q for eastern Washington relative to coastal California. Both the estimate of local rock and soil properties for the Hanford site and the differences in crustal Q between Washington and California were used by the TI Team to develop adjustment factors (described in Section 3.2.3.3 of this staff assessment) for the backbone GMPEs.

Because the Hanford site is located over a sedimentary basin, the TI Team also investigated whether to include an adjustment in the models to account for basin effects. Seismic waves travelling through sedimentary basins are usually amplified, and examples of this phenomena are documented worldwide. In order to assess the potential effects of the sedimentary basin, the TI Team sponsored a study that conducted 3D seismic waveform simulations of the limited number of recorded earthquakes near the site and also modeled waveforms of larger magnitude hypothetical earthquakes in the region. Due to the inconclusive simulation results and the fact that the shallow, mostly flat-lying sediments of the basin are above the baserock horizon level for which the GMPEs are calibrated, the TI Team decided that any potential basin effects at the site should be included as part of the site response analysis rather than as an adjustment factor for the GMPEs.

In addition to gathering and evaluating local and regional data and models, the TI Team also evaluated existing GMPEs for active crustal regions and GMPEs for subduction earthquakes. Important criteria developed by the TI Team for the selection of candidate GMPEs include:

- selection of the most recently published GMPEs over earlier versions,
- selection of GMPEs suitable for large magnitudes and distance ranges,
- exclusion of GMPEs developed only for small specific regions,
- exclusion of GMPEs that have not been peer reviewed or vetted by the larger scientific community, and
- exclusion of GMPEs developed as research tools rather than for engineering applications.

Based on these criteria, the TI Team selected four of the five Pacific Earthquake Engineering Research Center (PEER) NGA-West2 GMPEs to use for the crustal earthquakes. For the subduction zone sources, the TI Team determined that only the GMPE developed for BC Hydro project (BC Hydro, 2012) was suitable.

STAFF EVALUATION

Based on observations of the SSHAC workshops, review of the SSHAC report and knowledge of current GMPEs developed for active tectonic regions, the NRC staff concludes 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 compiled by the TI Team consist of several thousand earthquake records that cover a wide range of magnitudes and distances.

The staff also concludes that the GMC TI Team thoroughly evaluated whether to include adjustment factors for the GMC models to account for potential amplification of ground motions due to basin effects. Because the TI Team developed the GMC models to predict ground motions at the baserock horizon, which is located below the sedimentary basin underlying the Hanford site, the staff concurs with the TI Team's decision to account for potential basin effects as part of the site response analysis. With respect to the differences in crustal Q between eastern Washington and coastal California, the staff concludes that the TI Team evaluated the latest research results (Philips et al., 2014), which are based on a very large number of recordings obtained by the USArray, and concurs with the TI Team's finding that Q values are moderately higher in Washington compared to California.

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 GMPEs that have been formally peer reviewed, developed specifically for either shallow crustal earthquakes in active tectonic regions or for deeper subduction-zone earthquakes, and that are the latest versions of the developers published GMPEs. In addition, the staff finds that the TI Team appropriately excluded crustal earthquake GMPEs that do not include either parameters to account for different fault mechanisms (i.e., strike-slip, normal, and reverse), or an explicit hanging-wall term. These two criteria are important for characterizing the hazard associated with the YFTB faults, which are predominantly reverse faults.

In summary, the staff concludes that the TI Team developed a suitable ground motion database and selected an appropriate set of 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 GMC models, developed by the TI Team as input for the Hanford PSHA, consist of multiple GMPEs that predict median spectral accelerations for the baserock horizon (i.e., top of the Wanapum Basalt in the CRB) beneath the Hanford site. The two GMC models consist of a suite of GMPEs for crustal earthquakes and a suite of GMPEs for subduction-zone earthquakes. Each crustal earthquake GMPE predicts median spectral accelerations in terms of magnitude, various source-to-site distance measures, depth to the top of rupture, and fault dip angle and fault type (i.e., strike-slip, normal, or reverse). The crustal earthquake GMPEs also account for potential hanging-wall effects (i.e., increases in ground motion at short distances for sites on the hanging wall side of the rupture). The subduction-zone earthquake GMPEs predict median spectral accelerations in terms of magnitude, earthquake focal depth, and source-to-site distance. The GMPEs for both the crustal and subduction-zone earthquakes predict median spectral accelerations for 20 oscillator frequencies ranging from 0.1 Hz to 100 Hz.

To construct the GMC models for the crustal and subduction-zone earthquakes, the TI Team developed two logic trees with multiple nodes and branches in order to capture the epistemic uncertainty in the median as well as the host-to-target adjustment factors. Each of the logic trees start with a “backbone” GMPE, which is then expanded into multiple GMPEs through three-to-four sets of weighted branches that capture alternative models for magnitude and distance scaling, ground motion amplitude, and host-to-target adjustment factors.

The GMC logic tree for median ground motions for the crustal earthquakes consists of a single branch for the backbone GMPE, seven alternative weighted branches to represent the differences in site conditions (V_S and kappa) between the host and target regions, nine branches for alternative scaling and adjustments of the backbone GMPE, and three branches to account for potential differences in source properties between the host and target regions. The resulting GMC model for median motions for the crustal earthquakes consists of 189 weighted alternative GMPEs.

The GMC logic tree for median motions for the subduction zone earthquakes consists of a single branch for the backbone GMPE, three branches for epistemic uncertainty in the median, three branches to represent alternative magnitude scaling, two branches for alternative distance scaling, and four branches for differences in the host-to-target site conditions. The resulting GMC model for median motions for the subduction zone earthquakes consists of 72 alternative weighted GMPEs.

3.2.3.1 Median Models for Crustal Earthquakes

The objective of the GMC TI Team was to develop a suite of GMPEs that 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) required by the sources in the SSC model. The TI Team acknowledged that simply attaching weights to the four NGA-West 2 GMPEs, which it selected for the crustal earthquakes, would be insufficient to fully capture the epistemic uncertainty in the median predictions. As such, the TI Team implemented an approach referred to as the “scaled backbone approach.” The intent of the scaled backbone approach is to capture the epistemic uncertainty in predicted median ground motions by using a

set of weighted adjustment factors that produces a suite of GMPEs that encompass a wide range of ground motion amplitudes and alternative magnitude and distance scaling models.

To implement the scaled backbone approach, the TI Team first selected a set of earthquake scenarios in terms of magnitude, source-to-site distance, fault dip angle, and depth to the top of rupture. For each scenario, the TI Team determined the median predicted ground motions from the following four NGA-West2 GMPEs:

- Chiou and Youngs (CY14)
- Abrahamson, Silva, and Kamai (ASK14)
- Boore, Stewart, Seyhan, and Atkinson (BSSA14)
- Campbell and Bozorgnia (CB14)

For each rupture scenario, the TI Team determined the residual in the predicted medians from each of the four GMPEs with respect to the CY14 GMPE. The TI Team centered the backbone model based on the geometric mean of the residuals from the four NGA-Wes t2 GMPEs using a mixed effects model. The TI Team represented the uncertainty in scaling about the centered backbone with a two-dimensional Gaussian covariance matrix, which it then sampled with a nine-point discrete distribution. As a result of using the scaled backbone approach and the four NGA-West 2 GMPEs, the TI Team transformed its initial single backbone based on the CY14 GMPE to nine alternative weighted GMPEs.

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's implementation of the scaled backbone approach results in a set of GMPEs for crustal earthquakes that adequately captures the uncertainty in amplitude, magnitude scaling, and potential hanging-wall effects. For the crustal earthquake median GMC model, the TI Team developed a set of adjustment factors with respect to the CY14 backbone GMPE that results in nine alternative GMPEs.

To evaluate the range of alternative magnitude and distance scaling as well as the distribution of median spectral accelerations predicted by the nine GMPEs, the NRC staff examined the behavior of the GMPEs for multiple earthquake magnitude and source-to-site distance combinations. Figure 3.2-1a of this staff assessment shows the nine GMPEs for 1 Hz (blue) and 10 Hz (black) spectral acceleration as a function of source-to-site rupture distance for an **M**6 earthquake and Figure 3.2-1b shows the nine GMPEs as a function of magnitude for a rupture distance of 20 km. Figures 3.2-1a and b also show the CY14 backbone GMPE as a dashed red line. The staff also compared the nine GMPEs with the other three NGA-West 2 GMPEs used by the TI Team and notes that the nine GMPEs span a broader range of ground motions than the four input NGA-West2 GMPEs.

As demonstrated in Figure 3.2-1b, the staff notes that the nine GMPEs capture a range of alternative magnitude scaling models (i.e., crossing GMPEs) but, as shown in Figure 3.2-1a, only the distance scaling of the backbone CY14 GMPE. The NRC staff's evaluation of the backbone adjustment model found that the TI Team did develop alternative distance scaling but only for sites located on the hanging wall side of the fault and for source-to-site distances less

than about 10 km. Ideally, because GMPEs developed from datasets in active tectonic regions do exhibit multiple distance scaling approaches, the nine GMPEs developed by the TI Team should capture a wider range of alternative distance scaling. However, a comparison of the NGA-West2 GMPEs by Gregor et al. (Gregor et al., 2014) found similar distance scaling for magnitudes between **M**5 and **M**7 and distances from 10 km to 100 km. As such, because the dominant sources in the Hanford SSC fall within these magnitude and distance ranges, the staff concludes that increasing the differences in distance scaling between the nine GMPEs would not significantly impact the resulting hazard at the 10^{-4} and 10^{-5} annual frequencies of exceedance levels. In addition, the staff concludes that the implementation of the multiple host-to-target adjustment factors in the GMC logic tree, which expands the nine GMPEs to 189 GMPEs, adequately captures the epistemic uncertainty in the median predictions.

In summary, the staff concludes that the TI Team developed a suitable set of GMPEs to characterize the median ground motions and capture the epistemic uncertainty in the predicted medians from shallow crustal earthquakes in active tectonic regions consistent with the fundamental goal of the SSHAC process to capture the center, body, and range of technically defensible interpretations.

3.2.3.2 Median Models for Subduction-Zone Earthquakes

As noted in Section 3.2.2 of this staff assessment, the TI Team performed an extensive evaluation of existing subduction zone GMPEs by applying a set of selection criteria to existing models. Based on this evaluation, the TI Team concluded that only the recently completed BC Hydro project (BC Hydro, 2012) GMPE is appropriate for use in developing a subduction-zone GMC model for the Hanford site. However, rather than simply using the BC Hydro GMPE as the backbone model for the GMC, the TI Team made several revisions to this GMPE. Of these revisions, the most significant was the TI Team’s decision to perform a new regression analysis using the BC Hydro dataset augmented by newer data.

To develop an updated subduction-zone database for the Hanford PSHA, the TI Team compiled data from the BC Hydro project augmented by recent recordings from Japan (the KiK-net network), Central America (Arango et al., 2011), and Chile (Gregor et al., 2012). The final dataset consists of 9,946 earthquake recordings from 292 earthquakes. In addition, because the distance range of importance from the Cascadia subduction zone for the Hanford PSHA is approximately 200–400 km, the TI Team decided to give more weight to data at larger distances (i.e., beyond 100 km) from the source. Using this augmented and weighted database, the TI Team then performed a regression analysis to develop new coefficients for the BC Hydro GMPE.

To develop a suite of alternative median models based on its modified BC Hydro backbone GMPE, the TI Team developed a logic tree for the subduction zone GMC that captures epistemic uncertainty in large-magnitude scaling and uncertainty in the median model. Implementing the logic tree for these two sources of uncertainty, the single modified BC Hydro GMPE expands to nine GMPEs. Other sources of uncertainty captured by the logic tree include host-to-target adjustment factors, which are described and evaluated below in Section 3.2.3.3 of this staff assessment.

STAFF EVALUATION

Based on review of the SSHAC documentation and knowledge of current GMPEs developed for subduction zones, the NRC staff concludes that the TI Team's use and modifications to the BC Hydro (BC Hydro, 2012) GMPE result in a backbone model that is an appropriate starting point for the subduction zone GMC model. In addition, the NRC staff concludes that the TI Team adequately accounted for the epistemic uncertainty in the predicted median ground motions by developing a logic tree for the GMC that captures alternative magnitude scaling for large earthquakes and alternative median amplitudes.

The BC Hydro project (BC Hydro, 2012), which was conducted as a SSHAC Level 3 project, aggregated and evaluated available data from subduction zone earthquakes as well as recently developed subduction zone GMPEs. Therefore, the NRC staff concludes that the TI Team's use of the BC Hydro model and database, augmented with more recent recordings from subduction zone earthquakes, is an appropriate starting point for the GMC model for the Hanford PSHA. In addition, because the most significant contributions to the hazard from the Cascadia subduction zone are from large magnitude earthquakes at distances from 200 to 250 km, the NRC staff concurs with the TI Team's decision to assign greater weight to the data from larger distances.

In summary, the staff concludes that the TI Team developed a suitable set of GMPEs to characterize the median ground motions and capture the epistemic uncertainty in the predicted medians from subduction zone earthquakes consistent with the fundamental goal of the SSHAC process to capture the center, body, and range of technically defensible interpretations.

3.2.3.3 Host-To-Target Adjustment Factors

In order to develop median ground motions for the baserock horizon beneath the Hanford site, the TI Team developed adjustment factors for the crustal and subduction-zone earthquake GMC models. These adjustment factors capture the differences in the earthquake source properties, regional path characteristics, and site conditions between the host and the target regions. For the Hanford GMC models, the host region is defined as the seismically active crustal regions for which the input GMPEs were developed. The target region is defined as the region surrounding the Hanford site, which has elements of a more stable continental region due to its distance from the plate boundary and lower seismicity rates. To account for the epistemic uncertainty in the host-to-target adjustment factors, the TI Team developed a logic tree for both the crustal earthquake and the subduction zone earthquake GMC models. Each logic tree contains multiple weighted branches to capture a range of adjustment factors.

Source Host-To-Target Adjustment Factors

To capture the host-to-target differences in earthquake source properties, the TI Team developed a set of adjustment factors to account for potential differences in the stress drop (i.e., difference in stress across a fault before and after an earthquake). The TI Team included three factors in the crustal earthquake GMC logic tree with the highest weight of [0.6] given to the scale factor of 1.0 (i.e., no difference in the stress drop), a weight of [0.3] for the scale factor of 1.3, and a weight of [0.1] for the scale factor of 0.8. The weighted average scale factor of 1.1

reflects the TI Team's conclusion that the stress drop for crustal earthquakes in eastern Washington is likely to be slightly higher than that for more active crustal regions.

Path Host-To-Target Adjustment Factors

To capture the host-to-target differences in regional path characteristics, the TI Team developed a set of adjustment factors to account for potential differences in anelastic attenuation. The TI Team included two branches in the subduction zone earthquake GMC logic tree with the highest weight of [0.6] given to the scale factor of 1.0 and a weight of [0.4] for the scale factor of 0.5 (i.e., lower attenuation branch). The weighted average scale factor of 0.8 reflects the TI Team's decision to partially capture the lower attenuation predicted by the Atkinson and Macias (2009) GMPE.

Site Host-To-Target Adjustment Factors

To capture the host-to-target difference in site conditions, the TI Team developed a set of adjustment factors using the inverse random vibration theory (IRVT) approach developed by Al Atik et al. (Al Atik et al., 2013) to account for potential differences in shear wave velocity (V_S) and kappa. The TI Team included seven branches in the crustal earthquake GMC logic tree to model a range of V_S-kappa adjustment factors. Similarly, for the subduction zone earthquake GMC logic tree, the TI Team included four branches to model a range of V_S adjustment factors. The V_S-kappa adjustments account for impedance differences between the host and target V_S profiles and differences between the host and target kappa values, which mainly affect spectral frequencies above 10 Hz.

To develop the V_S-kappa adjustment factors for the crustal earthquake GMC model, the TI Team first assumed a host V_S profile (i.e., average profile for the host region) and measured kappa values for the host crustal earthquake GMPEs for multiple earthquake magnitude and distance combinations. Next, to estimate the target kappa value for the Hanford site, the TI Team used a dataset of 59 small magnitude earthquakes recorded in the 2005 to 2013 time frame at six sites within and around the Hanford site. Using this dataset, the TI Team implemented two approaches to estimate kappa: an inversion process and direct measurement of the high-frequency decay of the Fourier Amplitude Spectra (FAS), developed by Anderson and Hough (Anderson and Hough, 1984). The TI Team used the combined kappa estimates from the two approaches to develop a set of 36 target kappa values, which range from about 0.01 to 0.06 sec. Due to the limited frequency bandwidth of the ground motion dataset, which impacts the reliability of the kappa values estimated using the Anderson and Hough (1984) approach, the TI Team gave higher weight (0.67 vs. 0.33) to the kappa estimates determined using the inversion approach. Using its estimate of the host and target kappa values and the host and target V_S profiles, the TI Team implemented the IRVT approach (Al Atik et al., 2013) to develop 108 host-to-target adjustment factors for the crustal earthquake GMC model. To simplify the hazard calculations, the TI Team then re-sampled these 108 adjustment factors to obtain seven branches with appropriate weights.

For the subduction zone earthquake GMC model, the TI Team determined that the anelastic attenuation path effects are much more dominant than the kappa effects due to the large distances (beyond 200 km) from the Hanford site to the Cascadia subduction zone sources. As

such, the TI Team only developed adjustment factors to account for impedance differences between the host and target V_S profiles. The TI Team used two V_S profiles developed from Japanese data for the subduction zone host profile and profiles C-1 and C-2 for the Hanford site target profiles. Using these two host and two target V_S profiles, the TI Team developed four adjustment factors for the subduction zone GMC model.

STAFF EVALUATION

Based on review of the SSHAC documentation, the NRC staff concludes that the TI Team's development of the host-to-target adjustment factors results in a set of GMPEs for both the crustal and subduction zone earthquakes that adequately captures the uncertainty in the earthquake source properties, regional path characteristics, and site conditions between the host and the target regions. The staff notes that including the host-to-target adjustment factors broadens the epistemic uncertainty in the median predictions, resulting in 189 GMPEs for the crustal earthquake GMC model and 72 GMPEs for the subduction zone GMC model.

Based on the TI Team's conclusion that crustal Q for eastern Washington is moderately higher than that for the assumed host regions (e.g., coastal California), the NRC staff asked the licensee to justify its decision not to incorporate host-to-target adjustment factors to account for differences in regional path properties for the crustal earthquake GMC model. In response to the NRC staff's request for additional information (RAI), the licensee provided a detailed analysis comparing the seismic Q values between the host and target regions and the potential impact of these differences on the final hazard results for the Hanford site (Swank, 2015b). Based on its analysis, the licensee concluded that path host-to-target adjustment factors for the crustal earthquake GMC model are not needed because (1) the differences in Q values between the host and target regions are moderate; and (2) the dominant contributors to the hazard for the Hanford site at the 10^{-4} annual frequency of exceedance level are local small-to-moderate local earthquakes from the YFTB source zone. To confirm the licensee's RAI response, the staff used the Graizer and Kalkan (2016) GMPE for a range of Q values and found that the differences in the baserock hazard curves for the Hanford site due to the moderate differences in the host and target Q values are not significant, especially for smaller (within 100 km) source-to-site distances.

The NRC staff reviewed the TI Team's implementation of the inversion approach, as well as the Anderson and Hough (Anderson and Hough, 1984) approach to estimate the target kappa for the Hanford site and concludes that the TI Team appropriately recognized the impact of both the small number and limited quality of the local ground motion records on both approaches. To evaluate the TI Team's decision to give more weight to the inversion approach over the Anderson and Hough approach, the NRC staff performed a confirmatory analysis with alternative weights for the two approaches. Figure 3.2-2 of this staff assessment shows the V_S-kappa adjustment factors using the TI Team's weights for the two approaches (solid grey lines) and the adjustment factors giving no weight to the inversion approach (dashed black lines). As shown in Figure 3.2-2, the final V_S-kappa adjustment factors are not substantially impacted by alternative weights for the two approaches.

To evaluate the TI Team's decision to use only a single host V_S profile to develop the crustal earthquake V_S-kappa adjustment factors, the NRC staff performed a confirmatory analysis using

three host V_S profiles, which are shown in Figure 3.2-3a of this staff assessment. As shown in Figure 3.2-3b, the V_S-kappa adjustment factors using three host V_S profiles do not differ substantially from the V_S-kappa adjustment factors developed by the TI Team, which were developed using a single host V_S profile. The NRC staff's confirmatory analysis demonstrates that differences between the host and target kappa values have a much greater impact on the final V_S-kappa adjustment factors than impedance differences between the host and target V_S profiles.

To evaluate the overall effect of the TI Team's development of multiple host-to-target adjustment factors on the predicted median ground motions, the NRC staff examined the behavior of the 189 crustal earthquake GMPEs for multiple earthquake magnitude and source-to-site distance combinations. Figure 3.2-4a of this staff assessment shows the 189 GMPEs for 10 Hz spectral acceleration as a function of source-to-site rupture distance for an **M**6 earthquake and Figure 3.2-4b shows the 189 GMPEs as a function of magnitude for a rupture distance of 20 km. Also shown in the inset to Figure 3.2-4a is the weighted distribution of 10 Hz medians for an **M**6 earthquake at a rupture distance of 20 km, which is indicated by the vertical yellow line in both Figures 3.2-4a and b. As shown in Figures 3.2-4a and b, the TI Team's implementation of the source and site host-to-target adjustment factors considerably broadens the distribution of median spectral accelerations for the crustal earthquake GMC model. Similarly, the implementation of path and site host-to-target adjustment factors considerably broadens the medians for the subduction zone earthquake GMC model.

In summary, as a result of this review, the NRC staff concludes that the TI Team adequately accounted for the differences between the host and target regions by developing adjustment factors for source, path, and site properties. In addition, the staff concludes that the TI adequately captured the epistemic uncertainty in the host-to-target adjustment factors through its use of logic trees for the two GMC models. Based on this conclusion, the staff finds that the resulting set of host-to-target adjustment factors adequately captures the center, body, and range of technically defensible interpretations.

3.2.4 Ground Motion Variability

In addition to developing GMPEs that predict median ground motions, the TI Team developed models to characterize the random (i.e., aleatory) variability about the median ground motions. To develop these models, the TI Team used the ground motion databases and backbone GMPEs described in Sections 3.2.2 and 3.2.3 of this staff assessment. Because Enclosure 1 to the 50.54(f) letter (NRC, 2012a) requests that licensees perform a detailed site response analysis, the TI Team first separated the residuals between the predicted and observed ground motions into its component pieces in order to remove the repeatable effects of site response. The TI Team then combined the standard deviations for each of the remaining components of the total residuals to produce the total aleatory standard deviation, which 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 site host-to-target adjustment 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 site host-to-target adjustment factors is provided in Section 3.2.3.3 of this staff assessment and Section 3.4 provides the staff's review of the licensee's site response analysis for the CGS site.

The single-station sigma approach starts with separating the total residuals into 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 evaluates it as epistemic uncertainty.

To develop a model for single-station sigma for the crustal earthquake GMPEs, 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 on earthquake magnitude. The TI Team developed the τ model by averaging the τ models of the four NGA-West2 GMPEs that it used as a starting point to develop the median crustal earthquake GMPEs. For the φ_{SS} model, the TI Team used the model previously developed for the Thyspunt Nuclear Siting Project (TNSP; Bommer et al., 2015). The TI Team justified use of the TNSP φ_{SS} model based on recent research by Rodriguez-Market et al. (2013) showing the consistency of φ_{SS} estimates across multiple active tectonic regions.

To develop a model for the two components (τ and φ_{SS}) of single-station sigma for the subduction earthquake GMPEs, the TI Team used the residuals from its regression analysis performed to fit the modified BC Hydro (BC Hydro, 2012) backbone GMPE. For both τ and φ_{SS}, the TI Team developed magnitude- and period-independent single-value estimates, which it then combined to determine an estimate for single-station sigma.

In addition to developing models for each of the individual components of sigma (τ and φ_{SS}), 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, central, 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 concludes that the TI Team developed an appropriate set of models for the ground motion variability in order to capture the full distribution of ground motions generated by the multiple sources in the SSC model. The staff finds that the TI Team appropriately separated the individual components of the residuals in order to extract the site term, which it captured elsewhere by the site host-to-target adjustment factors and site response analysis. The staff also concludes that the TI Team used reasonable approaches to model the standard deviations for the individual components 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 of this staff assessment, 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 five recordings in order to estimate the site-term component of the variability for the subduction earthquake GMC model. In addition, the staff concludes that the TI Team used an appropriate

approach to combine the standard deviations for the individual components of the residuals into a final distribution for single-station sigma and that this distribution is adequately represented by including three branches in the logic trees for both of the sigma models.

To evaluate the ground motion variability about the predicted median spectral accelerations, the NRC staff compared the values predicted by the TI Team's τ and φ_{SS} models with estimates from other GMPEs. Based on these comparisons, the staff concludes that the TI Team's τ and φ_{SS} models, as well as the resulting single-station sigma model, produce reasonable estimates of the ground motion variability for each of the earthquake scenarios considered for the Hanford PSHA.

The staff notes that for each crustal earthquake scenario, the GMC model consists of 189 alternative median predictions, which after combining with the three alternative sigma values, results in a total of 567 alternative ground motion distributions. Similarly, for each subduction earthquake scenario, there are 216 alternative ground motion distributions (72 medians times 3 sigma alternatives). The staff finds that the TI Team's use of this large number of distributions for each of the earthquake scenarios considered in the Hanford PSHA adequately captures the epistemic and aleatory uncertainty in predicted ground motions for the baserock horizon beneath the Hanford site.

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

3.3 Probabilistic Seismic Hazard Analysis

The TI Team implemented the SSC and GMC models to develop baserock PSHA hazard curves, which then serve as inputs to the site response analysis. For the Hanford PSHA, the TI Team selected the top of the Wanapum Basalt in the CRB to be the reference baserock horizon beneath the Hanford site. 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 areal sources, which are reviewed in Section 3.1 of this staff assessment, the SSC TI Team developed logic trees in order to define the potential locations, magnitudes, 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 recurrence rates. Each of these parameters is represented as a node in the PSHA logic tree with multiple weighted branches at each node providing alternative parameter values.

The TI Team developed a logic tree for each of the areal source zones (Zones B, C, and D) as well as for the YFTB, which is the host zone to the Hanford and CGS sites. 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 known Quaternary faults and historical seismicity within each of the source zones. Because the Hanford site is located within the YFTB zone, the hazard contribution from the YFTB zone dominates the 10 Hz hazard and is also a significant contributor to the 1 Hz hazard for this site.

The TI Team characterized 19 fault sources associated with the YFTB as well as the Seattle fault in the SSC model (see Figure 3.1-3 of this staff assessment). For each of the individual fault sources, the TI Team modeled the faults as a series of straight-line segments, allowing future earthquake ruptures to potentially occur on one or more of the segments. For the YFTB faults, the TI Team determined that the Rattlesnake Mountain, Umtanum Ridge, Horse Heaven Hill, and Yakima Ridge faults are the main contributors to the total hazard for 10 Hz at an annual frequency of exceedance level of 10^{-4}. The TI Team also included the Seattle fault in the SSC model; however, due to its low slip rate (about 1 mm/yr) and large distance from the Hanford site (200 km), the hazard contribution from this fault is small relative to other faults in the YFTB.

To characterize the hazard from the Cascadia Subduction Zone, the TI Team updated parts of the BC Hydro model (BC Hydro, 2012), which includes an intraslab source zone and a plate interface fault source. Despite the large distance from the Hanford site to the Cascadia Subduction zone (beyond 200 km), the subduction zone interface source, due to its potential for very large earthquakes (i.e., **M**8.5), is a dominant contributor to the hazard for low-frequency ground motions (up to 1 Hz).

The GMC TI Team developed logic trees for the median and sigma models for both the crustal earthquake sources and the subduction earthquakes. The GMC logic tree for the crustal earthquake sources includes multiple nodes and branches for alternative host-to-target site and source adjustments as well as alternative scaling adjustments to the backbone GMPE. For the subduction sources, the GMC logic tree includes nodes and branches for alternative magnitude scaling, epistemic uncertainty in the median, and path and site host-to-target adjustments. The single-station sigma logic trees include nodes and branches for low, central, and high values as well as 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 baserock hazard curves at Hanford, the TI Team performed a deaggregation of the hazard for both 1 Hz and 10 Hz spectral accelerations for 10^{-4} and 10^{-5} mean annual frequencies of exceedance. For 10 Hz, the TI Team determined that local earthquakes with moderate-to-large magnitudes (i.e., **M**5 to **M**7 at distances from 0 to 20 km) dominate the hazard, whereas for 1 Hz, larger distant subduction earthquakes (i.e., **M**8.5 at distances around 250 to 300 km) dominate the hazard.

3.3.2 Staff Confirmatory Evaluation

To evaluate the acceptability of the PSHA, the NRC staff performed a confirmatory evaluation of the seismic sources that contribute the most to the hazard at CGS. The purpose of the staff's evaluation was to assess the reasonableness of the 1 Hz and 10 Hz mean hazard results for the

most significant seismic sources, and assess the impact of the most significant source and ground motion parameters on the final hazard results. For this confirmatory analysis, the NRC staff selected a subset of the SSC and GMC branches that focus on the highest weighted components of the logic tree.

The YFTB fault sources selected by the staff for its confirmatory evaluation are the Rattlesnake Mountain, Yakima Ridge, Umtanum Ridge, and Saddle Mountain faults (Figure 3.3-1a of this staff assessment). For each of the fault sources, the staff evaluated a plausible range of slip rates. Figures 3.3-1(b-c) of this staff assessment show the staff's 1 Hz and 10 Hz hazard curves for the Rattlesnake Mountain fault. For its confirmatory evaluation, the staff used 27 of the 189 crustal earthquake GMPEs, each of which are shown in Figure 3.3-1(b-c). Also shown in Figures 3.3-1(b-c) are hazard curves resulting from using the 5th and 95th percentile slip rates for the Rattlesnake Mountain fault. As shown in Figures 3.3-1(b-c), the staff's confirmatory results closely match the licensee's results for both the 1 Hz and 10 Hz mean hazard curves. Using similar methods, the staff was able to confirm the reasonableness of the licensee's 1 Hz and 10 Hz hazard curves for the Yakima Ridge, Umtanum, and Saddle Mountain faults.
The areal source selected by the staff for its confirmatory evaluation is the YFTB source zone, which as the host areal source zone contributes significantly to both the 1 Hz and 10 Hz total mean hazard for the CGS site. Similar to the TI Team's approach, the NRC staff assumed that the majority of the seismicity within the YFTB zone is not associated with YFTB faults. As such, the NRC staff developed a set of virtual faults to generate earthquakes that are not directly associated with known faults within the YFTB. Using the Hanks and Bakun magnitude-area scaling relationships (Hanks and Bakun, 2008), the staff derived the length for each of the virtual faults based on the median MMAX, faulting mechanism, dip angle, and seismogenic thickness as used in the logic tree for the YFTB zone. For each of the virtual faults in the YFTB zone, the staff calculated the hazard using a range of earthquake magnitudes from **M**5 to the median maximum magnitude earthquake, which is **M**6.8. The staff developed a suite of seismic hazard curves for each of the virtual faults and then averaged the results to obtain mean 1 Hz and 10 Hz hazard curves for the YFTB source zone.

Figure 3.3-2(a) of this staff assessment shows the location of the virtual faults for the YFTB source zone. For its analysis, the staff placed virtual faults more densely around the CGS site and more sparsely at distances beyond 100 km from the site. The staff used this placement of virtual faults to adequately capture the range of significant source-to-site distances.
Figure 3.3-2(a) shows the virtual faults for the reverse faulting mechanism, with each fault having a length of about 31 km and a down-dip width of about 20 km. To represent the predominant structural characteristics of the YFTB, the staff selected fault orientations randomly between N60°W and N120°W for the reverse-faulting mechanism. For the strike-slip and normal faulting mechanisms, the staff selected similar predominantly E-W fault orientations. Figures 3.3-2(b-c) of this staff assessment show the 1 Hz and 10 Hz hazard curves for each of the 324 YFTB virtual faults as well as the staff's and licensee's mean hazard curves. As shown in Figure 3.3.-2(b-c), the staff's confirmatory results closely match the licensee's results for both the 1 Hz and 10 Hz mean hazard curves.

In summary, the NRC staff concludes that the Hanford SSHAC TI Teams acceptably implemented the SSC and GMC logic trees, in developing the baserock hazard consistent with the guidance specified in Enclosure 1 to the 50.54(f) letter (NRC, 2012a).

Through its confirmatory analyses for five of the significant contributors to the hazard for the Hanford site, 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. 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 baserock conditions as defined for the GMPEs used in the PSHA. For both the shallow crustal and subduction zone earthquake GMC models, the TI Team adjusted the GMPEs to characterize the hazard at the top of the Wanapum Basalt in the CRB.

Detailed site response analyses typically were not performed for many of the older operating plants in the U.S. Consequently, 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. The purpose of the site response analysis is to determine the site amplification that occurs because of baserock ground motions propagating upward 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 baserock 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 baserock amplitude.

3.4.1 Site Base case Profiles

The licensee provided detailed site profile descriptions in Sections 2.3.1 and 2.3.2 of its SHSR (Swank, 2015a). The CGS site is located within the Pasco Basin and is underlain by approximately 160 m of soil and sedimentary strata that overlies the Saddle Mountain Basalt, which extends to a depth of approximately 400 m. The Saddle Mountain Basalt includes sediment interbeds, and is underlain by the Wanapum Basalt.

In Table 2.3.1-2 of its SHSR (Swank, 2015a), the licensee provides a brief description of the subsurface materials in terms of the geologic units, layer thicknesses, and shear wave velocities. Due to the amount of near-surface V_S data available for the soil and rock at the CGS site and the consistency between the velocity measurements, the licensee used a single base case V_S profile for the soils and sedimentary strata in the upper 160 m. To develop two V_S profiles for the Saddle Mountain Basalt and its sedimentary interbeds, which extend from 160 m to 400 m below the surface, the licensee used down-hole measurements and a P-S suspension log from the Waste Treatment Plant at the Hanford site. Following the recommendation of the TI Team, the licensee gave twice as much weight to the V_S profile from the down-hole measurements compared to the suspension log data in its site-response logic tree.

In order to incorporate aleatory variability in the site response analysis, the licensee generated 60 random velocity profiles for each of its base case profiles using log standard deviation values of 0.15 to 0.30 for the soil and sedimentary strata in the upper 160 m and values of 0.1 and 0.2 for the Saddle Mountain Basalt and interbeds. In addition, the licensee varied the layer thickness for each of its V_S profiles by amounts varying from ±10 percent to ±22 percent.

3.4.2 Dynamic Material Properties and Kappa

To model the potential nonlinear behavior in the upper 160 m of strata to input ground motions, the licensee used two sets of shear modulus degradation and damping curves. As recommended in the SPID (EPRI, 2012), the licensee gave equal weight to the EPRI and Peninsular Range curves and limited the amount of damping to 15 percent. For the basalt layers within the Saddle Mountain Basalt, the licensee assumed a linear response to input ground motions with constant damping values ranging between 0.46 percent and 1.03 percent. For the sedimentary interbeds within the Saddle Mountain Basalt, the licensee modeled the potential nonlinear behavior using the Darendeli shear modulus degradation and damping curves (Darendeli, 2001) because these curves account for confining stress dependence, which is important for the depths at which the interbeds are located. For the shear modulus degradation curves, the licensee accounted for aleatory variability by randomizing about each of the curves using a log standard deviation of 0.15. Similarly, for the damping curves, the licensee randomized about each of the curves using a log standard deviation of 0.30. In addition, the licensee also randomized the constant damping values for the Saddle Mountain Basalts using a log standard deviation of 0.40.

To estimate the kappa value for its site response profile, the licensee accounted for the small strain damping associated with the damping curves used in each of the layers. In addition, the licensee also included the constant damping values for each of the layers within the Saddle Mountain Basalts. The licensee's two estimated kappa values are 0.0064 and 0.0087 sec for the material in the 160-m-thick section above the reference baserock. Calculation of kappa at the reference rock location, which the TI Team used to develop the site host-to-transfer adjustment factors, is described and reviewed in Section 3.2.3.3 of this staff assessment.

3.4.3 Site Response Method and Results

The licensee described the methods used for its site response analysis in Section 2.3.5 of its SHSR (Swank, 2015a). The licensee used random vibration theory (RVT) for its site response analysis, which is a method considered state-of-practice (EPRI, 2012). To develop input ground motions for the site response analysis, the licensee used the Conditional Mean Spectra (CMS) described by Baker (2011), which it implemented by using the magnitude and distance pairs from the PSHA deaggregation results and the CGS GMPEs. After developing input motions for the site response, the licensee generated 60 random V_S profiles for each of the base case profiles to determine the median site amplification factor and its associated log standard deviation. The licensee did not limit the site amplification factors to values greater than 0.5 as recommended in the SPID (EPRI, 2012).

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, described in

Appendix B of the SPID (EPRI, 2012). 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 baserock hazard curves, determined from the initial PSHA (reviewed in Section 3.3 of this staff assessment), and the amplification factors and their associated uncertainties, determined from the site response analysis.

STAFF EVALUATION

Based on its review of the information provided by the licensee in the SHSR (Swank, 2015a) and information available in the CGS Final Safety Analysis Report (FSAR) (EN, 2013), the NRC staff concludes that the licensee's base case V_S profiles are consistent with the subsurface data at the CGS site and that the licensee used the geotechnical and geophysical measurements made at the Hanford site to model the epistemic as well as the aleatory uncertainty for the V_S profiles. In addition, the NRC staff concludes that the dynamic material property curves used by the licensee are consistent with the laboratory testing of the near-surface soils (i.e., EN, 1998), the geology of the site, and that the licensee appropriately accounted for uncertainty in the potential nonlinear response by following the guidance provided in the SPID (EPRI, 2012).

To evaluate the licensee's estimate of the kappa value for the site response profile, the NRC staff used an empirical model developed by Campbell (Campbell, 2009). The resulting kappa estimate is reasonably consistent (within 20 percent) with the values estimated by the licensee and, therefore, the NRC staff concludes that the kappa used by the licensee is appropriate. The NRC staff also concludes that the licensee's implementation of the CMS approach to develop input ground motions resulted in a wide range of input motions that appropriately capture the deaggregation results from the PSHA.

The NRC staff performed a confirmatory site response analyses to assess three different scenarios: (1) the effect of differing assumptions for the epistemic uncertainty and aleatory variability for the site base case V_S profiles; (2) the sensitivity of the site amplification factors to the thickness of the interbed layers within the Saddle Mountain Basalt; and (3) the licensee's use of the Darendeli shear modulus degradation and damping curves (Darendeli, 2001) for the sedimentary interbeds. To assess Scenario 1, the NRC staff developed three profiles for the upper 160 m using a log standard deviation of 0.25 to account for epistemic uncertainty in the subsurface properties, instead of using only a single base case V_S profile. Figure 3.4-1 of this staff assessment shows the NRC staff's middle, upper, and lower base case profiles along with the recorded V_S data in the upper 160 m. To evaluate the sensitivity of the site amplification factors to the thickness of the interbed layers within the Saddle Mountain Basalt (i.e., Scenario 2), the NRC staff performed its analysis by randomly removing a few of the interbed layers in the 60 randomized site profiles. To assess Scenario 3, the NRC staff also performed its site response analysis using either the Darendeli (2001) curves or by assuming a linear response for the interbeds. Figure 3.4-2 shows the staff's confirmatory analyses results for the three scenarios for both 1 Hz (a) and 100 Hz (b) median amplification factors and 1 Hz (c) and 100 Hz (d) log standard deviations. As shown in Figure 3.4-2, the impact of using multiple base case profiles, randomly varying the thickness of the interbeds, and assuming a linear response for the interbed layers, does not result in amplification factors that differ significantly from those developed by the licensee. Similarly, Figure 3.4-3 of this staff assessment shows that the 1 Hz

and 100 Hz control point hazard curves for each of the three scenarios do not significantly differ from the licensee's hazard curves.

In an RAI to the licensee, the NRC staff asked the licensee to justify its decision to not implement the minimum amplification factor of 0.5, as recommended in the SPID (EPRI, 2012). In its response (Swank, 2015b), the licensee stated that amplification factors less than 0.5 have been reported by other analysts using both equivalent linear and nonlinear methods. To demonstrate the impact of not using a minimum value of 0.5, the licensee performed a sensitivity analysis with minimum amplification factors set to 0.1 and 0.5. As shown in Figure 3.4-4 of this staff assessment, the results of the licensee's analysis showed that the GMRS in the frequency range of 1 Hz to 10 Hz is insensitive to the minimum amplification factor but that the higher frequencies are moderately impacted. Based on its confirmatory site response analyses, the NRC staff concludes that the combination of (1) the impedance contrast between the interbed and basalt layers; and (2) the material damping of the interbeds, results in the low amplification factors for the higher spectral frequencies. Because these two factors are actual physical characteristics of the Saddle Mountain Basalts, the staff concludes that limiting the site amplification factors to a minimum value of 0.5 is not necessary for this site. Therefore, the NRC staff concludes that the licensee's decision to not use the minimum value of 0.5 is appropriate for the CGS site.

In summary, based on its evaluation of the SHSR and its confirmatory analysis, the NRC staff concludes that the methods used by the licensee for its site response analysis result in a set of site amplification factors that appropriately characterize the response of the CGS site to input ground motions. In addition, the NRC staff concludes that the licensee appropriately accounted for the uncertainty in the site amplification factors through its use of Approach 3, as recommended in the SPID (EPRI, 2012) to develop the final site control point hazard curves.

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) requested that 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 (typically at 20 Hz to 30 Hz for the existing fleet of nuclear power plants); (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 (Swank, 2015a), the licensee described its seismic design bases for CGS site. The SSE for CGS is anchored at a PGA of 0.25g and has a Newmark-Hall spectrum shape. The licensee stated a PGA of 0.25g is consistent with the vibratory accelerations associated with a Modified Mercalli Intensity VIII earthquake, which is larger than any known earthquake east of the Cascades in Washington or Oregon. In its FSAR (EN, 2013), the licensee indicated that this earthquake was assigned to the Rattlesnake-Wallula alignment,

located 20 km from the site. In Section 3.2 of its SHSR, the licensee specified that the SSE control point for the CGS site is located at the surface of the finished grade at 134 m elevation.

The NRC staff reviewed the licensee's description of the SSE in the SHSR for the CGS site. Based on review of the licensing basis contained in the FSAR for CGS (EN, 2013) and supplemental information provided in Swank (2015b), the NRC staff confirms that the licensee's SSE is a 5 percent damped response spectrum anchored at 0.25g. Finally, based on review of the SHSR and the FSAR, the NRC staff confirms that the licensee's control point elevation for the CGS 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 of this staff assessment) and the soil amplification functions (reviewed in Section 3.4) to calculate control point hazard curves. The licensee then used these curves to develop 10^{-4} and 10^{-5} (mean annual frequency of exceedance) uniform hazard response spectra, and then computed the GMRS using the criteria in RG 1.208 (NRC, 2007). The licensee's horizontal GMRS for the CGS site is shown in Figure 3.5-1 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 SSC and GMC models in the PSHA. The staff also determined in Section 3.4 of this assessment that the licensee developed acceptable site amplification factors, which it then used to calculate 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 September 24, 2015, responses to the RAIs (Swank, 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. Although the licensee used a site amplification factor that was lower than recommended in the SPID, the NRC staff determined that this deviation from guidance appropriately represented site-specific conditions and did not affect the resulting hazard calculation significantly. Based on the results of its review, the NRC staff concludes that the GMRS determined by the licensee adequately characterizes the reevaluated seismic hazard for the CGS 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).

4.0 CONCLUSION

The NRC staff reviewed the information provided by the licensee for the reevaluated seismic hazard for the CGS site. Based on this review, the NRC staff concludes that the licensee conducted the seismic hazard reevaluation using present-day methodologies and regulatory guidance, it appropriately characterized the CGS 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 provided an acceptable response to Requested Information Items (1) – (3) and (5-7), and the comparison portion to Item (4), identified in Enclosure 1 of the 50.54(f) letter. Further, the licensee's reevaluated seismic hazard is acceptable to address other actions associated with NTTF Recommendation 2.1: "Seismic".

In reaching this conclusion, the NRC staff confirmed the licensee's conclusion that the licensee's GMRS exceeds the SSE at the CGS site. As such, the licensee will perform a seismic risk evaluation, SFP evaluation, and HF confirmation. The NRC staff's review and acceptance of Energy Northwest's plant seismic risk evaluation, including the HF confirmation, and SFP evaluation [i.e., Items (4), (8), and (9)] for the CGS site will complete the Seismic Hazard Evaluation identified in Enclosure 1 of the 50.54(f) letter .

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FIGURES FOR CGS STAFF ASSESSMENT

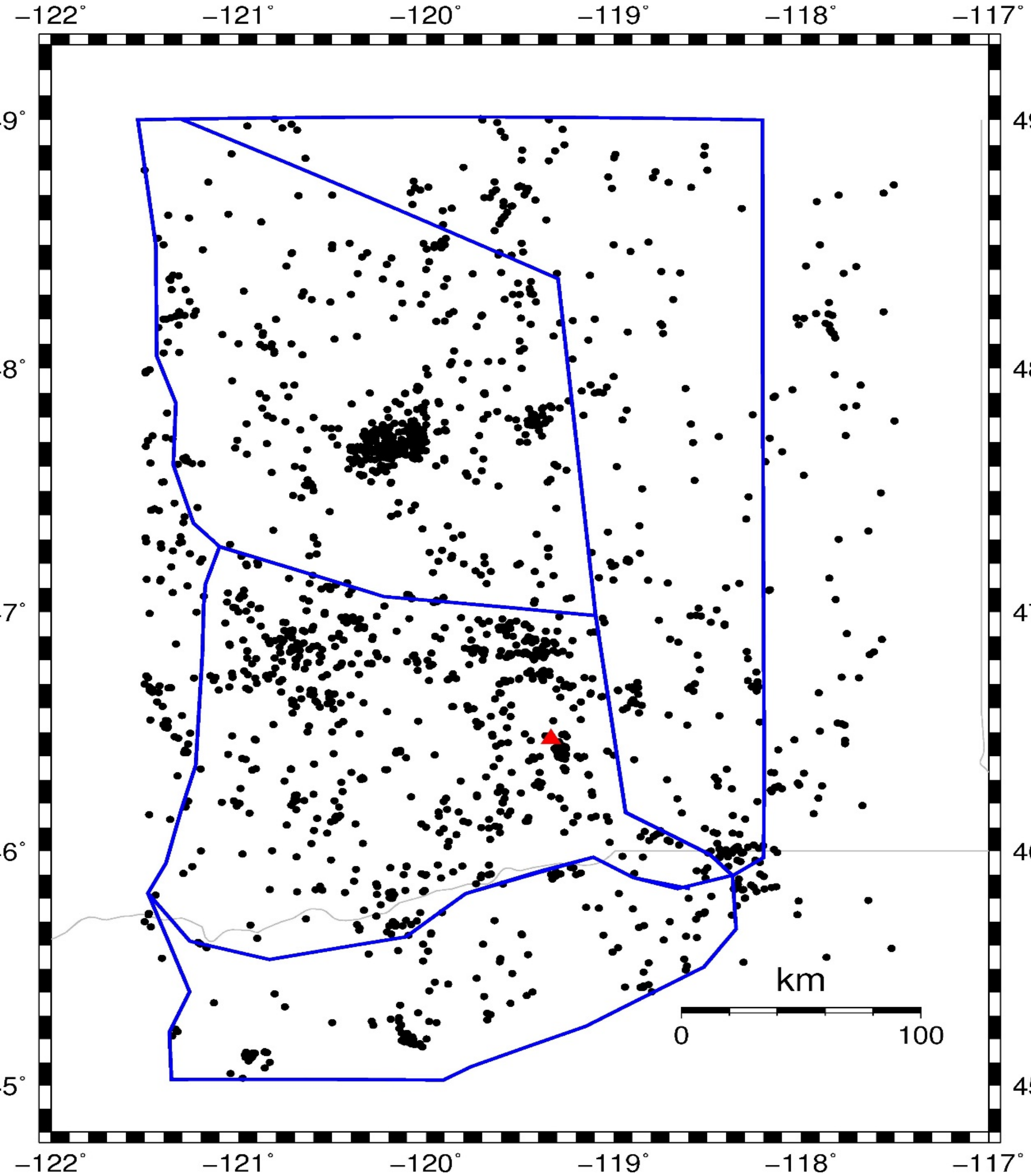

Figure 3.1-1. Independent earthquakes (dots) located in crustal source zones for the CGS site (triangle). Boundaries of the areal source zones are shown in blue solid lines.

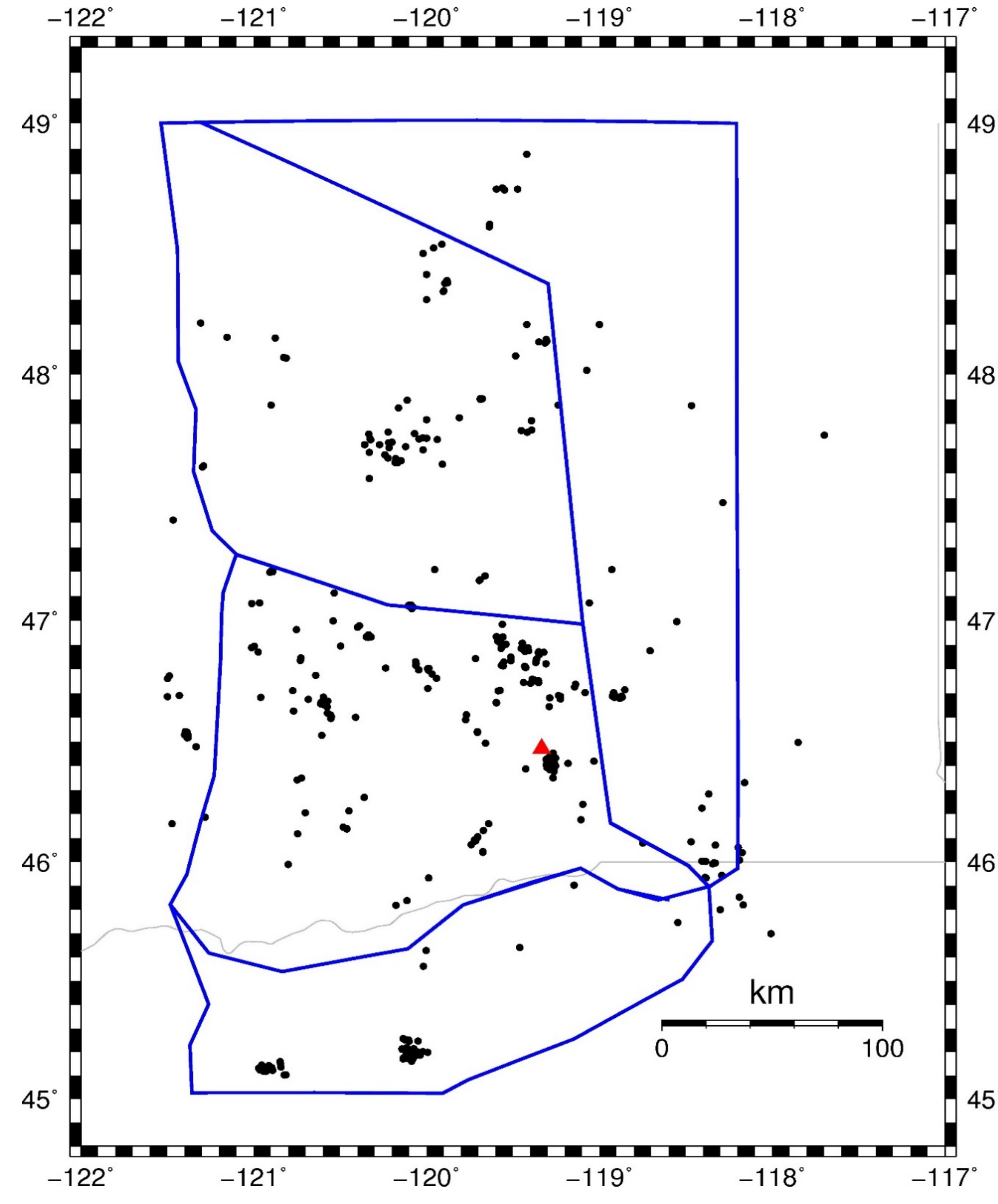

Figure 3.1-2. Dependent earthquakes (dots) located in crustal source zones for the CGS site (triangle). Boundaries of the areal source zones are shown in blue solid lines.

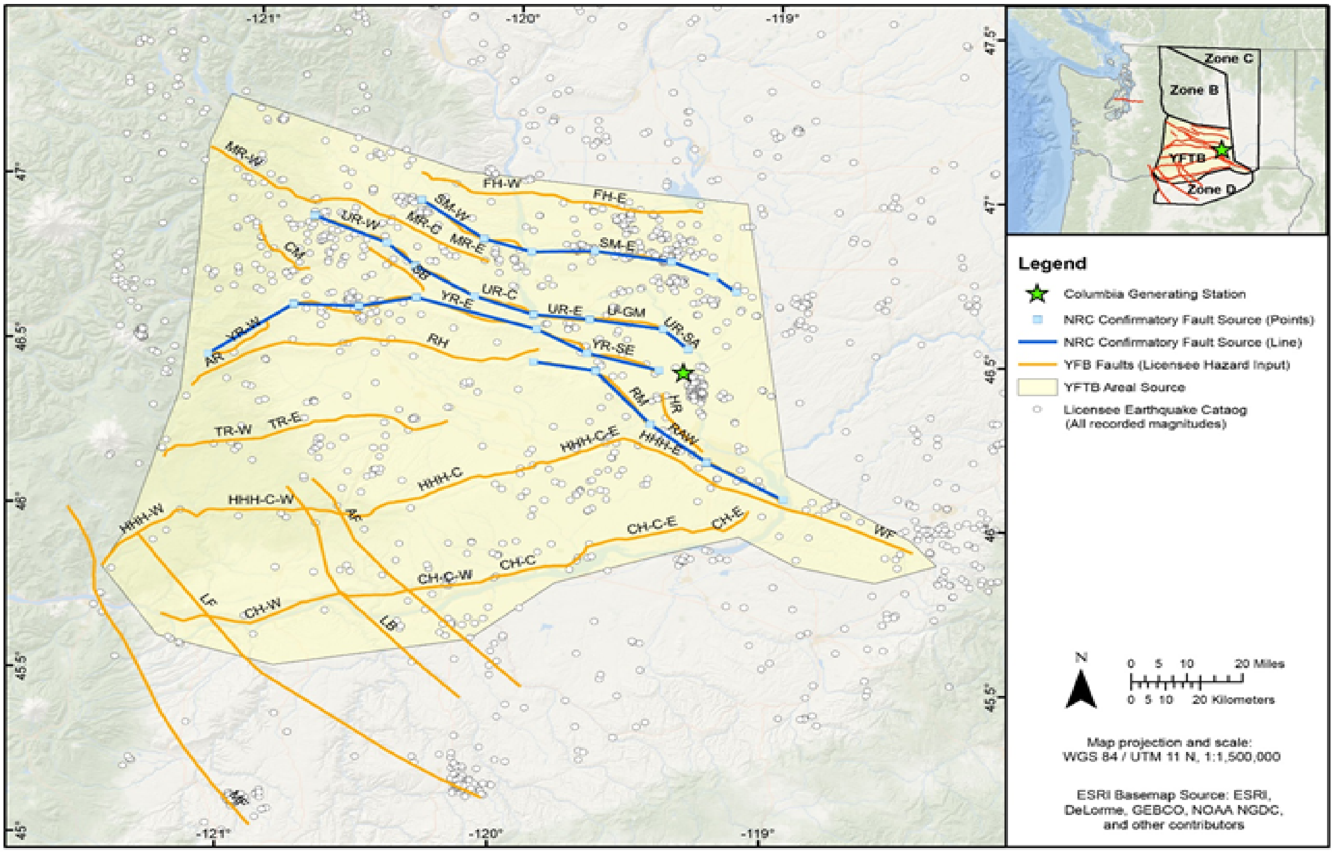

Figure 3.1-3. Licensee's 20 fault sources and NRC staff confirmatory fault sources: Ahtanum Ridge (AR), Arlington (AF), Cleman Mountain (CM), Columbia Hills (CH), Frenchman Hills (FH), Horn Rapids Fault (HR), Horse Heaven Hills (HHH), Laurel (LF), Luna Butte (LB), Manastash Ridge (MR), Maupin (MF), Rattles of the Rattlesnake-Wallula (RAW) alignment, Rattlesnake Hills (RH), Rattlesnake Mountain (RM), and Saddle Mountains (SM).

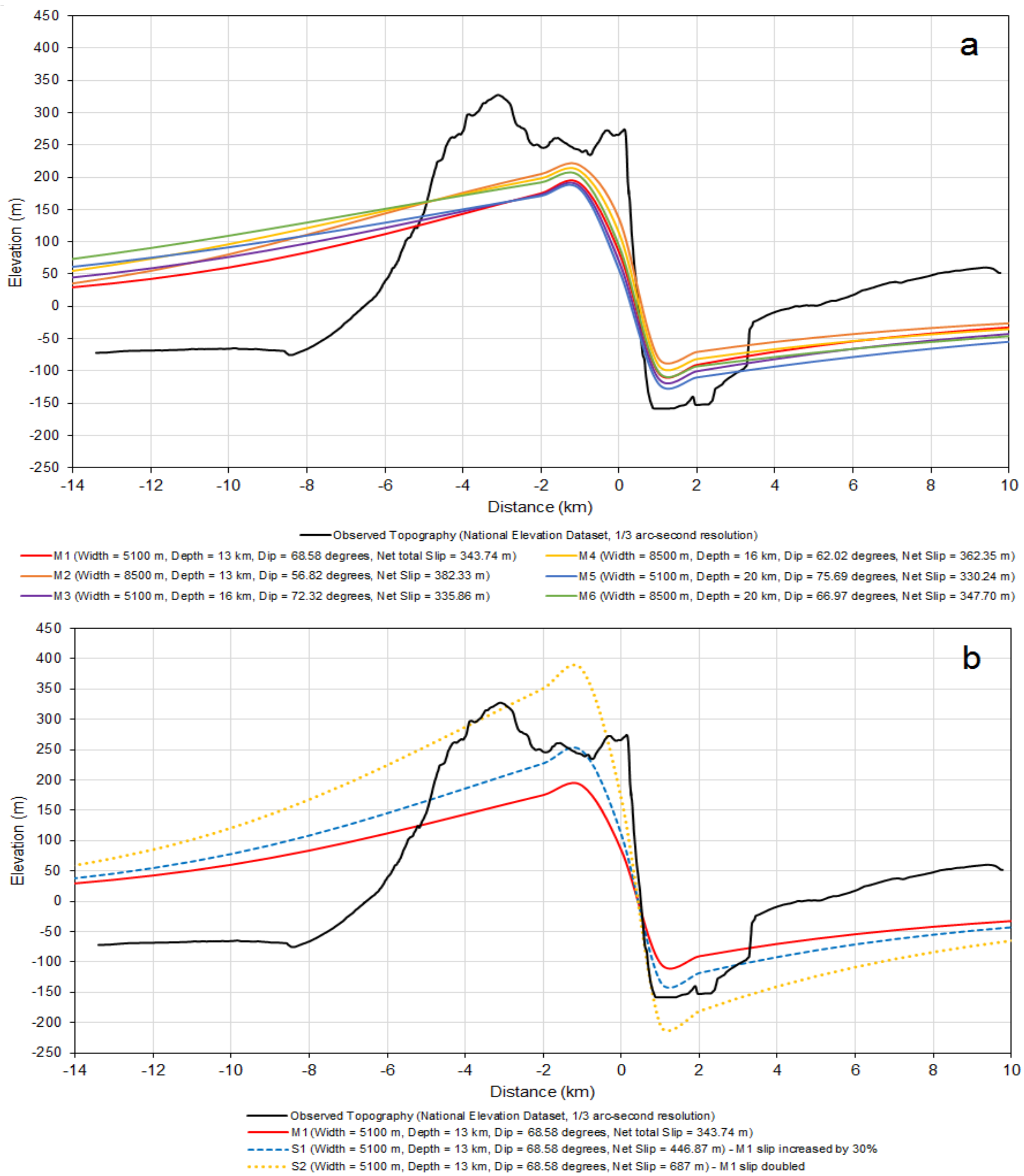

Figure 3.1-4. (a) Observed (black line) and modeled (colored lines) topography using the licensee's fault-source parameters and staff's elastic dislocation model for the Saddle Mountain Fault. (b) Observed (black line) topography and differences in modeled (colored lines) topography generated by increasing the fault slip-rate by 30 to 50 percent in staff's elastic dislocation model.

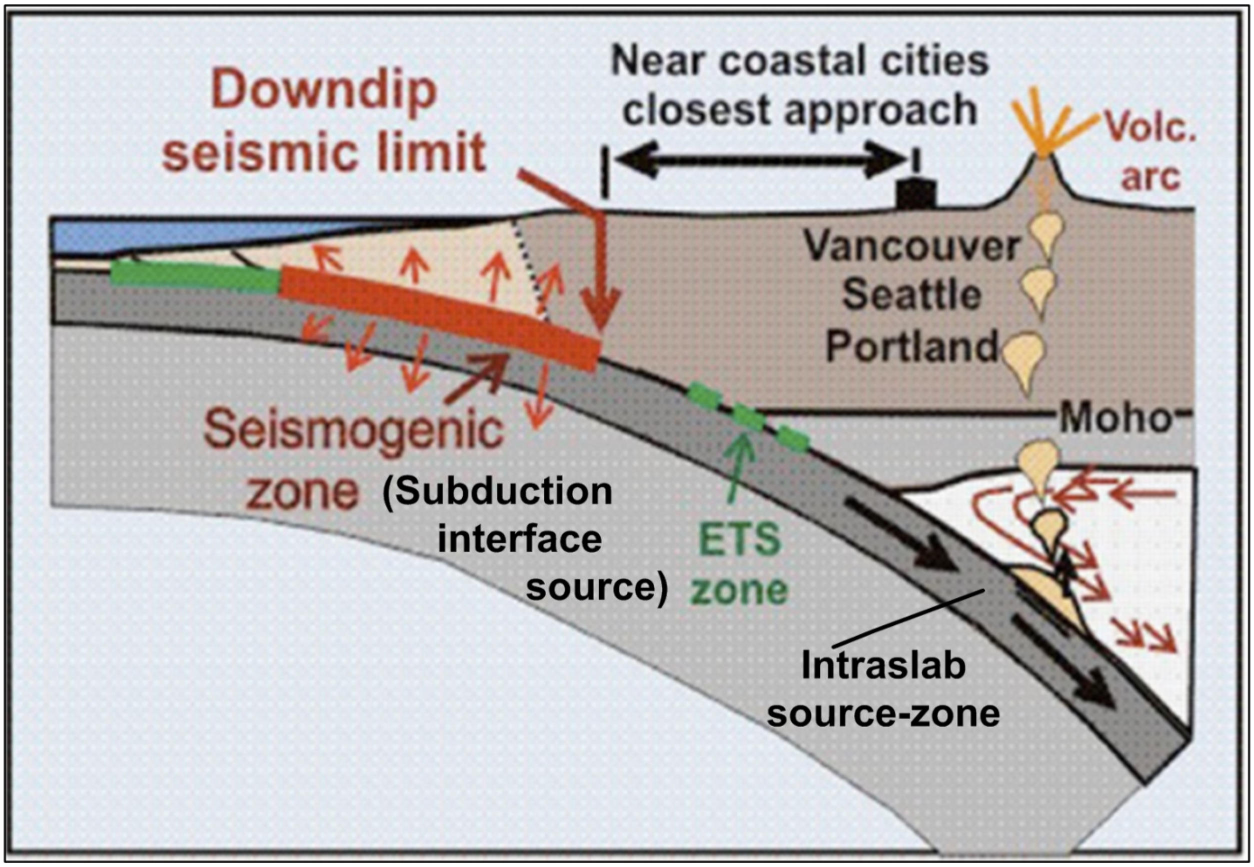

Figure 3.1-5. Seismic sources related to the Cascadia Subduction Zone, modified from Figure 8.8 in PNNL (2014). The subduction interface source is labeled as "seismogenic zone." The episodic tremor and slip (ETS) zone approximates the fore-arc mantle corner of McCrory et al. (2014), which is the line of intersection of the fore-arc Moho with the plate interface in the third dimension. The CGS site is right (east) of the volcanic arc, which is the axis of the Cascade Range.

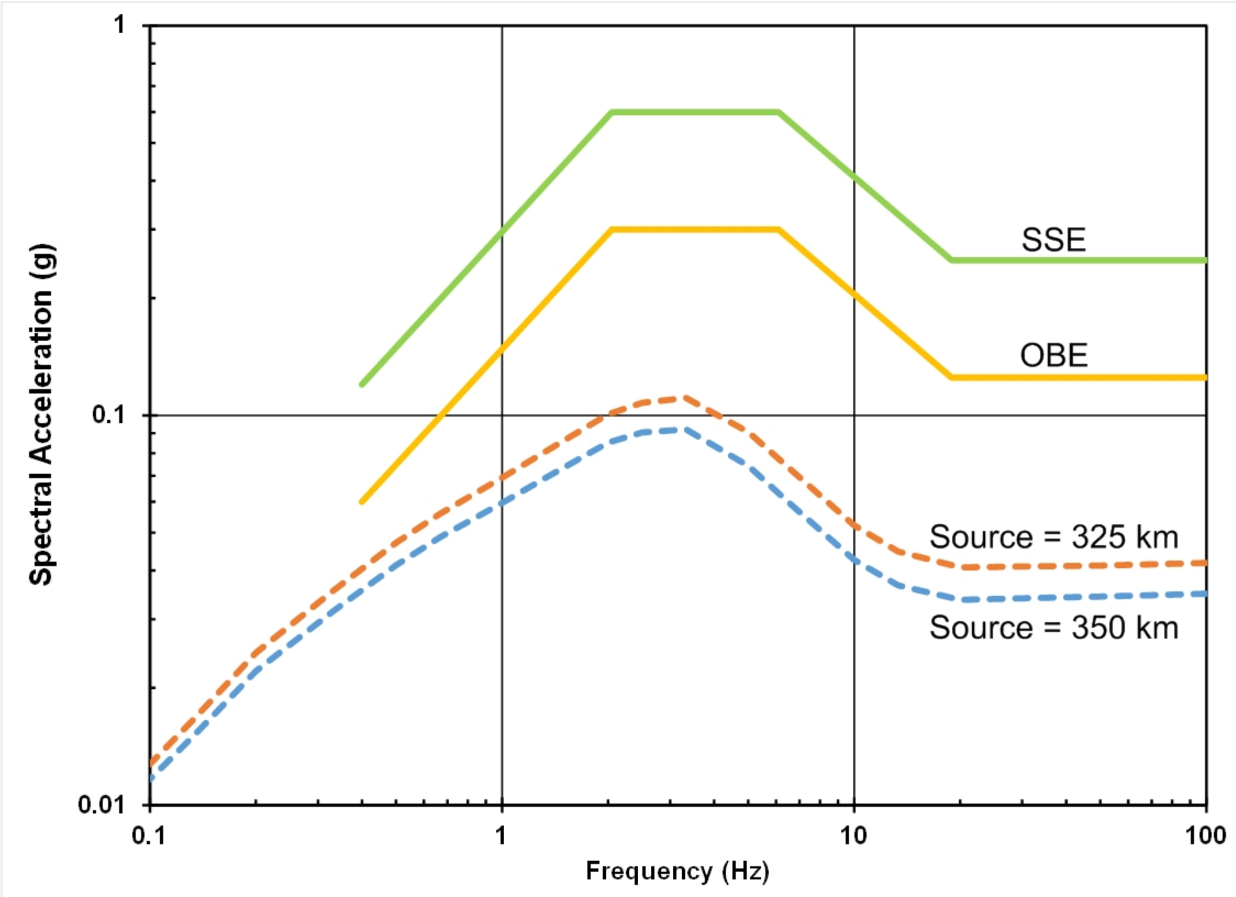

Figure 3.1-6. NRC staff's deterministic models of 84th percentile spectral acceleration at the CGS site from an **M**9.1 earthquake occurring 325 km (upper dashed line) and 350 km (lower dashed line) from the site in the Cascadia Subduction Zone. Safe shutdown earthquake (SSE) and operating basis earthquake for the CGS plant are shown for comparison.

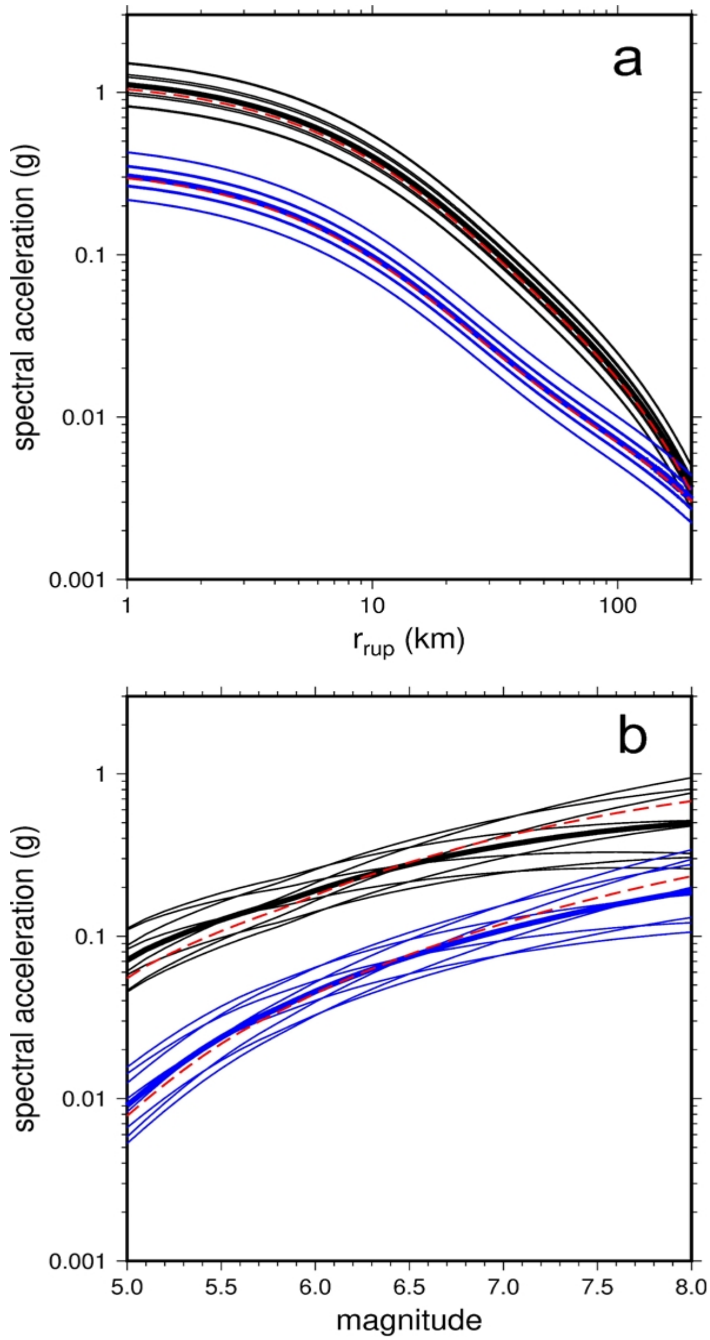

Figure 3.2-1. (a) Nine GMPEs for 1 (blue) and 10 (black) Hz spectral accelerations as a function of source-to-site rupture distance for an **M**6 earthquake. (b) The same nine GMPEs as a function of magnitude for a rupture distance of 20 km. Dashed red line is the CY14 backbone GMPE.

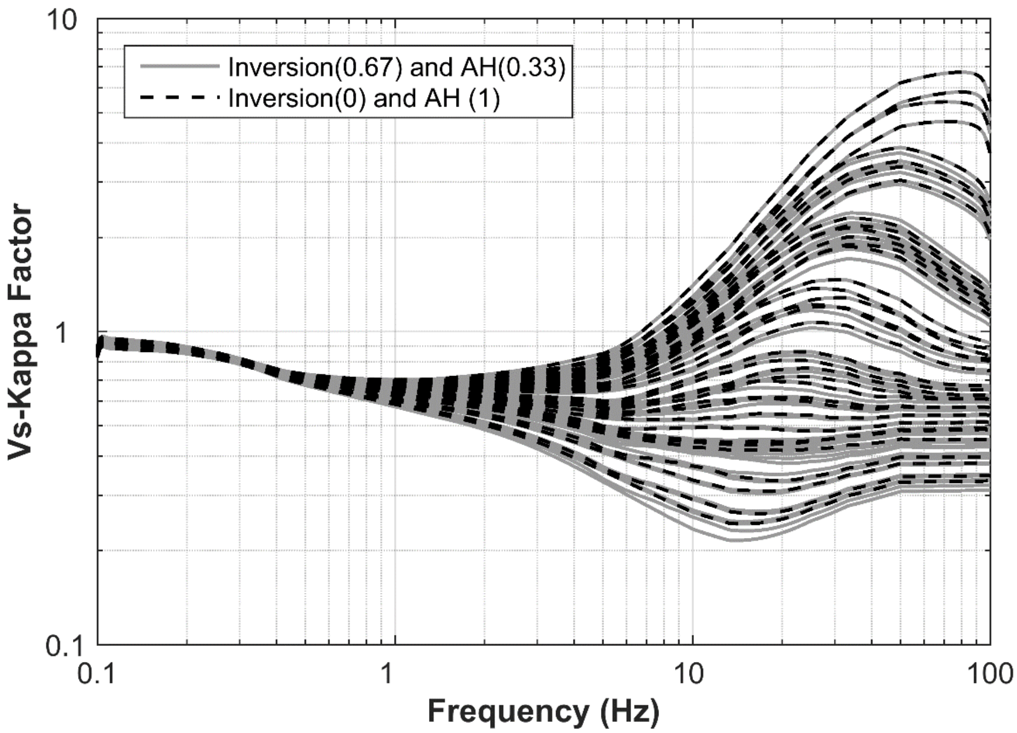

Figure 3.2-2. V_S-Kappa factors with alternative weighting applied to the target kappa based on NRC staff's confirmatory analyses.

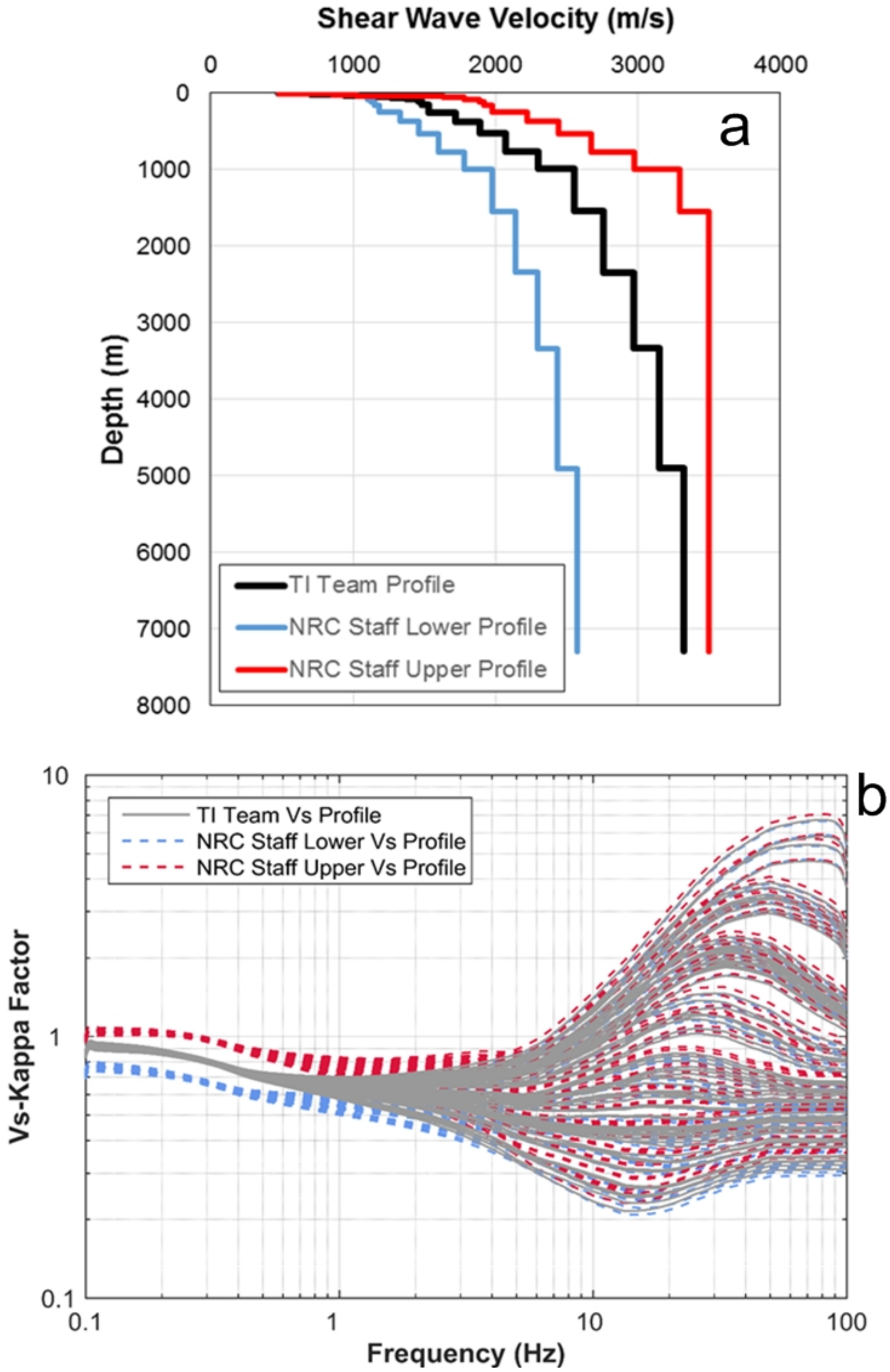

Figure 3.2-3. (a) NRC staff's alternative shear-wave velocity profiles for developing V_S-Kappa factors. (b) Comparison of V_S-Kappa factors when using alternative shear-wave velocity profiles for site amplification, based on NRC staff's confirmatory analyses.

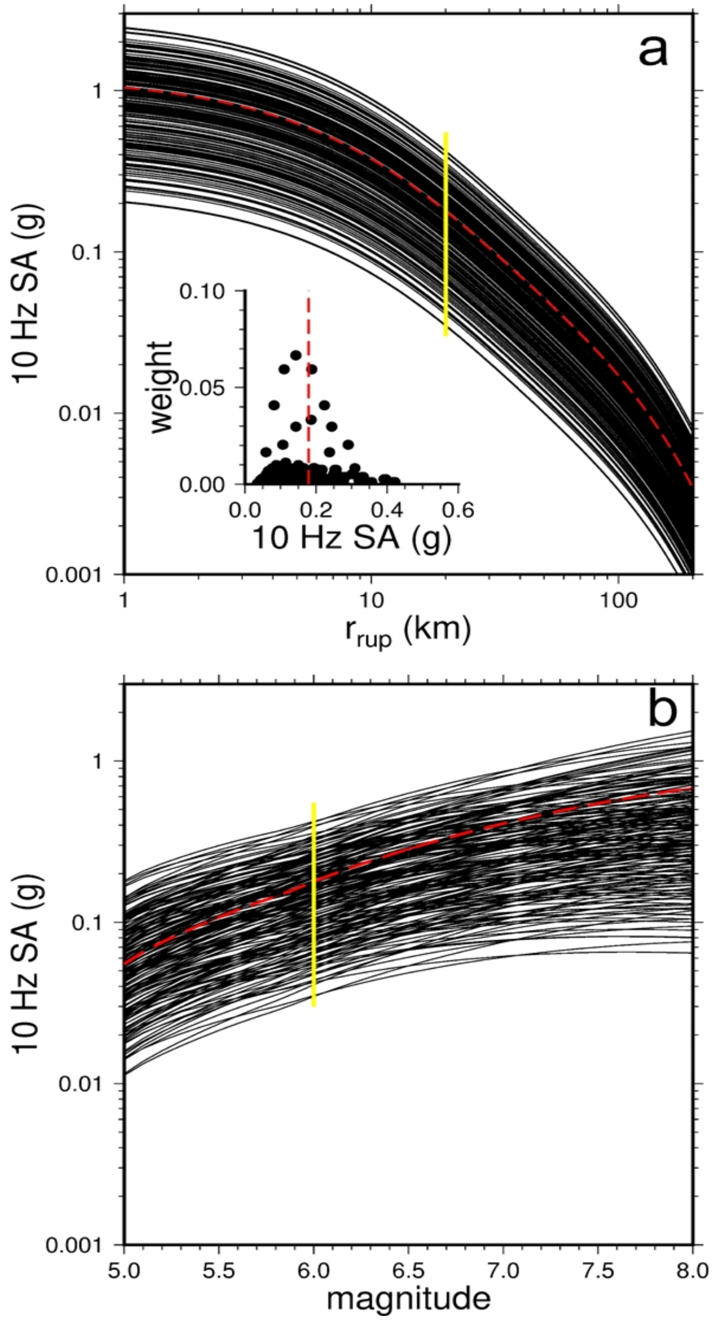

Figure 3.2-4. (a) 189 GMPEs for 10 Hz spectral acceleration as a function of source-to-site rupture distance for an **M**6 earthquake, based on NRC staff's confirmatory analyses. (b) The same 189 GMPEs as a function of magnitude for a rupture distance of 20 km. The inset to (a) shows the weighted distribution of median values for an **M**6 earthquake at a distance of 20 km as indicated by the vertical yellow lines in (a) and (b).

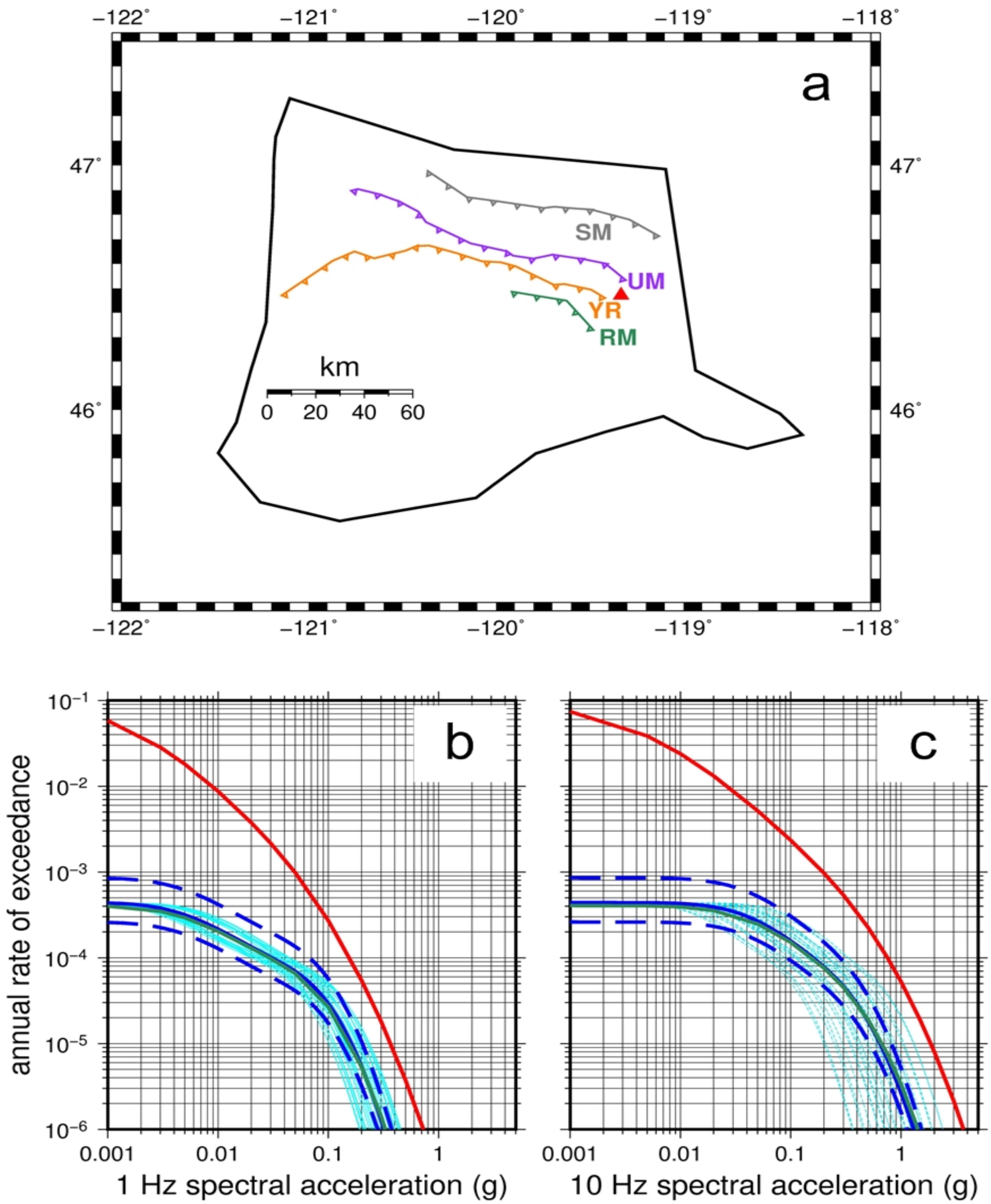

Figure 3.3-1. Staff's confirmatory calculation for the Rattlesnake Mountain fault, which uses 27 of the 189 crustal earthquake GMPEs (light blue lines). Hazard curves (blue dashed lines) result from using the 5th and 95th percentile slip rates for the Rattlesnake Mountain fault. The staff's confirmatory results (solid blue line) closely match the licensee's results (solid green line), for 1 Hz (b) and 10 Hz (c).

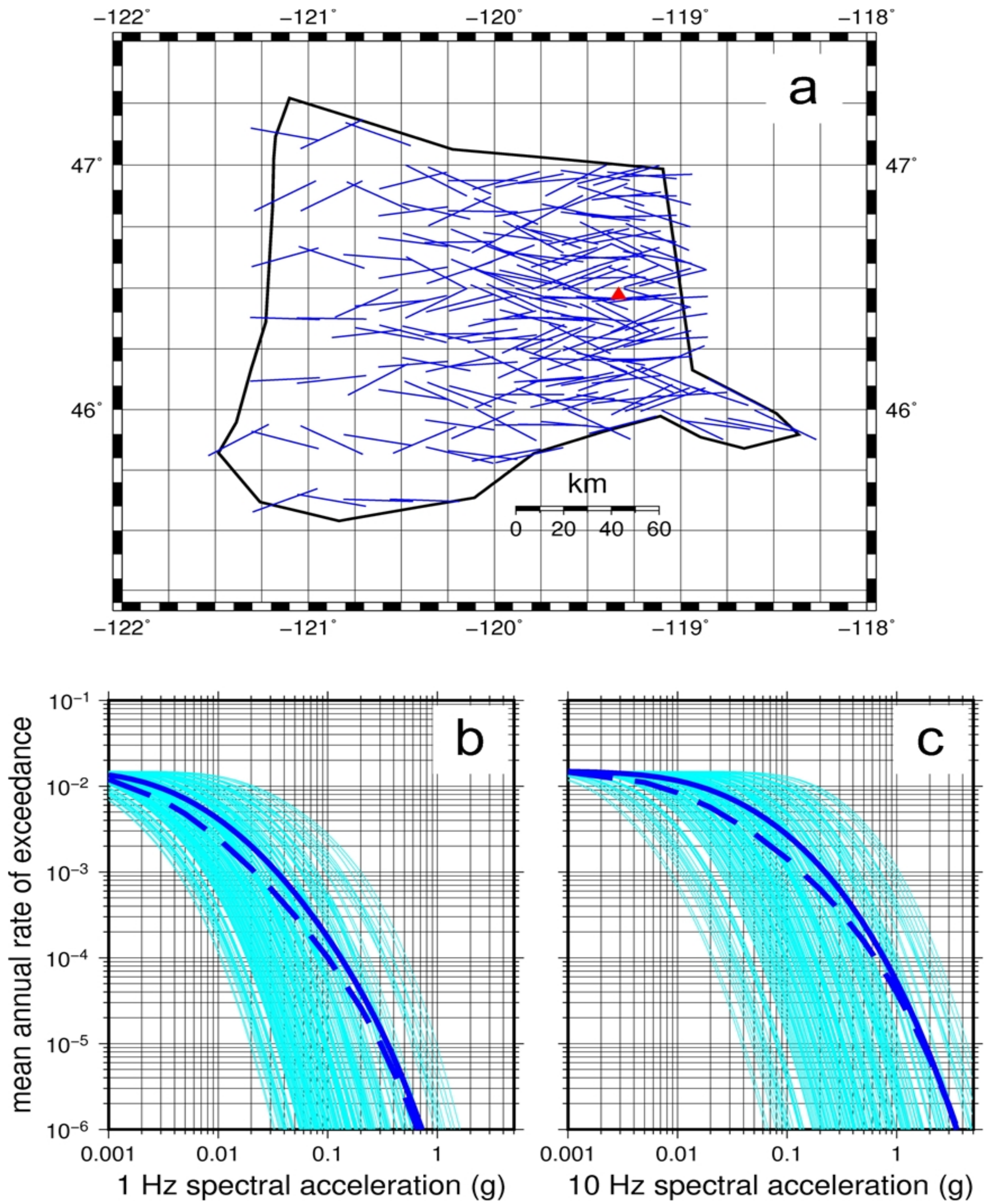

Figure 3.3-2. (a) NRC staff's confirmatory analysis showing the location of virtual faults for the YFTB source zone, with CGS site as red triangle. Staff's hazard curves for each of the 324 YFTB virtual faults (light blue lines) are shown with staff's (thick blue line) and licensee's (dashed blue line) mean hazard curves, for 1 Hz (b) and 10 Hz (c).

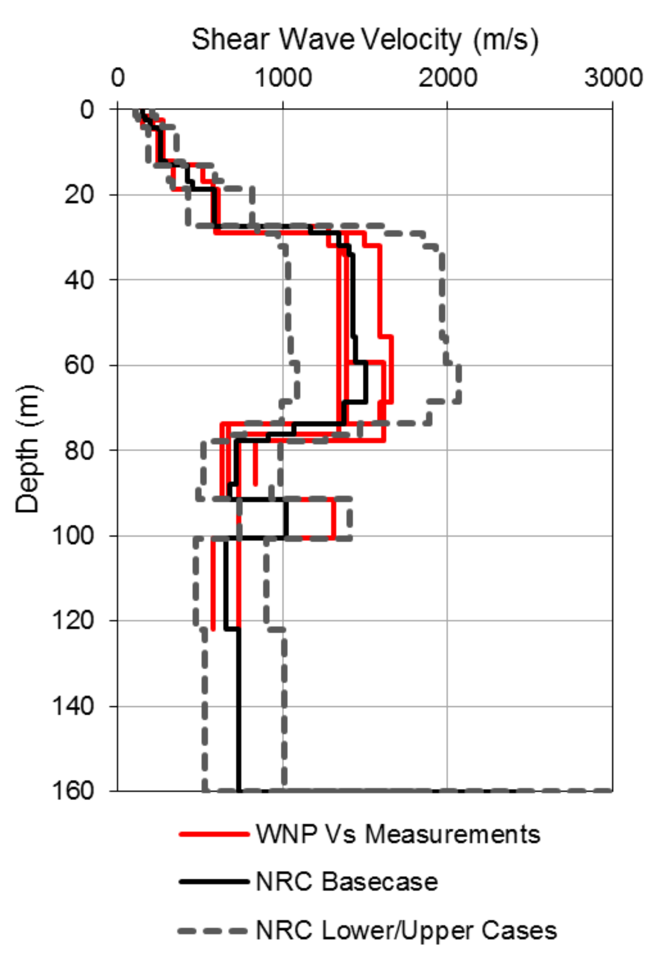

Figure 3.4-1. Measured shear wave velocities and NRC staff's shear wave profiles in upper strata. WNP (red lines) represents V_S measurements made for Washington Nuclear Power site investigations (PNNL, 2014).

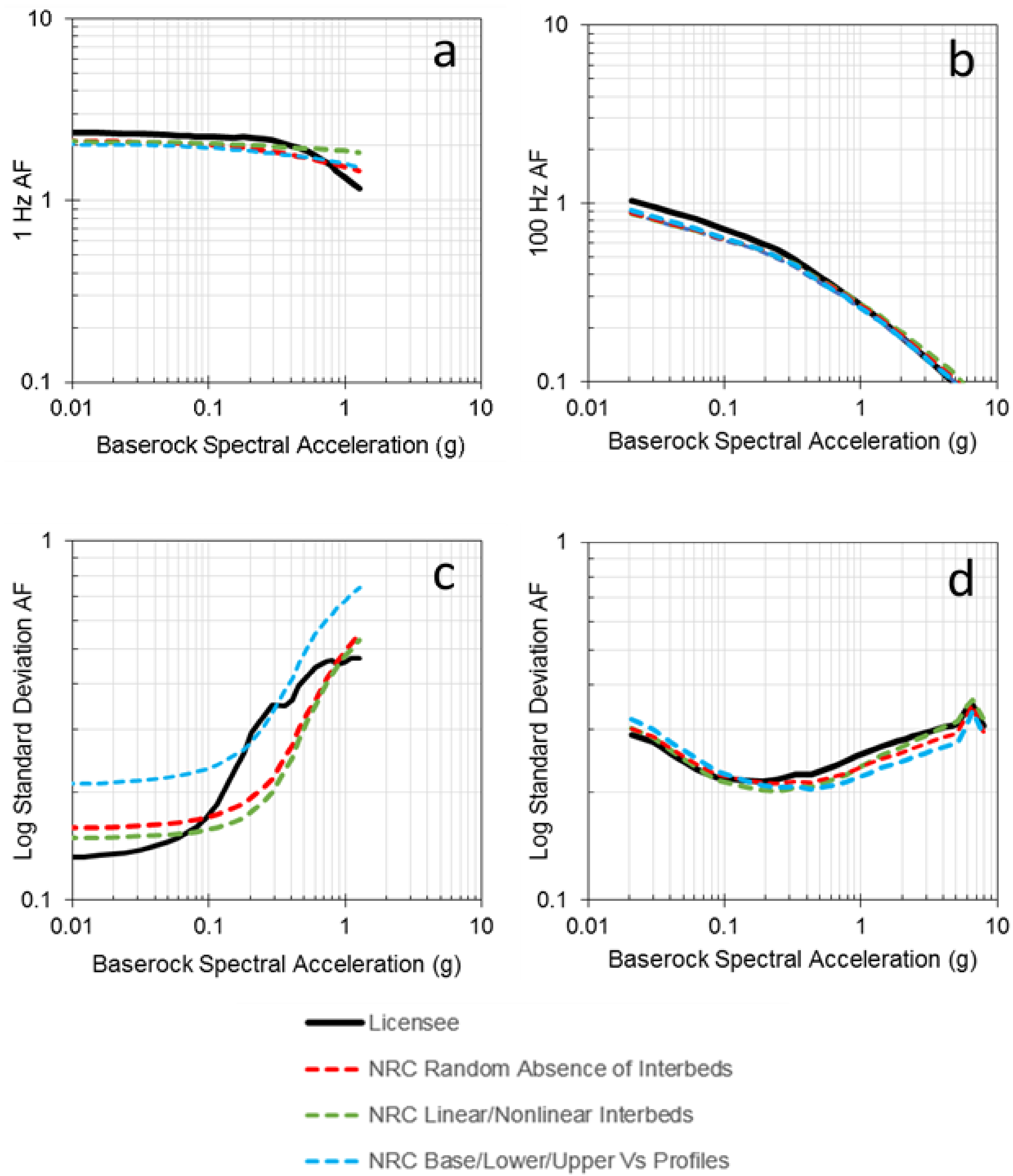

Figure 3.4-2. Comparison of NRC staff's confirmatory analyses with licensee's amplification functions and amplification function log standard deviation for (a) 1 Hz amplification, (b) 100 Hz amplification, (c) 1 Hz log standard deviation, and (d) 100 Hz log standard deviation.

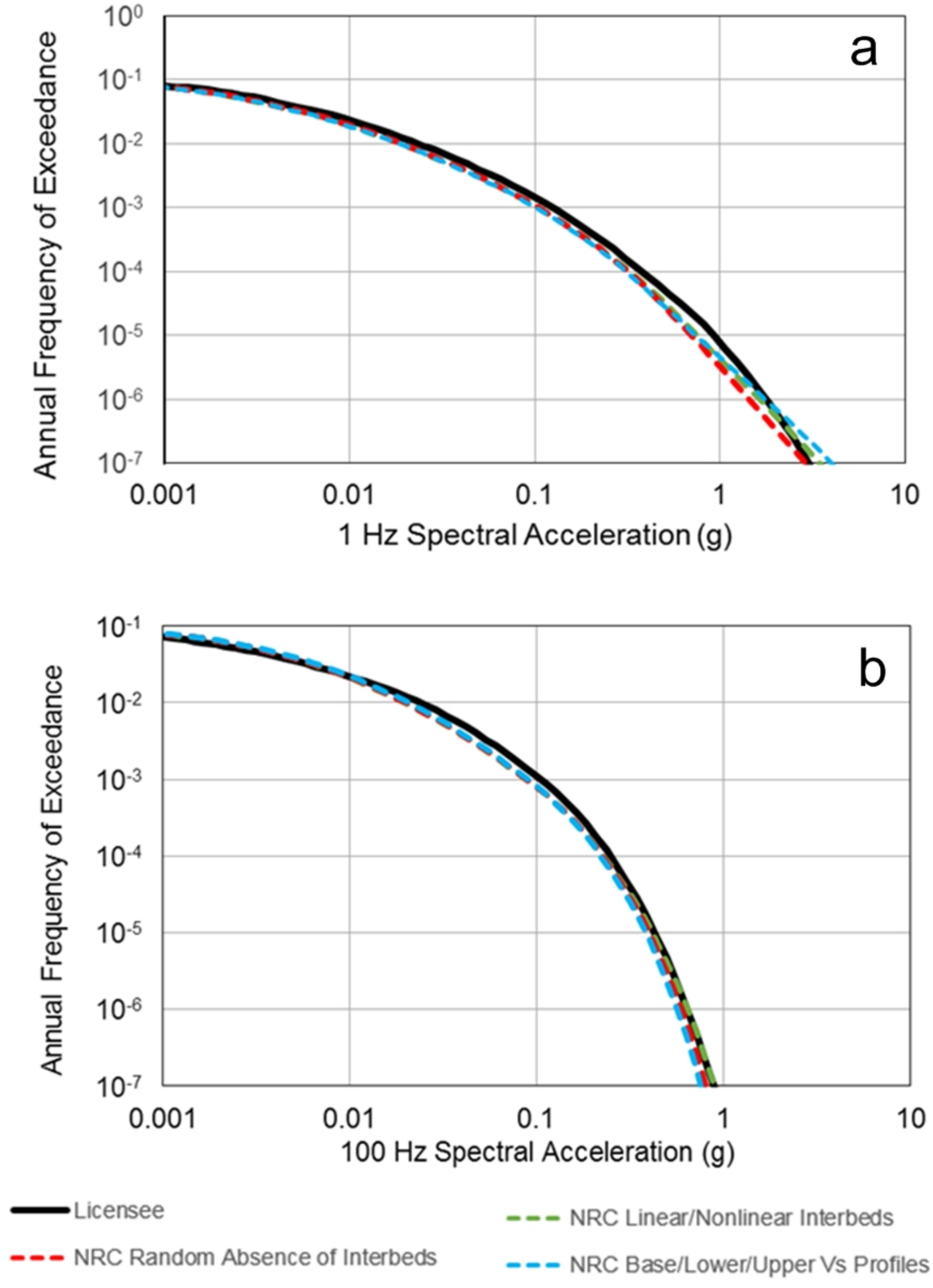

Figure 3.4-3. Comparison of licensee's and NRC staff's hazard curves at (a) 1 Hz spectral acceleration and (b) 100 Hz spectral acceleration.

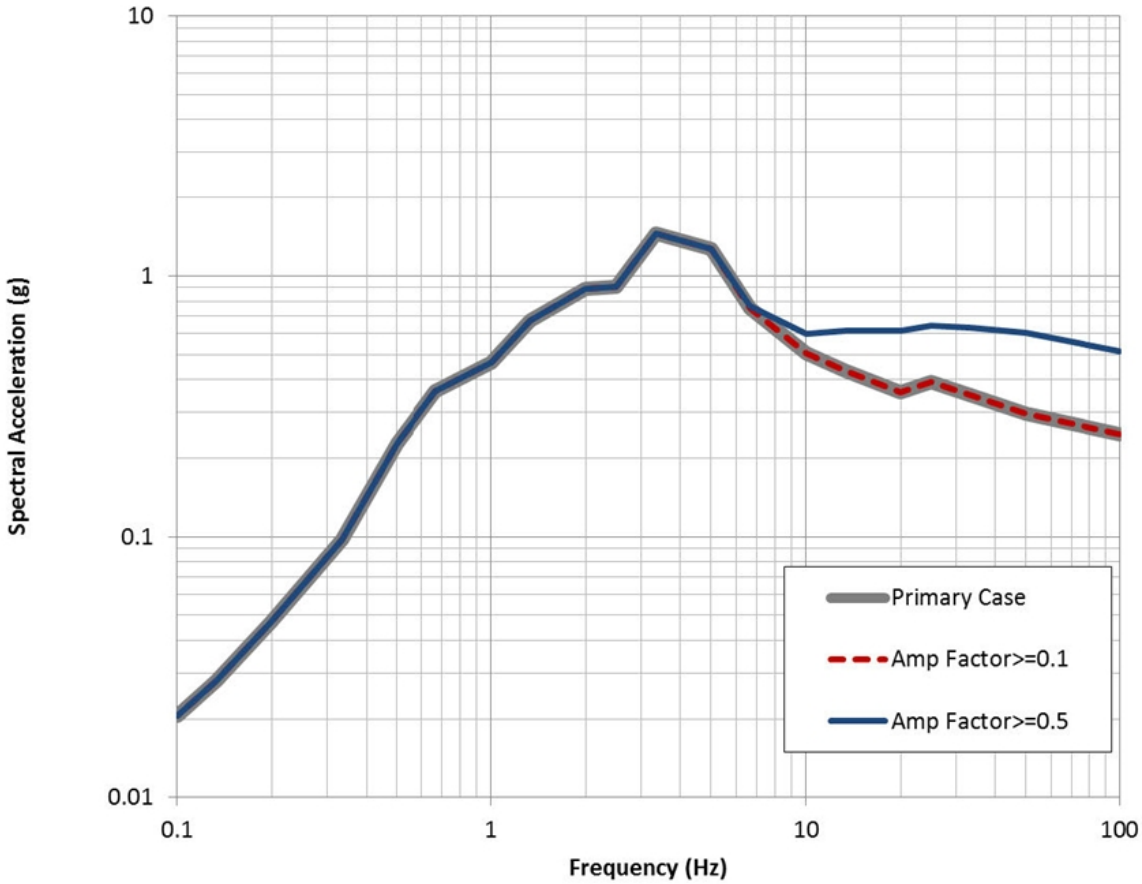

Figure 3.4-4. Licensee's sensitivity analysis of GMRS to minimum spectral amplification values, copied from Figure 4 in Swank (2015b).

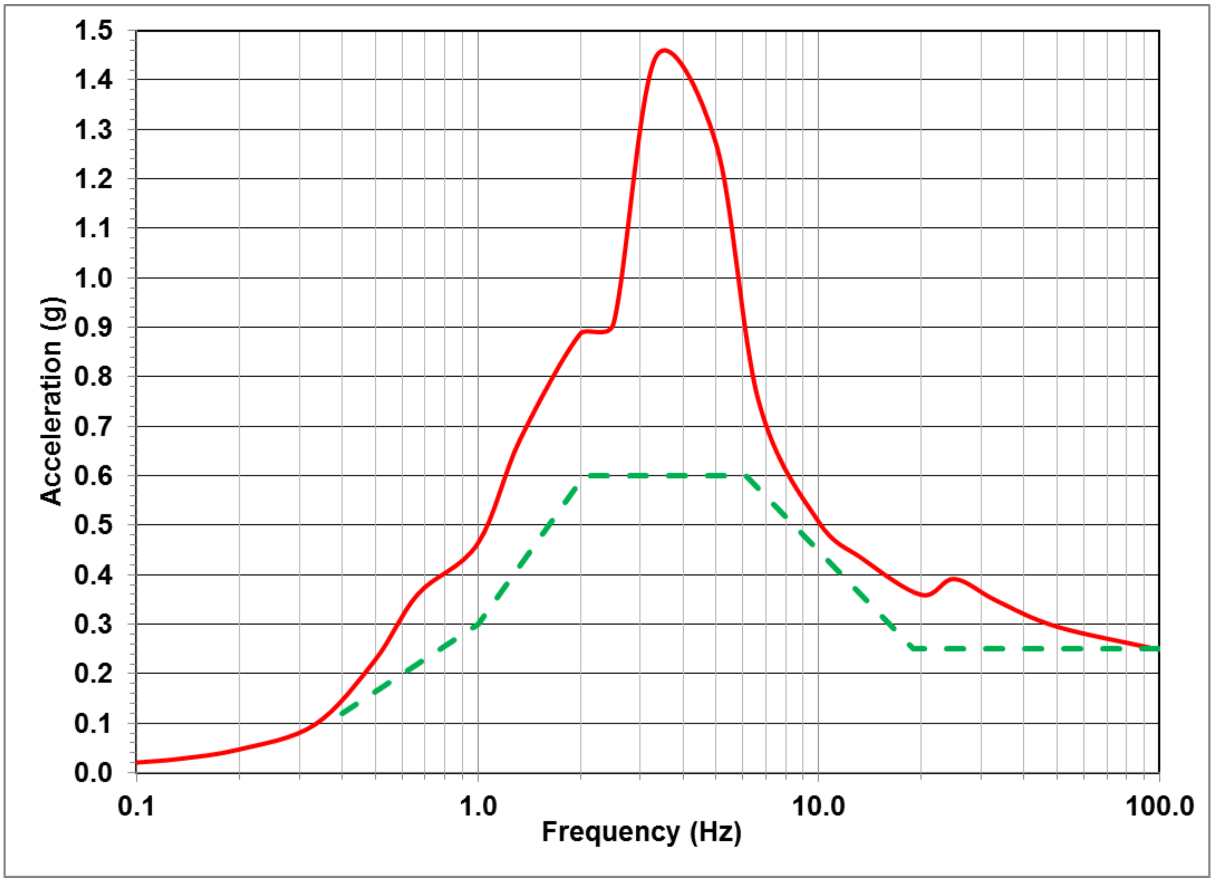

Figure 3.5-1. Ground Motion Response Spectrum (red solid line) and Safe Shutdown Earthquake (green dashed line) from SHSR for CGS (Swank, 2015a).