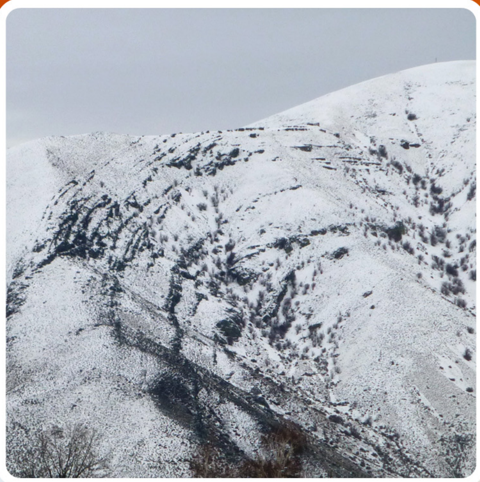
PNNL-23361

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*



Hanford Sitewide Probabilistic Seismic Hazard Analysis

November 2014

Prepared for the U.S. Department of Energy,
Under Contract DE-AC06076RL01830, and
Energy Northwest

U.S. DEPARTMENT OF ENERGY | RICHLAND OPERATIONS OFFICE
Office of River Protection

ENERGY NORTHWEST

LIMITED DISTRIBUTION NOTICE

Printed versions of the front matter, including the Executive Summary, and Appendixes A and B of this document are receiving limited distribution to the client. The full report is being delivered on a CD, copies of which are included in the back cover of each truncated printed deliverable.

This document was printed on recycled paper.
(9/2003)

PNNL-23361

Hanford Sitewide Probabilistic Seismic Hazard Analysis

Project Technical Integrator and Seismic Source Characterization Team Lead
Kevin Coppersmith

Ground Motion Technical Integration Team Lead
Julian Bommer

Seismic Source Characterization Team
Kathryn Hanson Jeff Unruh
Ryan Coppersmith Lorraine Wolf

Ground Motion Characterization Team
Bob Youngs Adrian Rodriguez-Marek
Linda Al Atik Gabriel Toro

Hazard Analyst
Valentina Montaldo-Falero

November 2014

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Author Affiliations	
Seismic Source Characterization Technical Integration Team	
Dr. Kevin Coppersmith	Coppersmith Consulting, Inc.
Mr. Ryan Coppersmith	Coppersmith Consulting, Inc.
Ms. Kathryn Hanson	AMEC Environment & Infrastructure, Inc.
Dr. Jeff Unruh	Lettis Consultants International, Inc.
Dr. Lorraine Wolf	Auburn University
Ground Motion Characterization Technical Integration Team	
Dr. Julian Bommer	Consultant, London, England
Dr. Linda Al Atik	Consultant, San Francisco, California
Dr. Adrian Rodriguez-Marek	Virginia Polytechnic Institute and State University
Dr. Gabriel Toro	Lettis Consultants International, Inc.
Dr. Robert Youngs	AMEC Environment & Infrastructure, Inc.
Hazard Analyst	
Dr. Valentina Montaldo-Falero	AMEC Environment & Infrastructure, Inc.

Abstract

This report presents the results of a Probabilistic Seismic Hazard Analysis (PSHA) of the Hanford Site in southeastern Washington State. It provides a detailed characterization of the vibratory ground motion hazard at the Hanford Site from potential future earthquakes. The study was conducted to fulfill the requirements for U.S. Department of Energy facilities and for the Columbia Generating Station to update the previous seismic hazard analysis. This PSHA was conducted using Level 3 procedures advanced by the Senior Seismic Hazard Analysis Committee (SSHAC) in detailed guidance published by the U.S. Nuclear Regulatory Commission, and provides results at five hazard calculation sites at Hanford. Project organization and the SSHAC Level 3 framework for the PSHA are described, followed by key project tasks and activities. The tectonic setting of the Hanford Site is described to provide context for the PSHA and potential seismic sources, prior to presenting a summary of new data collection and analytical activities conducted to reduce uncertainties in key aspects of the seismic source characterization (SSC) and ground motion characterization (GMC) models. Detailed descriptions are next provided of the elements of the SSC and GMC models and their technical justification. These models serve as input to the Hanford PSHA hazard calculations. The PSHA results are presented in the final chapter, which is followed by appendixes containing detailed supplemental information, including related studies and hazard input documents. The outputs of the PSHA can be used to establish the seismic design of new facilities and for safety reviews of existing facilities, by combining the PSHA results with site response analyses conducted using site-specific geotechnical information.

Executive Summary

This report documents the sitewide probabilistic seismic hazard analysis (PSHA) of the Hanford Site (hereafter Hanford PSHA) in southeastern Washington State that was undertaken by Pacific Northwest National Laboratory (PNNL) and its contractors for the U.S. Department of Energy (DOE) Office of River Protection (ORP), DOE Richland Operations Office (RL), and Energy Northwest to provide a detailed characterization of the vibratory ground motion hazard at the Hanford Site from potential future earthquakes.

ES.1. Project Purpose, Scope, and Objectives

The study reported herein was conducted to fulfill the requirements for DOE facilities as well as those for commercial nuclear power plants, through a collaboration and joint sponsorship between DOE and Energy Northwest. The study fulfills the commitment made by DOE to update the PSHA, which was made after the review of the current PSHA required by DOE Order 420.1C (Facility Safety). In addition, the study fulfills the requirement from the U.S. Nuclear Regulatory Commission (NRC) that Energy Northwest conduct a PSHA using Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 procedures for the Columbia Generating Station (CGS). Because the Hanford Site includes several facility sites, the PSHA has been conducted such that seismic hazard is calculated at five sites that are located across the Hanford Site (Figure ES.1); these are called “hazard calculation sites” in this document.

Earthquake-related studies have been conducted at the Hanford Site since the late 1970s when they were carried out for purposes of licensing of the Washington Public Power Supply System nuclear power plant sites. Likewise, studies for DOE were conducted over the past 40 years as part of a variety of activities, including the Basalt Waste Isolation Program. However, the most recent PSHA that followed conventional practice was the PSHA published by Geomatrix in 1996 for the Hanford Site. That study was sponsored by DOE and intended for use at the DOE nuclear facilities. The 1996 PSHA was conducted prior to the issuance of the SSHAC Guidelines, but the study corresponded generally to what would now be considered a SSHAC Level 2 study. From the time of its issuance, the results of the 1996 PSHA have provided the input “free field” ground motions for a variety of ground motion assessments for purposes of design or design review. These include DOE facilities such as the tank farm facilities, the Waste Treatment Plant (WTP), and the single-shell tank facilities. In all cases, the 1996 PSHA provided the input ground motions, at appropriate annual frequencies of exceedance, which were then modified to incorporate site-specific soil conditions and potential soil-structure interaction effects. Thus, although facility-specific seismic analyses have been conducted for many years at the Hanford Site since completion of the 1996 PSHA, the hazard analysis had not been updated since that time.

The decision by DOE to replace the 1996 PSHA was made in light of decision criteria that exist as DOE Orders and Standards that have been developed within the professional community. Similar decision criteria have more recently been put in place for NRC-regulated facilities. However, the decision by Energy Northwest to participate in the Hanford PSHA was also motivated by NRC directives that were developed in response to the Fukushima Daiichi nuclear power plant accident.

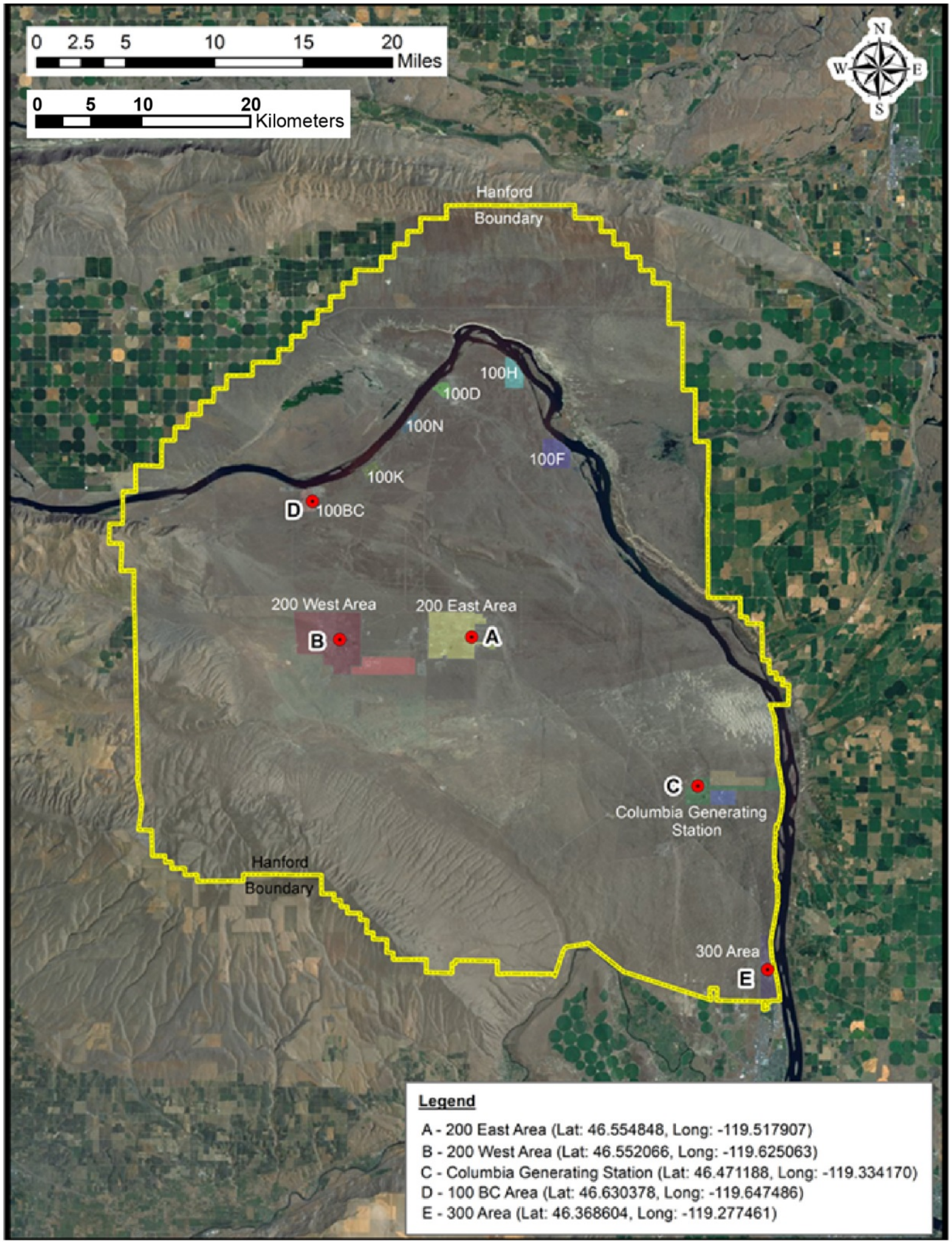


Figure ES.1. Map of the Hanford Site (border shown in yellow) and the five hazard calculation sites (indicated by the red dots). Sites A, B, D, and E are regions containing DOE facilities and Site C is Energy Northwest's Columbia Generating Station site.

The ultimate objectives of the Hanford PSHA are twofold: 1) develop a technically defensible seismic hazard analysis and associated hazard products that can be used for design and safety reviews at the Hanford Site, and 2) conduct the PSHA according to a SSHAC Level 3 process that is consistent with available regulatory guidance. The hazard is expressed at the ground surface in terms of 5%-damped horizontal response spectral ordinates at 20 oscillator frequencies between 0.01 and 10.0 sec. Because the near-surface materials are currently not characterized in sufficient detail for site response analyses at all of the facility locations (other than the WTP site and, to some extent, the CGS plant), the decision was made to limit the PSHA scope to the estimation of ground motions in a defined baserock horizon. These motions can be convolved with site amplification factors obtained from site response analyses at each location at which surface motions are required. Characterization of the near-surface sediment layers (above the basalts) and convolution of the baserock hazard with the site amplification functions are outside the scope of the PSHA project, but the project did include the characterization of all stratigraphic layers from the baserock horizon to the top of the basalts, and guidelines are provided for both the execution of the site response analyses and the convolution of the baserock motions with the site amplification functions. The scope of the PSHA project also included recommendations for vertical-to-horizontal (V/H) response spectral ratios to be applied to the surface motions in order to obtain vertical response spectra.

ES.1.1. Analytical Process: SSHAC Level 3

The Hanford PSHA was conducted using processes that are appropriate for a Study Level 3, as presented in the guidance advanced by the SSHAC in NUREG/CR-6372, *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*—known informally as the SSHAC Guidelines—as well as the detailed implementation guidance provided in NUREG-2117, *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*.

The input to the PSHA to calculate the hazard at the baserock horizon consists of a seismic source characterization (SSC) model and a ground motion characterization (GMC) model. The SSC model defines the location and average rates of all potential future earthquakes of different magnitudes up to the maximum considered physically possible within each source. The GMC model predicts the expected distribution (defined by a logarithmic mean value and an associated logarithmic standard deviation) of spectral accelerations at a site due to a particular earthquake scenario. The PSHA calculations calculate the resulting ground motions from all possible earthquake scenarios and from sampling the full distribution of ground motion amplitudes, to obtain estimates of the total rate at which each level of acceleration is expected to be exceeded at the site.

The quantity of data available regarding earthquake occurrence and ground motion generation in any region is never sufficient to unambiguously define the SSC and GMC models. One reason for this is that the completeness of the data, and sometimes its quality as well, are such that different experts assessing the data arrive at diverse interpretations, all of which may be technically defensible. Another reason is that the PSHA calculations will always consider earthquake scenarios for which no data at all are available, such as large-magnitude earthquakes at short distances from the site. These are examples of what is referred to as epistemic uncertainty, which reflects lack of knowledge regarding earthquake processes in general and in the study region in particular. This uncertainty is incorporated in the PSHA calculations.

The SSHAC Level 3 process as given in current regulatory guidance defines clear roles and responsibilities for all participants. All technical assessments including the final hazard model and documentation are developed by Technical Integration (TI) Teams that perform this work in two stages: evaluation and integration. In the evaluation stage, the TI Teams assess available data, methods, and models both for their inherent quality and reliability, and specifically for their applicability to the region and site under consideration. In the integration phase, the TI Teams construct logic trees that capture the center, the body, and the range of technically defensible interpretations. The work is conducted under the continuous observation of the Participatory Peer Review Panel (PPRP), which is charged with performing both technical and process reviews. The PPRP is responsible for reviewing the activities of the TI Teams to ensure that the project satisfactorily considers available data, methods, and models; captures the center, body, and range of technically defensible interpretations; and adequately documents the technical bases of all decisions. PPRP concurrence that these goals have been met is the key indicator of successful compliance with the requirements of a SSHAC Level 3 process.

The Hanford PSHA was conducted from April 2012 to October 2014. The project included a kick-off meeting in April 2012 conducted at PNNL facilities in Richland, Washington, and a tour of the Hanford region. Three workshops were held in Walnut Creek, California. Workshop 1 identified significant seismic hazard issues and data available to address those issues. Workshop 2 reviewed the databases assembled by the teams and discussed alternative models that related to the seismic source or ground motion models for the project. Workshop 3 provided an opportunity for the technical integration teams to present their preliminary SSC and GMC models to the PPRP and receive feedback. Hazard feedback based on hazard calculations using the preliminary models was also provided at Workshop 3. Seven working meetings (four for seismic source characterization and three for ground motion characterization) were held in Oakland, California, over the course of the project to facilitate interaction between the team members; due to family circumstance preventing travel, the first GMC Working Meeting was conducted as a conference call. As is typical of SSHAC Level 3 projects, the total number of participants entailed a large group of about 50 individuals.

ES.1.2. Hanford Site Tectonic Setting

The Hanford Site is located east of the region tectonically dominated by the Cascadia subduction zone, where the Juan de Fuca plate under-thrusts northern California and western Oregon and Washington along the Cascadia subduction zone. Magmatism related to the subduction zone is represented by the Cascade volcanoes, which lie to the west of the Hanford Site. Following establishment of the Cascadia subduction zone and related volcanic chain, the later geologic history of eastern Washington was dominated by eruption and deposition of the Columbia River basalts (CRBs). The CRB flows in eastern Washington are deformed in a series of generally east-west-trending anticlines underlain by reverse faults that are known collectively as the Yakima Fold Belt (YFB). The reverse faults of the YFB dominate the post-CRB tectonics and topography in eastern Washington. The Yakima folds are anticlines that have accommodated approximately north-south shortening. Seismicity and geodetic indicators of contemporary tectonics confirm that north-south stresses continue to be the dominant stress mechanism. However, the rates of shortening, uplift, and fault slip, as recorded by the deformation of various units of the CRB, show that rates of deformation are low relative to the slip rates of faults within active tectonic regions.

The Hanford Site is characterized by a relatively thin layer of supra-basalt sediments (mainly the Hanford and Ringold formations), which have thicknesses ranging from 60 to 200 m at the five hazard calculation sites. These sediments are underlain by the basalt flows of the Saddle Mountain basalts (SMB) sequence and interbedded Ellensburg formation sediments; the basalt-interbed stacks have a thickness of about 250 m at the hazard calculation sites. Below the SMB are the Wanapum basalts (WBs) and Grande Ronde basalts, collectively forming the CRB, with a total thickness of 2 to 3 km at the hazard calculation sites. The CRB is underlain by a thick layer of pre-Miocene sediments, with the crystalline basement encountered at depths ranging from 7.5 to 9 km at the five hazard calculation sites.

Regional seismicity in the YFB region is dominated by small-magnitude earthquakes that occur within the CRB units in the upper 3 km, and more diffuse seismicity that extends to depths of about 20 km. Rates of moderate-to-large earthquakes are low relative to plate boundary regions. Within the YFB region, the largest observed earthquakes are the 1936 Milton-Freewater earthquake (M 6) and the 1872 Lake Chelan earthquake (M 6.5–7). To the west of the site region, earthquakes are mainly associated with the Cascadia subduction zone and Holocene crustal faults in the Puget Lowland.

ES.2. Technical Foundation for the PSHA

The technical foundation for the Hanford PSHA was developed through the SSHAC Level 3 processes of *evaluation* and *integration*. The *evaluation* phase of the project entails the identification, compilation, and review of data, models, and methods that exist within the larger technical community. During the *integration* phase of the project, the TI Teams develop their SSC and GMC models that represent the center, body, and range of technically defensible interpretations.

The evaluation phase of the Hanford PSHA entailed the gathering and reviewing of existing literature and data sets, collecting new data and information focused on key SSC and GMC issues, and assembling the earthquake catalog for the region. Data compilation began at the time of project authorization and continued to the point at which the final SSC and GMC models were developed. The data compiled by the project team include references from the literature, site-specific information developed for the Hanford Site, publicly available information developed by other agencies, and other hazard studies. As part of this evaluation activity, data focused on specific technical issues of interest were presented at Workshop 1, and alternative models and methods that were potentially applicable to the Hanford PSHA were presented and discussed at Workshop 2. As the project progressed, the database development activity included preparation of derivative maps and products that are directly applicable to the PSHA (e.g., seismicity maps) and conducting analyses that provided input information to the TI Teams (e.g., geochronology results, shear-wave velocity profiles).

Aspects of the data developed for the evaluation phase of the project that are specific to the SSC and GMC subprojects are described in the following sections.

ES.2.1. Seismic Source Characterization Data

The SSC component of the Hanford PSHA entailed the compilation and review of a wide range of data and information that exist within the technical community. Data sources included available information from the following sources: professional literature; data held in the public domain, such as studies conducted for facility sites at Hanford; private domain data such as those developed as part of oil exploration activities; and unpublished data including the results of ongoing investigations. To the extent possible, mapped information was compiled in geographic information system (GIS) formats that allowed the TI Team to superimpose various combinations of data layers for use in interpretations and developing the SSC model. In addition to the GIS database, a comprehensive bibliography of literature was compiled for use by the TI Team. This bibliography built upon the seismic/geologic bibliography already developed by PNNL.

In addition to data existing within the community, the Hanford PSHA evaluation process also included the collection of new data that were focused specifically on the reduction of uncertainties in the key inputs to the SSC models. New data that were developed during these efforts are also included in the database and were used extensively by the SSC TI Team. Activities conducted to supplement existing data included the following:

- Quaternary Geologic Studies: Field mapping, geomorphic analyses, and structural geologic data analyses were conducted to support the quantitative structural analysis of the Yakima folds. These analyses were conducted in conjunction with tectonic geomorphic analyses of the Yakima River terraces, geochronological analyses, and other geologic investigations designed to characterize the timing and rate of Quaternary uplift—or lack of uplift—associated with various folds. The structural analyses included limited field reconnaissance and topographic analyses to establish the relationship between topographic relief and structural relief associated with each Yakima fold in the site region. In turn, these data were used with fault models to assess the downdip geometry of the folds and faults, as well as the amount and rates of fault slip.
- High-Resolution Seismicity Relocations: Using state-of-the-art double-difference relocation techniques, high-resolution three-dimensional (3-D) earthquake locations were determined using the programs HypoDD and TomoDD and existing high-quality seismicity data. This task also involved a review of the focal mechanisms and consideration of the spatial distribution of seismicity relative to hypocentral depth distributions and possible associations with faults.

The SSC data compilation activities also included the evaluation of the data, following the guidance provided by the NRC in NUREG–2117. The SSC TI Team developed data summary/evaluation tables that are appropriate for the types of data that were compiled for the Hanford Site. The purpose of the data tables was to clearly document all data that had been considered by the SSC TI Team and, for those data that were actually used to develop the SSC model, to document the degree of reliance afforded to specific data sets in the development of the SSC model.

ES.2.2. Earthquake Catalog

Like all seismic hazard analyses, the earthquake catalog provides an essential database needed in the development of an SSC model. For the Hanford PSHA, two earthquake catalogs were compiled: the crustal earthquake catalog and the Cascadia subduction zone catalog. These two earthquake sources have different characteristics, so for the purpose of calculating earthquake recurrence parameters for the crustal and subduction seismic sources, they were maintained in two separate catalogs. The process of compiling the two earthquake catalogs was the same as that given in Central and Eastern United States Seimic Source Characterization for Nuclear Facilities in NUREG-2115; records from multiple sources were merged, compared, and uniformly processed to obtain a complete catalog with a uniform size measure for all earthquakes. The purpose of merging earthquake records from different sources is to limit the effect of partial network coverage in time and space, and to obtain a data set of alternative magnitude measures for use in deriving magnitude conversion equations. The process of homogenizing the magnitudes to a uniform moment magnitude measure and calculating unbiased earthquake counts to be used in recurrence analysis allows proper treatment of the uncertainty in the magnitude estimates and in the magnitude conversions. For earthquake recurrence assessments, the catalog undergoes a declustering process to remove all foreshocks and aftershocks, the completeness of the catalogs is assessed as a function of location, time, and earthquake size.

ES.2.3. Ground Motion Characterization Data

Three components of the database were used to carry out the GMC model development for the Hanford PSHA: 1) a list of the ground motion prediction equations available worldwide that can potentially be applicable to the project, together with their characteristics; 2) data that can be used to constrain the applicability of any equation to the Hanford Site; and 3) characterization of the representative near-surface geological profiles at the Hanford Site that define the target site conditions to which the prediction equations will need to be adjusted. These profiles also define the dynamic site response models used to transfer the baserock hazard to the top of the basalts.

The GMC TI Team established exclusion criteria for ground motion prediction equations (GMPEs) for both crustal and subduction earthquakes, based on considerations of the state of the art in ground motion modeling and the specific conditions and requirements of the Hanford sitewide PSHA. These criteria were applied to global listings of GMPEs, which led to a small number of equations considered suitable for this application. For crustal earthquakes, the criteria included that the models should be well calibrated for reverse-faulting earthquakes, because the hazard was expected to be dominated by the YFB faults. In addition, it was decided that the equations should include the 30-m time-averaged shear-wave velocity, V_{S30}, as an explicit parameter, in order to facilitate adjustments to the local site conditions. This led to the final selection of four of the Next Generation Attenuation Relationships for the Western United States (NGA-West2) GMPEs, although other equations from southern Europe, and other active crustal regions were retained for subsequent comparisons with the final GMC model.

For the subduction earthquakes, it was noted that the recent SSHAC Level 3 PSHA conducted for BC Hydro dams in British Columbia had evaluated existing GMPEs for subduction earthquakes and concluded that none of these were suitable for application to the Cascadia subduction zone. The new subduction GMPE developed by the BC Hydro study was therefore retained as the only candidate, although the GMC TI Team identified improvements that could be made to this model for application to the Hanford PSHA.

The usual starting point for deriving, assessing, or adjusting GMPEs for a region is the database of strong-motion (accelerograph) recordings from that area. In the Hanford Site region, such recordings are limited in number and in amplitude. Nevertheless, all available site ground motion data were cataloged in terms of the date, time, magnitude, depth, and location of the earthquake; the location and geological/geotechnical classification of the recording site; and the instrumental characteristics (component orientation, sampling rate, etc.). Strong-motion records from the broader region in which the site is located were also compiled.

To make meaningful inferences regarding potential differences in attenuation between the host regions from which the selected GMPEs had been obtained and the target application region, the data compilation and evaluation also included Q (crustal attenuation parameter) models for eastern Washington.

Profiles of shear-wave velocity, V_S, and mass density (which together with damping are the three basic parameters required for site response characterization) were developed for all five hazard calculation sites. The stratigraphic information for sites other than WTP was inferred from various data sources, including boreholes, wells, and refraction studies. Velocities and densities measured at the WTP site were assumed to apply uniformly to each stratigraphic unit across the site.

The initial assumption was that the baserock elevation for the GMC model—and thus for the hazard calculations—would be defined at the top of the SMB. However, analyses demonstrated that the velocity inversions associated with the Ellensburg formation sedimentary interbeds would not be consistent with the assumption of an elastic half-space below the baserock horizon. For this reason, the baserock was defined as the top of the Lolo flow (but excluding the ~4 m of vesiculated and brecciated flowtop), which is the uppermost unit of the WB.

Recordings from the Hanford Site from sites with thin sedimentary cover, which could therefore be considered as analogs for either SMB or WB outcrops, were analyzed by Specialty Contractor Dr. Walt Silva in order to estimate kappa values for the Hanford Site. Spectral Analysis of Surface Waves measurements were conducted by the University of Texas at Austin at several of the recording sites to provide characterization of the sites in order to facilitate the kappa analyses. The GMC TI Team also performed its own analyses of the recordings, using the Anderson-Hough approach, to obtain additional estimates of kappa. The GMC TI Team evaluated all of the kappa estimates to obtain best estimate models for this key parameter and the associated epistemic uncertainty. The difference in kappa values at the top of the SMB stack and at the baserock horizon at the top of the WB was assigned as damping in the basalt and interbed layers of the SMB stack at each of the five hazard calculation sites.

The GMC TI Team commissioned Dr. Art Frankel of the U.S. Geological Survey to conduct simulations to explore the possibility of 3-D basin effects at the Hanford Site. The results of Dr. Frankel's study were carefully considered by the GMC TI Team and the Team concluded that 3-D basin effects would be encountered at certain locations on the Hanford Site for particular earthquake scenarios but that these would not be exceptional in terms of amplification. The TI Team concluded that any 2-D and 3-D effects at the Hanford Site would be consistent with the basin effects captured in the sigma (standard deviation) values of GMPEs for soil sites in general.

Because there was also a requirement to provide V/H spectral ratios for application to the surface motions, criteria were established by the GMC TI Team for such ratios to be applicable to the Hanford project and available relationships for these ratios were evaluated in light of these criteria.

ES.3. Seismic Source Characterization Model

An SSC model in a PSHA defines the seismogenic potential, locations, sizes, and rates of future earthquakes. The SSC model-building process for the Hanford PSHA began with the identification of criteria that would be used by the TI Team to define seismic sources. These criteria were identified based on consideration of the tectonic regime, the types of seismic sources that might be present (e.g., fault sources and source zones), and precedent from recent SSC models developed for similar tectonic environments and for nuclear facilities. Based on these considerations, unique seismic sources are defined to account for distinct spatial differences in the following criteria: earthquake recurrence rate, maximum earthquake magnitude (Mmax), expected future earthquake characteristics (e.g., style of faulting, rupture orientation, seismogenic thickness), and probability that a fault is seismogenic.

Three sets of seismic sources are included in the SSC model: Cascadia subduction zone sources, seismic source zones, and fault sources. The SSC model is based on the notion that an appropriate SSC model should be one that is no more complex or detailed than required by the pertinent data. The process of identifying and characterizing seismic sources for the SSC model was hazard-informed such that highest priority was given to aspects of the model that had the highest potential hazard significance. Likewise, the level of complexity of the SSC model was consistent with current knowledge and importance to hazard. The region over which the SSC model was developed was designed to extend somewhat beyond the distances that would be expected to contribute significantly to the site hazard, based on the hazard sensitivity analyses conducted prior to Workshop 1 and confirmed by sensitivity analyses conducted using the preliminary SSC model prior to Workshop 3.

The basic elements of the SSC model that define and characterize the three types of seismic sources are given below. Given the large number of SSC characteristics assessed for the SSC model, the TI Team gave careful attention to the epistemic uncertainties associated with each characteristic, as well as the aleatory (random) variability that defines some of the characteristics. The former are given in the maps and logic trees that compose the SSC model; the latter are given as aleatory distributions of parameter values that are each associated with their relative frequency in the model.

Sensitivity analyses conducted early in the Hanford PSHA project showed that the plate interface seismic source of the Cascadia subduction zone could contribute to long-period ground motions at annual frequencies of exceedance of interest to the Hanford Site. For completeness, both the plate interface and the intraslab sources are included in the SSC model. Fortunately, the recently completed SSHAC Level 3 PSHA conducted by BC Hydro provided a technically defensible source model that includes a full characterization of uncertainties. In addition to reviewing the BC Hydro model, the activities associated with the Hanford PSHA included updating the earthquake catalog and the TI Team evaluating new data that have become available since completion of the BC Hydro PSHA in 2012. The revisions made in light of new data included the assessment of the landward extent of the plate interface source and the maximum depth of the intraslab source.

The seismic source zones identified in the site region by the TI Team are shown in Figure ES.2 together with the earthquake epicenters from the project crustal earthquake catalog. Two types of seismic source zones are identified: the Yakima Fold and Thrust Belt (YFTB) source zone is a "background" zone to the fault sources of the YFTB, and Zones B, C, and D are source zones that do not include identified fault sources. Because of their distance from the site, individual faults within Zones B, C, and D are not specifically identified and characterized.

Unlike fault sources, which must be evaluated for their seismogenic probability, seismic source zones are assessed to be seismogenic with a probability of unity. That is, all seismic source zones in the SSC model are judged to have the ability to generate moderate-to-large ($M \geq 5$) earthquakes. Consistent with current SSC practice for PSHAs and consistent with the GMPEs developed for the Hanford PSHA, the occurrence of future earthquakes within seismic source zones is modeled by virtual faults that have random locations within the zone. In the SSC model, the future earthquake characteristics on the virtual faults are modeled by their style of faulting, 3-D rupture geometry, magnitude-dependent rupture dimensions, and relationship with zone boundaries. These characteristics of the modeled virtual faults within the zone incorporate source-specific seismotectonic information and uncertainties are included in logic trees.

Additional SSC characteristics assessed for each source zone are their Mmax, recurrence rates, and spatial variation in recurrence parameters. These assessments are source zone-specific and account for the specific data differences among the zones. An element in the logic tree for the YFTB source zone is whether or not the observed seismicity is associated with the fault sources or with the zone itself. For all source zones, the assessment of earthquake recurrence incorporates fully the earthquake catalog, uncertainties in the magnitude estimates for each event, incompleteness of the record, and the elimination of dependent events (foreshocks and aftershocks). In addition, assessments were made of the spatial homogeneity of the observed earthquake epicenters within each source zone to discern whether or not spatial variations of the activity rate (a-values) should be modeled using a spatial smoothing approach. The uncertainty in this decision is captured in the logic trees for each source zone.

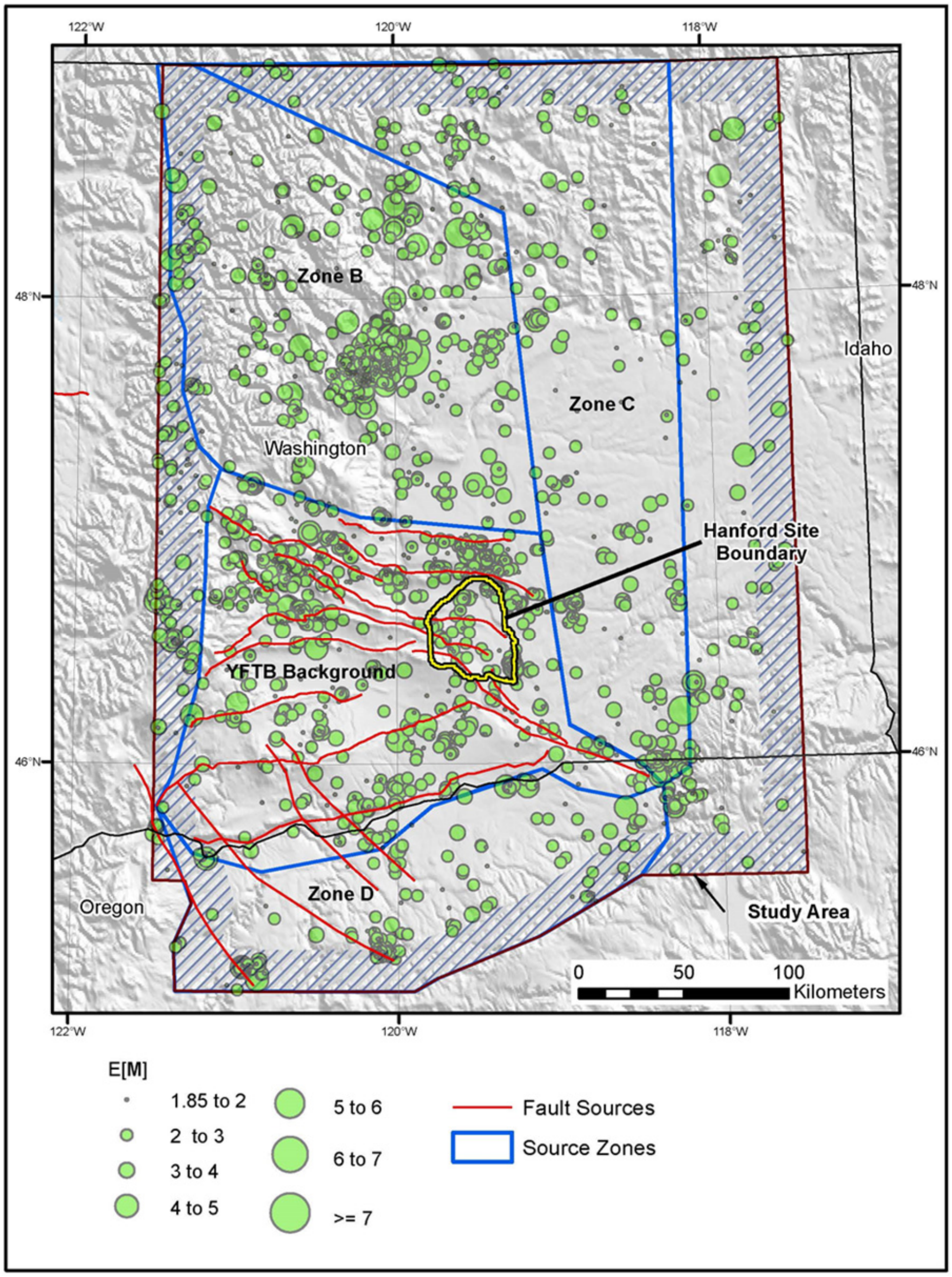


Figure ES.2. Seismic source zones characterized in the SSC model and earthquake epicenters in the Hanford PSHA crustal catalog having E[M] ≥ 1.85. Fault sources are also shown by the red lines.

The 20 fault sources included in the SSC model and that are part of the YFB are shown in Figure ES.3. In addition, the Seattle fault is included in the model for completeness. Sensitivity analyses show that it contributes very little to the hazard at the site because of its distance from the site, but it is included in the model because it is the most active fault within the Puget Sound region.

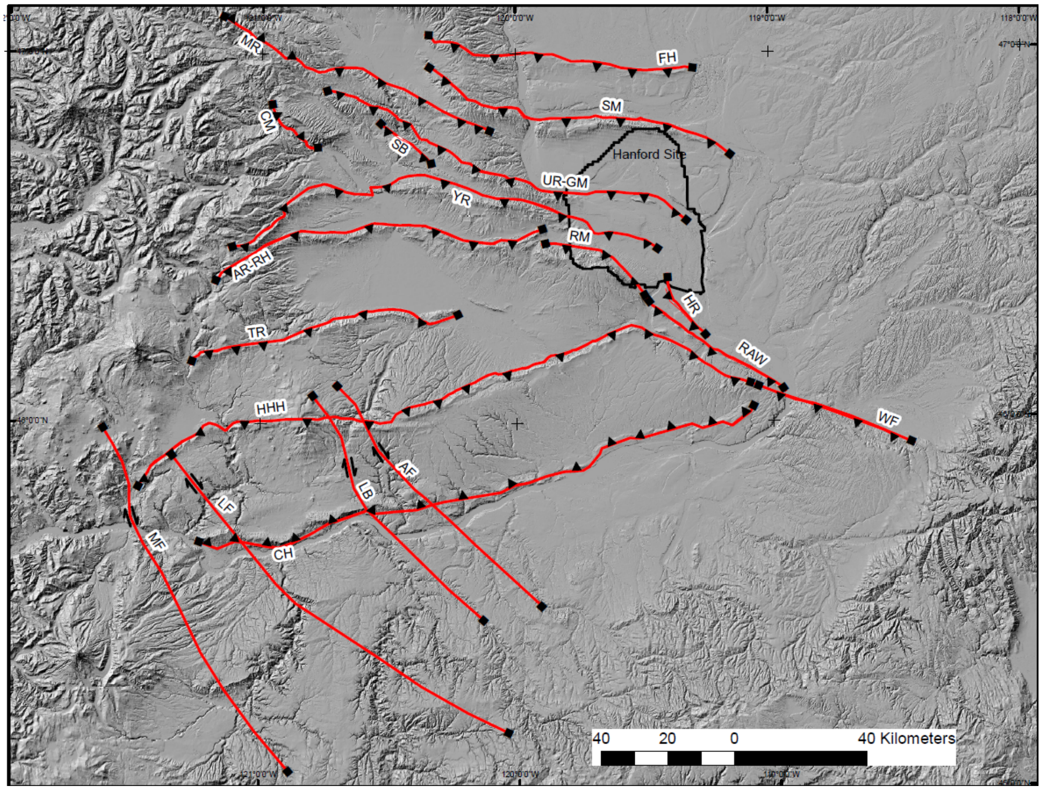


Figure ES.3. Fault sources included in the SSC model. Teeth are shown on the hanging wall of the faults. Arrows indicate relative sense of movement of strike slip faults. The names of the fault sources are Ahtanum Ridge (AR), Arlington (AF), Cleman Mountain (CM), Columbia Hills (CH), Frenchman Hills (FH), Horn Rapids Fault (HR), Horse Heaven Hills (HHH), Laurel (LF), Luna Butte (LB), Manastash Ridge (MR), Maupin (MF), Rattles of the Rattlesnake Wallula Alignment (RAW), Rattlesnake Hills (RH), Rattlesnake Mountain (RM), Saddle Mountain (SM), Selah Butte (SB), Toppenish Ridge (TR), Umtanum Ridge (UR), Wallula Fault (WF), Yakima Ridge (YR). The Seattle fault lies off the map to the west.

All fault sources were evaluated for their seismogenic probability and the criteria used by the TI Team to evaluate seismogenic probability related primarily to geologic evidence for involvement within the contemporary tectonic regime, evidence that they are capable of generating M > 5 earthquakes, and hazard significance that suggest that they should be represented as a fault source that localizes seismicity above the background source zone. The most important geologic indicators in this regard are the geomorphic surfaces and deposits that are Quaternary (<2.6 Ma) in age or that show evidence of deformation post-CRB (post about 6−10 Myr). Such a time period is judged by the TI Team to be reasonably indicative of the potential for continuing activity during the contemporary tectonic regime. Fifteen of the faults identified within the YFB, as well as the Seattle fault, were evaluated by the TI Team and assessed to have a seismogenic probability of p[S] = 1. Four of the YFB faults were assessed to have a lower seismogenic probability.

The fault sources within the SSC model are characterized using three logic trees that provide a full expression of the knowledge and uncertainties regarding important fault source characteristics. Given the nature of the available data, which show differences in the geometry and structural relief along the lengths of individual faults, the faults are characterized according to the segments identified along their lengths. The first logic tree includes the characteristics that define the 3-D geometry and net slip rate for each fault segment. Included are the seismogenic thickness, approach to assessing fault dip, seismogenic probability, sense of slip, start time, and net slip rate. The resulting distributions of net slip rate are then used as input to the logic tree related to earthquake recurrence rates. A few of the faults have documented evidence for Quaternary deformation and, as a result, Quaternary slip rates have also been assessed and these are combined in the logic tree with the long-term slip rates as weighted alternatives.

The second logic tree for fault sources includes the assessments that lead to a distribution of characteristic magnitudes, Mchar. The assessments relate to the expected dimensions of rupture, defined by the seismogenic thickness, rupture length, and average downdip width. Given estimates of rupture length and rupture area, alternative approaches to calculating Mchar are included in the logic tree as well as alternative rupture versus magnitude relationships for a given approach.

The third logic tree includes the assessments that lead to earthquake recurrence rates for each fault segment. The temporal scale factor accounts for the possibility of non-Poissonian behavior related to a renewal process of earthquake generation. The factor is multiplied by the Poissonian recurrence rate to account for the large uncertainties that exist for the timing of past earthquakes on these fault sources. For three fault sources, sufficient data exist to estimate earthquake recurrence intervals as well as slip rate; hence, these alternative approaches to recurrence estimation are included in the logic tree. For all fault segments the net slip rates combined with the dimensions of the fault define the seismic moment rate, which is input to a magnitude frequency distribution to arrive at the equivalent Poisson rate for all magnitudes up to the maximum, Mmax. The final distributions are then input directly into the seismic hazard model.

Special Studies Results Put to Good Use

As shown in Figure ES.1, the observed seismicity in the study region shows rather swarm-like spatial patterns of earthquake epicenters in the region within which faults were identified and evaluated for this study. This is especially true of the seismicity in the shallow crust that represents the CRBs. As part of the high-resolution seismicity relocation analyses performed for this study, the investigators considered the spatial distribution of earthquake hypocenters and evaluated whether or not the hypocenters showed alignments that could represent active faults. The general conclusion of these studies was that no such alignments were evident. Further, the TI Team evaluated whether spatial associations with mapped faults existed and generally concluded that such associations could not be made with confidence and this assessment is part of the logic trees for the fault sources.

The Quaternary geologic studies (QGS) were conducted with the specific intention of identifying Quaternary geological deposits and geomorphic surfaces that could be dated and mapped to define the presence or absence of fault displacement or other deformation. In this respect, the QGS greatly added to the applicable database needed to identify potentially seismogenic faults and to assess their recency of displacement. These studies provided a basis for comparing the Quaternary rates of deformation for some faults with the long-term rates assessed over the past 6–10 Myr. In doing so, the evidence clearly shows that the long-term rates are comparable and that the post-CRB deformation rates of the faults of the YFB have been relatively constant over that time period.

Many of the characteristics of the fault sources in the SSC model are defined by their structural geologic features. For example, the mapped location and spatial pattern of structural relief is used to identify potential lengths of rupture segments and, in turn, the range of characteristic magnitudes (Mchar) for the fault source. The mapped pattern of structural relief also provides information related to the dip of the fault at depth, and the amount of relief is used together with assessments of the deformation start time to assess the vertical and net rates of slip. The careful consideration of that type of local geologic evidence has provided a firm technical basis for assessing the characteristics of all of the fault sources within the YFB.

ES.4. Ground Motion Characterization Model for Baserock Horizon

The ultimate goal of the Hanford sitewide PSHA is to enable the characterization of the ground-shaking hazard at the location of several surface facilities on the Hanford Site. The GMC model consists essentially of two logic trees, one for ground motions from crustal earthquakes and the other for motions caused by subduction earthquakes. In both cases, GMC models apply to the baserock elevation at the top of the WBs, which have a shear-wave velocity, V_s, very close to 3,000 m/s. For both the crustal and subduction logic trees, there are branches for the median motions and also for the associated aleatory variability (sigma). For the crustal earthquakes, one of the NGA-West2 models (CY14) was chosen to serve as a backbone and the ranges of alternative median predictions (reflecting epistemic uncertainty within the host region predictions) were inferred from the amplitudes obtained from other NGA-West2 equations, using slightly different subsets of these models for footwall and hanging-wall locations. The backbone equation was adjusted to be applicable to the top of WB baserock horizon through the application of factors to account for differences in host and target region V_S profiles and site kappa values. The host V_S profile was assumed to be a generic model for California and the host kappa values were inferred from the high-frequency portion of the predicted median response spectra for a number of earthquake scenarios. Scaling factors, reflecting inferred ranges of potential host-to-target region differences in stress drops, were then applied to the V_S-kappa adjusted models to develop additional equations to occupy the logic-tree branches. One of the terms in the backbone GMPE is an explicit function of the parameter Z_{TOR} (depth to top of rupture), which captures the influence of higher stress drops associated with buried fault ruptures. To capture the influence of ruptures in the strong basalt layers near the surface, which are unusual and could lead to higher than average stress drops for shallow ruptures, a condition was imposed that Z_{TOR} would always take a value of at least 3 km, regardless of the actual depth to rupture (but this did not affect the calculation of rupture distances).

For the subduction earthquakes, a new GMPE was derived using an expanded version of the BC Hydro model database and a slightly modified functional form for the equation. One of several motivations for this change was the fact that the Hanford Site is located at distances of 250−300 km from the Cascadia subduction sources, leading to a requirement for well-constrained models at such distances in the backarc (beyond the volcanic arc associated with the subduction) region. Alternative models were developed considering different options for large-magnitude scaling and for the attenuation function, and then host-to-target scaling factors were applied to fully populate the logic-tree branches. For the subduction GMPE, the adjustment to the local site conditions was made only in terms of host-to-target differences in V_S profiles because at such long distances the influence of kappa (which represents high-frequency attenuation in the uppermost part of the crust) is masked by crustal attenuation along the travel path. The host V_S profile was based on Japanese recording sites, because Japanese data dominate the subduction data set, particularly for the larger magnitudes.

The multiple branches considered in the site-specific adjustments (for V_S and V_S-kappa) and the recommended capture of variability in the site response calculations, together meant that the site-to-site component of the ground motion variability (sigma) was accounted for, at least at higher response frequencies. Therefore, for the baserock model, single-station sigma models were developed, adapted from models developed in other SSHAC Level 3 and 4 projects in South Africa and Switzerland. The single-station sigma models were applied at all response frequencies, but these may not apply at intermediate and longer response periods. This is the result of the influence of 3-D basin effects being captured in the sigma value for intermediate response periods (0.5−1.0 sec), and the fact that variability in site response calculations having almost no impact at response periods much beyond 1 sec. However, because these effects are all associated with the suprabasalt sediments, it would not have been appropriate to modify the single-station sigma model at the baserock rock, where it was retained across the entire period range. Instead, the additional variability required at intermediate and longer response periods was made part of the specification for the convolution of the site amplification functions with the baserock hazard.

The GMC model also provides a recommendation for V/H response spectral ratios that may be used to transform the horizontal motions at the surface to the vertical component. The proposed V/H ratios are defined as a function of magnitude, distance, style of faulting and V_{S30}, and can applied to the horizontal response spectra using magnitude-distance pairs obtained from disaggregation of the hazard. The suggested V/H ratios are derived from crustal earthquakes, but have been adjusted at longer periods to accommodate observed V/H ratios from large subduction earthquakes.

ES.5. Site Response Models and Combination with Baserock Hazard

The GMC model also provides a suite of models of the SMB stacks for use in subsequent site response analyses. These profiles include layered models with V_S (giving low-strain stiffness), mass density, and low-strain damping in each layer. Damping curves and stiffness degradation curves are defined for the interbeds. Randomizations of the profiles are defined with suitable layer-to-layer correlations for use in the site response analyses, together with similar randomized profiles for the suprabasalt sediments (to be defined by those conducting the site response analyses). The recommended procedure for combining the site amplification functions with the baserock hazard is the Approach 3 convolution described in NUREG/CR-6728. Minimum values of the variability in the site amplification functions are specified at longer periods, with the clarification that these should not be obtained by adding greater uncertainty into the site response profiles but by simply increasing the variability if insufficiently large. The PSHA report provides detailed guidelines for the execution of the site response analyses, the convolution of the baserock hazard and the calculated site amplification factors, and a fully worked example for the WTP location.

ES.6. Hazard Calculations and Results

The implementation of the comprehensive seismic hazard model described above results in calculations of seismic hazard and seismic hazard sensitivity analyses at the five sites shown in Figure ES.1: Site A in the 200-East Area, Site B in the 200-West Area, Site C, the Columbia Generating Station, Site D in the 100 BC Area, and Site E in the 300 Area. In all cases, the baserock elevation for the hazard calculations was selected as being the top of the WBs (minus the ~4-m flowtop of the uppermost Lolo flow), which is encountered at depths of between 332 and 446 m at the hazard calculation Sites A−E. The results provided in this report are based on twenty structural periods (peak ground acceleration [PGA], and T 0.02, 0.03, 0.04, 0.05, 0.07, 0.1, 0.15, 0.20, 0.30, 0.40, 0.50, 0.75, 1.0, 1.5, 2.0, 3.0, 5.0, 7.5 and 10-sec spectral acceleration) and extend from annual frequencies of exceedance (AFEs) of 10^{-2} to 10^{-8}. For each site, results are shown in the report as seismic hazard curves showing the mean total hazard and percentiles at each of the structural periods. An example at Site A for T 0.1 sec is shown in Figure ES.4.

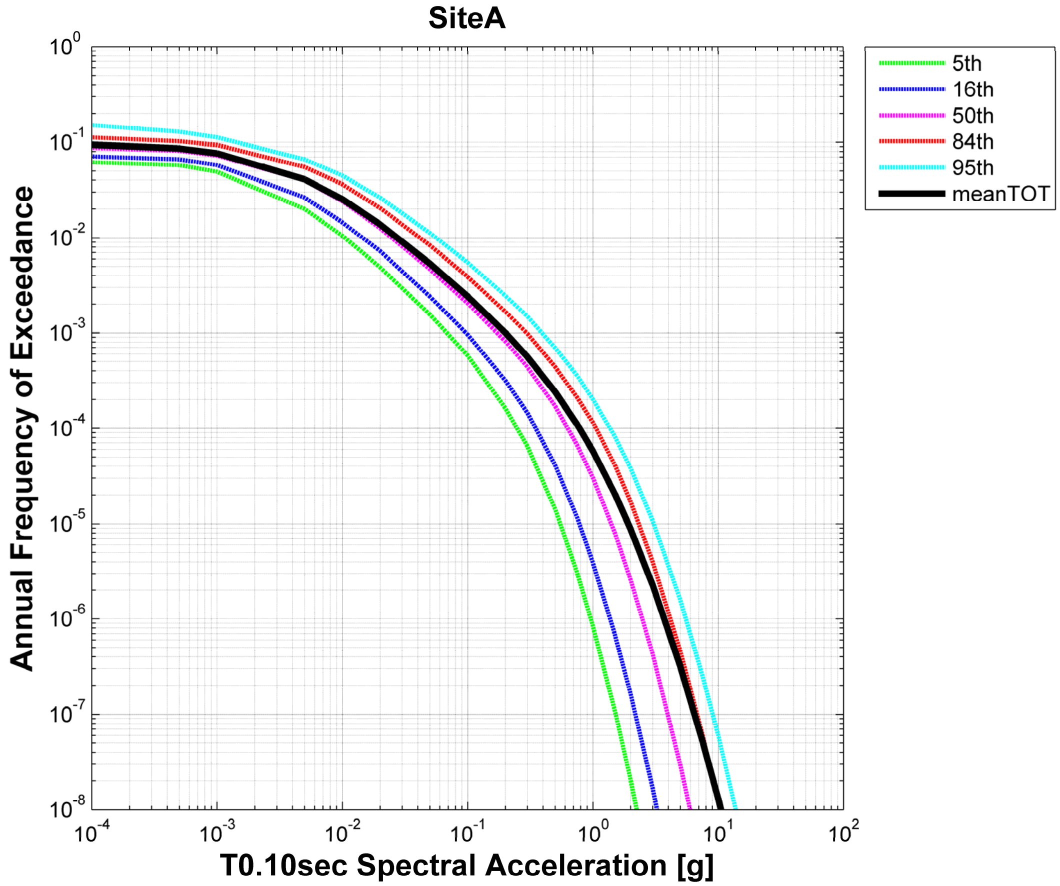


Figure ES.4. Total mean seismic hazard at Site A and percentiles at structural period of T 0.1 sec.

The contribution of individual sources and groups of sources (all crustal sources, all subduction sources, source zones, faults) are also provided as a function of structural period. Figure ES.5 provides an example at Site A for T 0.1 sec.

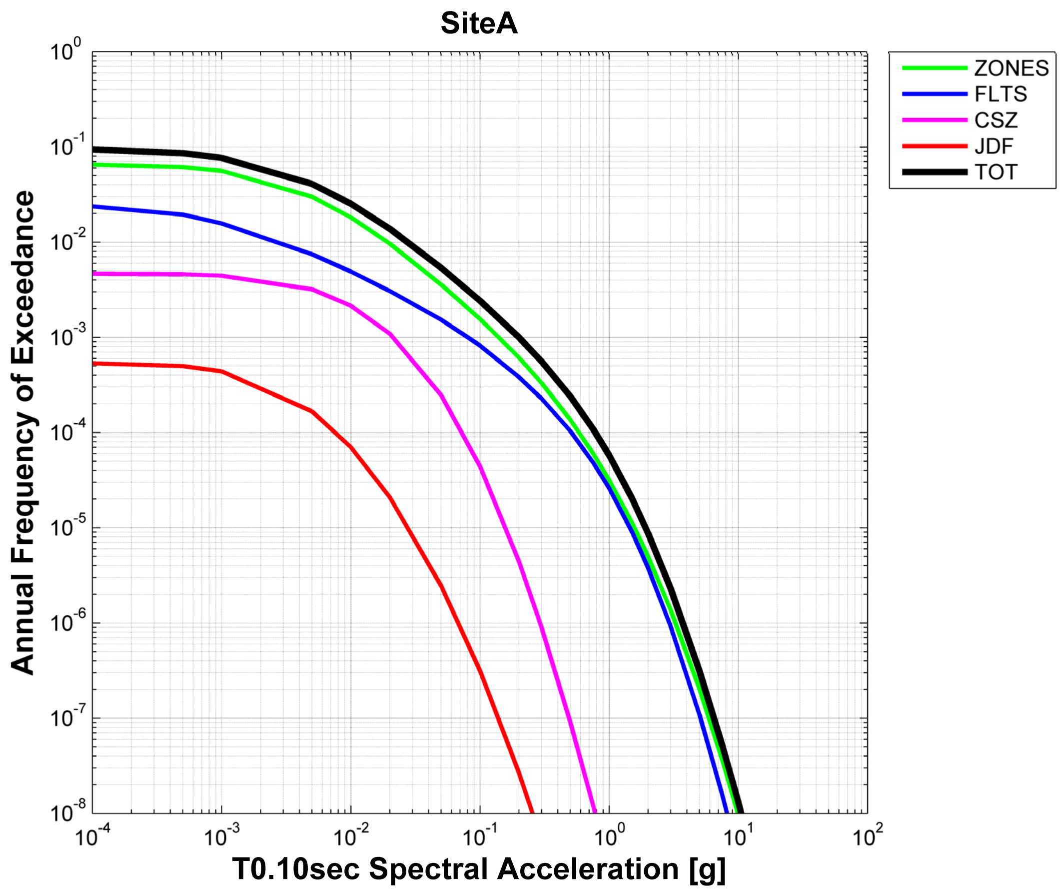


Figure ES.5. Comparison between the total mean seismic hazard at Site A (black curve) and the contribution of crustal source zones (green curve), faults (blue curve), the Cascadia interface (CSZ - magenta curve), and Cascadia intraslab source (JDF - red curve) at structural period of T 0.1 sec.

Uniform hazard response spectra are provided for the full range of AFEs and mean, 50th percentile, and 84th percentile hazard. An example is shown in Figure ES.6 of the mean uniform hazard response spectrum at Site A.

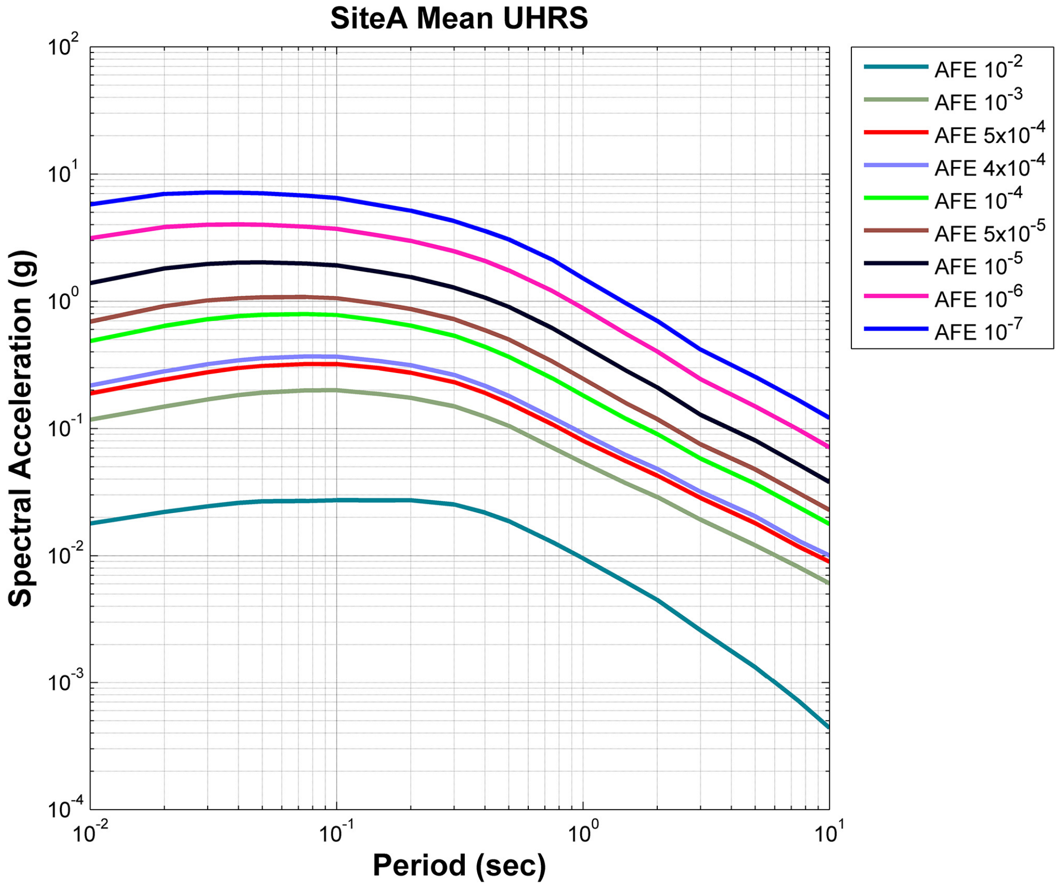


Figure ES.6. Uniform hazard response spectra at AFEs of 10^{-2}, 10^{-3}, 5×10^{-4}, 4×10^{-4}, 10^{-4}, 5×10^{-5}, 10^{-6}, and 10^{-7} (return periods of 100, 1,000, 2,000, 2,500, 10,000, 20,000, 100,000, 1 million, and 10 million years) for mean hazard.

Deaggregation analysis is used to identify the combination of magnitude and distance pairs that contribute the most to the total seismic hazard at each site. The results of the deaggregation are represented by histograms and are calculated at the various values of AFE. An example is shown in Figure ES.7 for T 0.1 sec and an AFE of $4x10^{-4}$. To assist in evaluating the consistency of the hazard results, comparisons are provided between the uniform hazard response spectra and response spectra for representative earthquake scenarios. The selected scenarios are mean magnitude and distance of shallow crustal earthquakes contributing to the hazard at periods of 0.01, 0.1, 1, and 10 sec, and the mean magnitude and distance of Cascadia interface earthquakes.

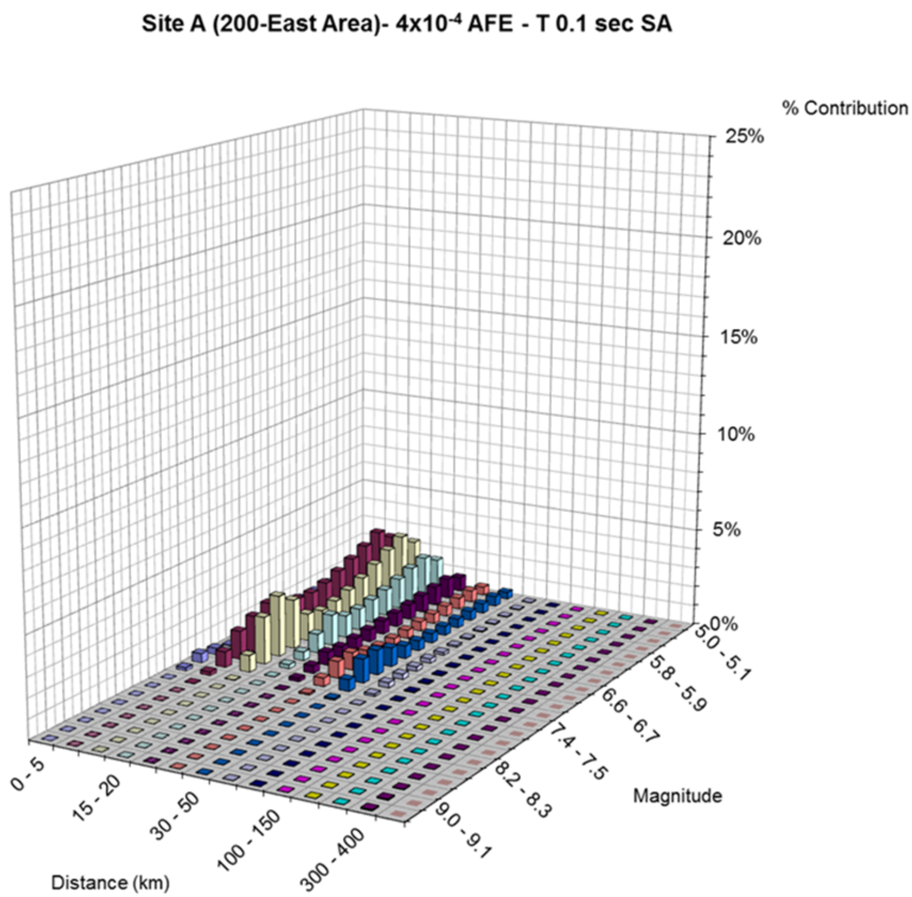


Figure ES.7. Deaggregation histogram showing magnitude-distance contributions to the total mean hazard at Site A for T 0.1-sec spectral acceleration and an AFE of 4×10^{-4}.

In addition to the source contribution, seismic hazard curves are produced to show the relative effect on the seismic hazard of various elements of the GMC and SSC inputs at Sites A and C based on results at PGA, and T 0.1-, 1.0-, and 10-sec spectral acceleration. The relative importance of the alternative branches at each node of the logic tree is assessed by the variance contribution histograms, which are used to represent how much variability is introduced in the seismic hazard by the various levels of the logic tree. Tornado plots are produced to compare the mean total hazard to the results that would be obtained assigning full weight alternatively to each branch at specific nodes of the logic tree.

To compare the hazard at the five sites, the uniform hazard response spectra calculated for each site is compared at three AFEs: 10^{-2}, 10^{-4}, and 10^{-6}. An example of the comparison is shown in Figure ES.8 for mean hazard at an AFE of 10^{-4}. The hazard result comparisons differ by AFE and are related to the proximity to particular seismic sources (e.g., proximity to faults versus source zones) and details of the characterization (e.g., local recurrence rates).

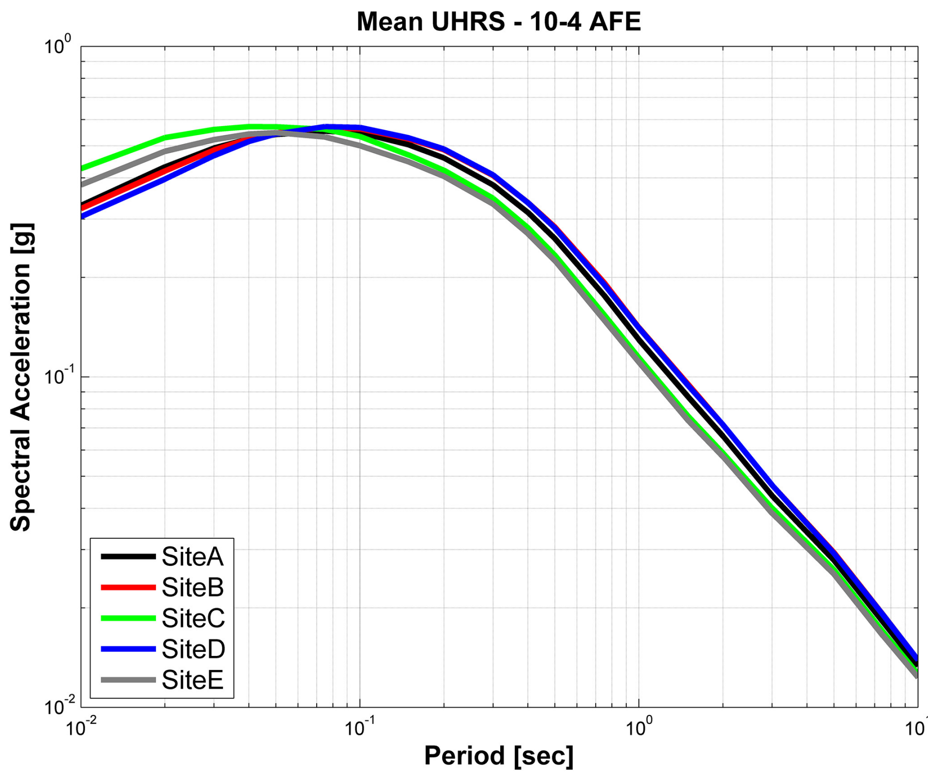


Figure ES.8. Comparison between the mean uniform hazard response spectra at Sites A, B, C, D, and E for a 10^{-4} annual frequency of exceedance.

ES.7. Conclusions Regarding the Hanford PSHA

The goal of the Hanford PSHA project was to conduct a PSHA using the SSHAC Level 3 methodology at the five hazard calculation sites. From the time of the initial project planning throughout the implementation of the project, all procedural aspects of the project were designed to be consistent with applicable regulatory guidance for the conduct of a SSHAC Level 3 PSHA. For example, the project organizational structure, roles and responsibilities of project participants, key activities and their sequence, participatory peer review activities, and project documentation steps were all structured to meet the intent of the original SSHAC guidelines in NUREG/CR-6372 and the specific guidance in NUREG-2117. Accordingly, the project moved from the planning stage through the evaluation phase where data, models, and methods of the larger technical community were considered; through the integration phase where models were developed for the SSC and GMC aspects of the project to capture the center, body, and range of technically defensible interpretations; and into the hazard calculation and documentation phase. All of these phases of the project were conducted under the continual review by the PPRP, which provided feedback and review comments along the way to improve the ultimate product. The issuance of the PPRP Closure Letter confirms that SSHAC Level 3 process has been adequately followed. Accordingly, it is concluded that the Hanford PSHA provides a complete update of the seismic hazard at the Hanford Site and the hazard products from the study can be used for subsequent seismic design and safety analyses at facility sites.

Acknowledgments

The primary authors of this probabilistic seismic hazard analysis (PSHA) report are the 10 members of the Technical Integration (TI) Teams and the Hazard Analyst, who, in keeping with the specifications for a Senior Seismic Hazard Analysis Committee process, assume responsibility for the seismic source characterization (SSC) and ground motion characterization (GMC) models and the analyses presented herein. Those authors hereby acknowledge the contribution of others who made this effort possible.

The U.S. Department of Energy (DOE), Office of River Protection and Richland Operations Office along with Energy Northwest provided funding for this effort. The work was initially overseen by Randy Nielson of DOE and later by Dan Knight and Jim Sondall of DOE and Greg Lisle of Energy Northwest.

Independent technical review was provided by the Participatory Peer Review Panel led by Ken Campbell. The review and feedback provided by Ken and the other peer reviewers, Carl Stepp, Woody Savage, Brian Chiou, and Bill Lettis, was invaluable in improving the PSHA effort and documentation.

The study could not have been carried out without the scientists and engineers of the seismic hazard community who participated as proponent and resource experts in the workshops. They are too many to list here, but their names appear in Chapter 2.0 where the workshops are discussed. The TI Teams also acknowledge the contribution of specialty contractors who addressed specific information needs for the project including Ken Stokoe and his team of the University of Texas at Austin; Colin Amos and Skyler Sorsby of Western Washington University; Brian Sherrod, Rick Blakely, Art Frankel, and Jim Paces of the U.S. Geological Survey; Paul Bierman of the University of Vermont; Walt Silva; Felix Waldhauser of Lamont Doherty Earth Observatory; Cliff Thurber of the University of Wisconsin-Madison; and Steve Reidel of Washington State University. The authors also thank Shrey Shahi, Nick Gregor and Brady Cox for their contributions.

The authors thank the staff of the Pacific Northwest National Laboratory (PNNL) for their contribution to the project. PNNL provided project management and quality assurance oversight for the project as well as logistics support for workshops and working meeting. The project was managed by Bob Bryce; quality assurance oversight was provided by Ron Schrotke, Emily Wilson, and Kary Cook. Charla Saranovich established the venues for workshops and working meetings and worked tirelessly to make sure they came off without a hitch. PNNL staff also provided technical support to the project. Alan Rohay provided data and insight regarding the history of seismic monitoring and characterization activities over the past three decades at the Hanford Site, George Last and Paul Thorne provided information on Hanford Site and regional geology, Chris Ross and Duane Ward managed the project data. Chris also set up and managed the SharePoint site used by the project to communicate among the team members, retain project records, and collaborate on project documents. Final hazard calculations were performed using PNNL Institutional Computing resources.

Roseanne Chambers of AMEC assisted the TI Teams in assembling the final PSHA document. Susan Ennor and Mike Parker of PNNL edited the PSHA document and handled all aspects of document production. The authors also thank Ana Luz Acevedo-Cabrera of AMEC for her assistance with the hazard calculations and Chris Slack of AMEC for his assistance with the Quaternary geologic studies task.

Abbreviations, Acronyms, and Symbols

ACR	active crustal region
AD	anno domini (in the year of the Lord)
AFE	annual frequency of exceedance
AIC	Akaike Information Criterion
AICc	second-order AIC
AM	ante meridiem (before noon)
AMEC E&I	AMEC Environment and Infracture, Inc.
ANS	American Nuclear Society
ANSI	American National Standards Institute
ANSS	(U.S.) Advanced National Seismic System
ARH	Ahtanum-Rattlesnake Hills
ASBL	Arlington-Shutler Buttes lineament
BC	before Christ
BIC	Bayesian Information Criterion
bgs	below ground surface
BP	before present
BPT	Brownian Passage Time
cal. yr BP	calendar years before present
CBR	center, body, and range
CCU	Cold Creek unit
CDF	cumulative distribution function
CEUS	central and eastern United States
CFR	Code of Federal Regulations
CGS	Columbia Generating Station (formerly WPN-2)
CI	confidence interval
CLEW	Cle Elum-Wallula lineament
cm	centimeter(s)
CMS	conditional mean spectra
CMT	Centroid Moment Tensor
COV or CV	coefficient of variation
CRB	Columbia River Basalt
CRBG	Columbia River Basalt Group
CSZ	Cascadia subduction zone
CTZ	coseismic transition zone

CURATE	cumulative rate analysis
1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
D_{90}	the depth above which 90% of earthquakes occur
DD	double difference
DE	deaggregation earthquake
DEM	digital elevation model
DFF	directivity functional form
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DPP	Direct Point Parameter
ECSZ	eastern California shear zone
E[**M**]	expected moment magnitude or expected value of moment magnitude
EN	Energy Northwest
EPRI	Electric Power Research Institute
EPRI-SOG	Electric Power Research Institute–Seismicity Owners Group
EQID	earthquake ID (identification)
ETS	episodic tremor and slip
FAS	Fourier amplitude spectra
FLTS	Faults
FMC	forearc mantel corner
ft	foot(feet)
FW	footwall
g	gram(s)
g/cc	gram(s) per cubic centimeter
G	shear modulus
GIS	geographic information system
GM	ground motion or geometric mean
G_{max}	maximum shear modulus with very low deformation
GMC	ground motion characterization (models)
GMPE	ground motion prediction equation
GMRS	ground motion response spectra
GMT	Greenwich Mean Time

GPS	global positioning system
GR	Grand Ronde
GSC	Geological Survey of Canada
HAWA	the seismograph at the Nike missile facility on Rattlesnake Mountain
HCMT	Harvard Centroid Moment Tensor
HHH	Horse Heaven Hills
HID	hazard input document
HPSHA	Hanford Probabilistic Seismic Hazard Analysis
HR	Horn Rapids (fault)
H/V	horizontal-to-vertical (ratio)
HW	hanging-wall (factor)
Hz	hertz
HZ-pga	hertz-peak ground accleration
I_0	maximum intensity or macroseismic intensity
IDC	International Data Center
IF	interface (earthquake)
InSAR	interferometric synthetic aperture radar
IRIS	Incorporated Research Institutions for Seismology
IRSL	Infrared Stimulated Luminescence
IRVT	Inverse Random Vibration Theory
IS	intraslab (earthquake)
ISC	International Seismological Centre
ISI	Institute for Scientific Information
JBA	Jack Benjamin & Associates
JDF	Juan de Fuca
k	kappa
ka	thousand years ago
kHz	kilohertz
km	kilometer(s)
km^2	square kilometer(s)
km^3	cubic kilometer(s)
km/s	kilometers per second
kyr	thousand years

LCI	Lettis Consultants International, Inc.
LiDAR	Light Detection and Ranging
m	meter(s)
M	magnitude
M	moment magnitude
Ma	millions of years ago (or before the present)
m_b	body-wave magnitude (short period)
m_{bLg}	body-wave magnitude determined from higher-mode (Lg) surface waves
M_C	coda-wave magnitude
Mchar	characteristic magnitude
M_D	duration magnitude
MFD	magnitude frequency distribution
MI	magnitude from intensity
M_I	macroseismic intensity
MIS	marine oxygen isotope stage (commonly referred to as oxygen marine isotope stage [OIS])
M_L	local magnitude
mm	millimeter(s)
M_{max}, Mmax	maximum earthquake magnitude
M_{min}	lower bound magnitude
MMI	modified Mercalli intensity
mm/yr	millimeter(s) per year
MRE	most recent event
m/s or m/sec	meter(s) per second
M_S	surface-wave magnitude
msl	mean sea level
M_{SZ}	surface-wave magnitude computed with vertical component
M_W	moment magnitude
Myr	millions of years of duration
NA	not applicable
NBR	northern Basin and Range province
NED	National Elevation Dataset
NEDB	National Earthquake Database
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NGA	next-generation attenuation

NGA-West2	Next Generation Attenuation Relationships for the Western United States
NPH	natural phenomena hazard
NRC	U.S. Nuclear Regulatory Commission
ns	nanostrain(s)
OCR	over-consolidation ratio
ORP	DOE Office of River Protection
OSL	optically stimulated luminescence
OWL	Olympic-Wallowa lineament or quarter wavelength (method)
P_a	probability of activity (of being seismogenic)
PEER	Pacific Earthquake Engineering Research Center
PEGASOS	Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-Stand-Orte in der Schweiz – probabilistic seismic hazard analysis conducted for the Swiss nuclear power plant sites
PGA	peak ground acceleration
PGD	peak ground displacement
PGL	Pasco gravity low
PGV	peak ground velocity
PI	Plasticity Index
PM	Project Manager or post meridiem (after noon)
PNNL	Pacific Northwest National Laboratory
PNSN	Pacific Northwest Seismic Network
PPRP	Participatory Peer Review Panel
PRP	Pegasos Refinement Project
P[S]	seismogenic probability
PS	technique that measures velocities of P and S waves
pSA	pseudo-spectral acceleration
PSHA	probabilistic seismic hazard analysis
PTI	Project Technical Integrator
QA	quality assurance
QGS	Quaternary geologic studies
QWL	quarter wavelength
RAW	Rattlesnake-Wallula
RCTS	resonant column and torsional shear
R_{jb} or R_{JB}	Joyner-Boore distances

RL	(DOE) Richland Operations Office
RLD	rupture length at depth
RLME	repeated large magnitude earthquake
RM	Rattlesnake Mountain
RMS	root mean square
R_{rup} or R_{RUP}	closest distance to the rupture plane
RVT	random vibration theory
s or sec	second(s)
SA	spectral acceleration
SASW	spectral analysis of surface waves
SD	standard deviation
SH	shear horizontal
SHEEF	Seismic Hazard Earthquake Epicenter File
SH_{max}	maximum horizontal stress, compression, or principal stress
SCR	Stable Continental Region
SDC	seismic design category
SMA	strong-motion accelerometer
SMB	Saddle Mountains Basalt
SMS	scaled median spectra
SNR	signal-to-noise ratio
SPID	screening, prioritization, and implementation details
SRI	square-root impedance
SSC	seismic source characterization
SSC TI	seismic-source characterization technical integration
SSHAC	Senior Seismic Hazard Analysis Committee
SSI	soil–structure interaction
STA/LTA	short time average over long time average (algorithm)
STID	station ID (identification)
STREC	SeismoTectonic Regime Earthquake Calculator
SWUS	Southwestern United States
SZ	source zone or subduction zone
TA	Transportable Array
TDI	technically defensible interpretation
Th	thorium
TI	technical integration
TL	thermoluminesence
TNSP	Thyspunt Nuclear Siting Project

TR	Toppenish Ridge
U	uranium
UHR	uniform hazard response
UHRS	uniform hazard response spectra
UHS	uniform hazard spectra
USBR	United States Bureau of Reclamation
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
V/H	vertical-to-horizontal
V_P/V_S	ratio of P-wave velocity to S-wave velocity
V_P	compression-wave velocity (or Poisson's ratio)
V_S or Vs	shear-wave velocity
V_{S30}	average shear-wave velocity over the uppermost 30 m of a geologic column
WAACY	Wooddell, Abrahamson, Acevedo-Cabrera, Youngs (model)
WB	Wanapum Basalt
WCC	Woodward-Clyde Consultants
WF	Wallula Fault
WGCEP	Working Group on California Earthquake
WLA	William Lettis & Associates, Inc.
WLB	Walker Lane belt
WM	working meeting
WFZ	Wallula Fault Zone
WS	Workshop
WS1	Workshop 1
WS2	Workshop 2
WTP	Waste Treatment Plant
WUS	western United States
YC85	Youngs and Coppersmith 1985 (characteristic earthquake magnitude frequency distribution)
YF	Yakima Folds
YFB	Yakima Fold Belt
YFTB	Yakima Fold and Thrust Belt
yr	year(s)
yr BP	years before present

Contents of the Full PSHA Report

Appendix A

Biographies of Project Participants

Appendix A

Biographies of Project Participants

A.1 Technical Integrator Leads

Kevin J Coppersmith, PhD, of Coppersmith Consulting, Inc., is the Project Technical Integrator and the Technical Integration (TI) Lead of the Seismic Source Characterization (SSC) Team for the Hanford Probabilistic Seismic Hazard Analysis (PSHA) Project. He has 33 years of consulting experience, with primary emphasis in probabilistic hazard analyses (seismic, volcanic, and related geohazards) for design and review of critical facilities within regulated environments. He has pioneered approaches to characterizing earth sciences data and their associated uncertainties for PSHAs for a range of critical facility sites, including nuclear power plant sites, high-level waste repositories, dams, offshore platforms, pipelines, and bridges. Dr. Coppersmith was a member of the Senior Seismic Hazard Analysis Committee (SSHAC), which provided PSHA methodology guidance to the U.S. Nuclear Regulatory Commission (NRC), U.S. Department of Energy (DOE), and Electric Power Research Institute (EPRI). As a co-principal investigator, he recently completed a study for the NRC on reviewing lessons learned from the application of SSHAC Study Level 3 and 4 methodologies over the past 10 years. In light of that study, he worked with NRC research staff to develop NUREG-2117, which provides detailed implementation guidance for SSHAC Level 3 and 4 studies.

Dr. Coppersmith has extensive experience in leading SSHAC Level 3 and 4 studies for nuclear facilities. He served as the SSC Technical Facilitator/Integrator (TFI) for SSHAC Level 4 seismic hazard studies at the Yucca Mountain, Nevada, high-level waste repository, and he was the SSC TFI for the PEGASOS (Pan-European Gas-AeroSOls Climate Interaction Study) SSHAC Level 4 study for four nuclear power plants in Switzerland. He was also the TFI for the probabilistic volcanic hazard analysis conducted in 1996 for Yucca Mountain, as well as for the update to that study completed in 2008. He was the TI lead for the Central and Eastern United States Seismic Source Characterization for Nuclear Facilities project, which was a SSHAC Level 3 project conducted under the joint sponsorship of the NRC, DOE, and several nuclear utilities. Dr. Coppersmith served on the Participatory Peer Review Panel (PPRP) for BC Hydro’s SSHAC Level 3 seismic hazard analysis for 41 sites in the service area in British Columbia, Canada. He also served as SSC TI Lead for the SSHAC Level 3 PSHA conducted for the Thyspunt nuclear power plant in South Africa. He also chairs the PPRP for the SSHAC Level 3 PSHA being conducted for the Diablo Canyon nuclear power plant in central California.

In addition to conducting more than 100 major projects worldwide as part of his consulting career, Dr. Coppersmith has served on numerous advisory panels for both the public and private sectors, providing advice regarding probabilistic hazard and risk decisions for natural phenomena. He has been an invited speaker and lecturer regarding the practical implementation of earth science knowledge at academic forums and professional conferences on several continents. He has published more than 60 papers in peer-reviewed journals, served as a member of the Board of Directors of the Seismological Society of America, and has been a member of the editorial boards of the journal *Earthquake Spectra* and the *Journal of Geophysical Research, Solid Earth*. In addition, he has served on multiple panels and committees of the U.S. National Research Council, which is the operating arm of the U.S. National Academy of Sciences. Dr. Coppersmith received his BS in geology from Washington & Lee University in 1974 and his PhD from the University of California, Santa Cruz, in 1979. His dissertation research included the development of paleoseismic data for a major branch of the San Andreas Fault in central California.

Julian J Bommer, PhD (Ground Motion Characterization [GMC] TI Lead), is a consultant in the fields of seismic hazard and risk assessment. He is engaged in this role for several major engineering projects around the world, including serving as a member of Seismic Advisory Board for the Panama Canal during the design of the canal expansion. He has worked on many other seismic hazard and risk-related studies for dams, bridges, and large buildings around the world. After the 2001 destructive earthquake in southern Peru, he was engaged as an expert witness with regard to the ground motion levels and damage at the Ilo-2 power plant. His work has also covered several projects related to the hazard and risk from induced seismicity, including enhanced geothermal projects in Berlín (El Salvador), Basel (Switzerland), and the United Kingdom, reservoir-induced seismicity in Spain, and earthquake activity associated with natural gas extraction in The Netherlands.

Dr. Bommer has extensive experience in nuclear projects, including serving on the Seismic Advisory Board for the Diablo Canyon power plant in coastal California, and serving as a member of review panels for the assessment of seismic hazard for nuclear plants in Romania and Abu Dhabi. He is currently advising Eletronuclear on the re-assessment of seismic hazard at the Angra dos Reis power plant in Brazil, and he served as the Project TI and GMC TI Lead on the SSHAC Level 3 PSHA for the Thyspunt nuclear power plant in South Africa. Dr. Bommer chaired the PPRP for the first 2 years of the SSHAC Level Next-Generation Attenuation (NGA)-East project in the United Kingdom and he holds the same position for the SSHAC Level 3 Blue Castle Holdings site-specific PSHA for a new-build nuclear site in Utah, USA. In the United Kingdom, Dr. Bommer is a member of the Expert Panel on Seismic Hazard and Climate Change of the Office for Nuclear Regulation. Dr. Bommer is a registered expert in seismic hazard assessment with the International Atomic Energy Agency (IAEA). He was also part of the team engaged by the NRC to develop the implementation guidelines for SSHAC Level 3 and 4 hazard studies in NUREG-2117.

Dr. Bommer is a Civil Engineer with a Master's degree in geotechnical engineering and a PhD in engineering seismology. He is currently a Senior Research Investigator in the Department of Civil & Environmental Engineering of Imperial College London, where he was Professor of Earthquake Risk Assessment until 2011. Prior to joining the faculty at Imperial College, Dr. Bommer worked at the Jesuit-run Universidad Centroamericana in El Salvador, developing modules in engineering seismology and initiating research in seismic hazard and risk assessment, including the installation of a network of digital strong-motion accelerographs. He has published extensively on topics related to the characterization and prediction of earthquake ground motion, seismic hazard assessment, and earthquake loss estimation, as well as several field studies of damaging earthquakes (he has conducted post-earthquake field studies in Algeria, Armenia, California, Colombia, El Salvador, Greece, Italy, Japan, Mozambique, Peru and Turkey). His publications have been widely cited in the technical literature: at the date of publication of this report, he has a total of 109 publications listed in the Thomas Reuters *Web of Science*, with an average of 31 citations per paper and an *h*-index of 34. He has served as an Associate Editor for the *Bulletin of the Seismological Society of America* and as a member of the Editorial Boards of *Bulletin of Earthquake Engineering*, *Engineering Geology* and *Soil Dynamics & Earthquake Engineering*. From 2000 to 2002 Dr. Bommer was chairman of the Society for Earthquake and Civil Engineering Dynamics, the United Kingdom chapter of the European and International Associations for Earthquake Engineering.

A.2 SSC TI Team

Ryan T Coppersmith is a Senior Project Geologist with Coppersmith Consulting, Inc., in Walnut Creek, California. His experience is in structural geology specializing in bedrock mapping, seismic hazard analysis, and SSC. He has worked on several nuclear siting projects and PSHA projects in the United States and internationally. He participated in the SSHAC Level 3 PSHA study for the Thyspunt nuclear power plant in South Africa as a member of the SSC TI Team.

Mr. Coppersmith's consulting experience includes several PSHA studies and participation as an SSC TI Team member in two SSHAC Level 3 studies for nuclear facilities. He has been involved in the completion of responses to Requests for Additional Information from the NRC for the Harris, Levy, and DTE Fermi nuclear power plants' combined operating license (COL) applications. He has also been involved in several field-mapping efforts for nuclear sites to characterize both regional and site-specific structures. He has experience in mapping geomorphic surfaces, paleoseismic trenches, and bedrock structures to characterize faults as well as in mapping fluvial and marine terraces to assess regional uplift rates. Mr. Coppersmith has expertise in the use of the geologic data in building SSC models and quantifying the associated uncertainties. Other major geologic studies carried out in support of PSHAs for nuclear facilities include reviewing and documenting geologic literature, compiling project and geographic information system (GIS) databases, interpreting site geological data, and characterizing seismic sources. As part of a probabilistic fault displacement hazard analysis for oil-production facilities within the Caspian Sea, Mr. Coppersmith characterized submarine faults using seismic reflection data. As part of detailed site-specific studies, he has experience in collecting and interpreting ground-based light detection and ranging (LiDAR) data to interpret geologic structures and to map fault zone exposures. He is proficient in computer software such as ArcGIS, Canvas, Adobe, Matlab, GoCad, and Cyclone (3D software). His academic research focused on the structural analysis of outcrop-scale faulting along sea-cliff exposure near the San Simeon fault zone in California. This study resulted in a revised understanding of the history of the fault zone and of the way strike-slip systems evolve over time. Mr. Coppersmith received his BS in geology from Washington & Lee University in 2006 and his MS from the University of Texas at Austin in 2008.

Kathryn L Hanson is a Principal Geologist with AMEC Environment & Infrastructure, Inc., in Oakland, California. She has more than 35 years of applied research and consulting experience, conducting and directing investigations to quantitatively assess geologic hazards to critical facilities in the United States and abroad. Her work has involved the integration of earth science data and treatment of the uncertainty in these data to assess seismic, volcanic, and related geohazards in a variety of tectonic environments, both onshore and offshore. She has conducted both probabilistic and deterministic geohazard assessments to support successful siting, engineering, and design of nuclear facilities, dams, pipelines, and other critical facilities.

Ms. Hanson's consulting experience has emphasized regional and site-specific geologic, seismologic, and geophysical studies to identify and evaluate geohazards such as potential earthquake ground motions, surface faulting and related secondary deformation, landslides, and tsunamis. Her work incorporates state-of-the-art methods in the use of geologic data to understand fault behavior and characterize seismic sources. She was the technical lead for SSC and surface faulting investigations in support of Early Site Permits (ESPs) and COL applications for several potential nuclear power plant sites and existing nuclear plants in the Central and Eastern United States, and she participated as a reviewer for similar studies for new-build nuclear plants in the United Kingdom. She has extensive SSHAC 3 experience, having been a key participant in the EPRI/DOE/NRC Central and Eastern United States Seismic Source Characterization (CEUS SSC) Project, the BC Hydro PSHA, the Thyspunt nuclear power plant in South Africa, and ongoing Pacific Gas and Electric Diablo Canyon PSHA SSHAC 3 projects.

Ms. Hanson chaired an American Nuclear Society working group that developed national guidelines and criteria for performing investigations of nuclear facilities sites for seismic hazard assessments (ANSI/ANS 2.27). She was the senior author of the NRC's NUREG/CR 5503. In addition, she has written numerous major consulting reports and abstracts summarizing technical studies, and she has written or co-written more than 20 papers published in peer-reviewed journals and proceedings volumes. She earned a BS in geology from Iowa State University (1974) and an MS from the University of Oregon (1977).

Dr. Jeffrey Unruh is a Senior Principal Geologist and President of Lettis Consultants International, Inc., in Walnut Creek, California. He is a registered Professional Geologist with more than 22 years of research and consulting experience in neotectonics, structural geology, and seismic hazard evaluation.

Dr. Unruh has conducted comprehensive multidisciplinary studies of seismic hazards for large engineered structures such as nuclear power plants, dams, water transportation systems, and liquid natural gas facilities. Most of these studies have been performed for state and federal agencies and large utilities, and many were conducted under regulatory review. Dr. Unruh performed and managed SSCs in support of COL applications for new nuclear power plants in Virginia and Texas. These studies were conducted as SSHAC Level II investigations. Dr. Unruh served as part of the TI staff for the BC Hydro SSHAC Level III seismic hazard investigation, and has conducted analyses of stress, strain, and structural geology for PG&E in support of the ongoing SSHAC Level III update of the seismic hazard model for the Diablo Canyon nuclear power plant in California.

Dr. Unruh is an expert in the neotectonics of the Coast Ranges, Sierra Nevada, Walker Lane belt, and Central Valley of California. He recently participated in a study funded by the U.S. Army Corps of Engineers and the National Science Foundation to investigate the seismotectonics of the southern Sierra Nevada and San Joaquin Valley. Dr. Unruh has also performed numerous seismotectonic and neotectonic investigations in support of geothermal exploration and development. Representative projects include studies at the Coso, Steamboat, Salton Sea, and Dixie Valley geothermal fields, as well as evaluations of geothermal prospects in the Imperial Valley (California), Klamath Valley (Oregon), and Guam. Dr. Unruh has published more than 30 research papers in peer-reviewed journals, and he currently holds an appointment as a Research Geologist in the Department of Earth and Planetary Sciences at the University of California, Davis.

Lorraine Wolf, PhD, is a Professor of Geophysics in the Department of Geology and Geography and the Director of Undergraduate Research in the Office of the Provost at Auburn University in Auburn, Alabama. Dr. Wolf has more than 22 years of experience in conducting investigations in the field of applied geophysics, with expertise in seismology and potential fields. Her work has involved the application of these methods to earthquake hazards, including site response and fault characterization, and environmental contamination. Dr. Wolf has participated in PSHAs for Makushin Volcano and southern Alaska. She has been an active researcher for more than 15 years in the New Madrid Seismic Zone of the Central United States, where she has been involved in paleoseismic investigations and site characterization. She has participated in studies of recent earthquakes and induced seismicity, archaeological sites, and sites with ground failure due to carbonate dissolution (sink-holes). More recently, she has been involved in collecting and modeling gravity and magnetic data for fault characterization in Washington and Alabama.

Dr. Wolf has expertise in electrical resistance tomography, magnetic and gravity modeling, self-potential and seismic surveying, and microtremor analyses. She has developed geophysical survey methodologies for locating and mapping buried earthquake-induced soil liquefaction features, such as sand dikes and sand blows, and is currently co-authoring a training manual for NRC personnel on the use of paleoliquefaction features for seismic hazard analyses. As part of her research, Dr. Wolf has been involved in developing coupled deformation and fluid pressure modeling algorithms for use in studying the hydrological response to coseismic strain resulting from large earthquakes. Her work has been funded by the U.S. Geological Survey (USGS) National Earthquake Hazards Program, the NRC (subcontract from Tuttle and Associates), the USGS Water Resources Division, the National Science Foundation, and the Petroleum Research Fund of the American Chemical Society.

Dr. Wolf earned a BA (1974) and MA (1976) in English literature from Binghamton University (formerly SUNY-Binghamton) and a PhD (1989) in geophysics from the University of Alaska Fairbanks. She was a Post-doctoral Scholar for 2 years at the Air Force Geophysics Laboratory (Phillips Lab) in Boston before joining the staff at the National Research Council in Washington, D.C., as a Program Officer on the Board of Earth Sciences and Resources and the Director of World Data Center A. Later, Dr. Wolf served as the Assistant Executive Director for the Commission on Geosciences, Environment and Resources before coming to Auburn University in 1993. Dr. Wolf served for 9 years as Associate Editor for the *Bulletin of the Seismological Society of America*. She has written numerous consulting reports and abstracts summarizing technical results, has served in an editorial role for 13 NRC reports, and has authored or co-authored more than 35 papers in peer-reviewed journals and proceedings volumes.

A.3 GMC TI Team

Linda Al Atik, PhD, is an independent consultant in earthquake engineering in San Francisco, California. She is an established expert in the ground motion characterization in geotechnical earthquake engineering. In addition to her role on the GMC TI Team for the Hanford PSHA, Dr. Al Atik leads working groups on the characterization of ground motion variability for the Next-Generation Attenuation Relationships for Central and Eastern North America (NGA-East) and for the Next-Generation Attenuation Relationships for active tectonic regions (NGA-West 2) projects. She also serves as member of the TI Team for the ground motion characterization of the SSHAC Level 3 NGA-East Project and serves as a member of a support team to the GMC TI Team of the SSHAC Level 3 Southwestern U.S. Ground Motion Characterization (SWUS GMC) project.

Dr. Al Atik has been called on by other SSHAC projects to provide technical expertise in ground motion modeling. She developed a new method for the adjustment of empirical ground motion prediction equations to different reference bedrock conditions for the SSHAC Level 4 PEGASOS Refinement Project. She also participated as a GMC Proponent Expert on Vs-Kappa scaling issues at Workshop 2 of the SSHAC Level 3 Thyspunt Nuclear Siting Project. She participated as a resource expert on the characterization of the variability of ground motion and the development of hybrid empirical models for the PEGASOS Refinement Project. Linda has worked on numerous other PSHA and GMC projects in North America.

Prior to working as an independent consultant in earthquake engineering, Dr. Al Atik served as a Post-doctoral Scholar in the Dept. of Civil and Environmental Engineering, University of California, Berkeley. In this position she studied effects of soil nonlinear response on the variability of ground motion models and provided a modified method for the application of the random effects approach for the development of ground motion models. She also evaluated single-station standard deviation of ground motion models. While in this role she developed an improved approach for spectral matching and worked on developing a spectral matching approach to the Newmark displacement target response spectrum. Dr. Al Atik developed an NGA Excel tool that allows the computation of weighted spectral values from all the NGA models and updated the random effects, the probabilistic seismic hazard, and the spectral matching codes.

Dr. Al Atik has a PhD in geotechnical engineering from the University of California, Berkeley; a MS in Geotechnical Engineering from the University of California, Berkeley and a BE in Civil and Environmental Engineering from American University of Beirut, Lebanon.

Adrian Rodriguez-Marek, PhD, is an Associate Professor of Civil Engineering at Virginia Polytechnic Institute and State University (Virginia Tech) in the United States. He is an established expert in the field of ground motion prediction, seismic site response, and earthquake geotechnical engineering. He participated in the SSHAC Level 3 PSHA study for the Thyspunt nuclear power plant in South Africa as a member of the GMC TI Team. Prof. Rodriguez-Marek has also led work on the development of single-station models for the SSHAC Level 4 PEGASOS Refinement Project in Switzerland, and is a key member of the Sigma Working Group for the NGA-East project, where he is participating in the development of single-station models for the Central and Eastern United States. He has also been invited to contribute to the SSHAC Level 3 PSHA studies currently under way for the Diablo Canyon nuclear power plant, the Blue Castle nuclear site ESP application in Utah, and the SWUS seismic hazard study for nuclear power plants in the Southwestern United States. Outside of seismic hazard studies, Prof. Rodriguez-Marek has also provided geotechnical consulting services in a variety of projects involving, among others, the peer review of the seismic response of a bridge over the Orinoco River in Venezuela, and dynamic analysis for the design of launch platforms for NASA space shuttles.

Prof. Rodriguez-Marek obtained his PhD in civil engineering from the University of California at Berkeley in 2000. Prior to his appointment at Virginia Tech, he held an Assistant (and later Associate) professor post at Washington State University. He has also held visiting professor positions at the University of Concepción, Chile, at the Laboratoire de Géophysique Interne et Technophysique, in Grenoble, France, and the École Nationale des Ponts et Chaussées (Paris Tech), in France. His research and his teaching are focused on geotechnical earthquake engineering. Past research projects include research on site amplification of earthquake ground motions, characterization of near-fault ground motions, soil-structure interaction, performance-based design of structures subject to near-fault ground motions, paleoliquefaction analysis, geotechnical stability of coal combustion residual products, and site-specific site-response analysis using single-station standard deviations. He is currently directing a five-university research study on the characterization of topographic amplification for earthquake ground motions. Prof. Rodriguez-Marek has also led post-earthquake investigations of various events, including the 2001 Southern Peru Earthquake and the 2003 Colima Earthquake in Mexico. He has 24 articles in peer-reviewed publications and more than 40 technical reports and conference publications. In addition to his publications, he has been invited to give numerous technical presentations, and served as a reviewer for more than 15 journals. Dr. Rodriguez-Marek is the incoming chair of the Earthquake Engineering and Soil Dynamics committee of the Geo-Institute of the American Society of Civil Engineering in the United States.

Gabriel R Toro, PhD, is a Senior Principal Engineer at Lettis Consultants International. He has more than 30 years of experience in PSHA, development of ground motion prediction equations, probabilistic modeling of soils and their effects on earthquake ground motion, and probabilistic modeling of other natural hazards and their effects on special structures and on the built environment. He has been an active participant in nearly all large-scale PSHA projects and methodology-development efforts since the 1980s, including the first Diablo Canyon PSHA, the EPRI-SOG (Seismicity Owners Group) study, the SSHAC study, the Yucca Mountain PSHA (SSHAC Level 4), the PEGASOS study (SSHAC Level 4), the recently completed CEUS SSC (SSHAC Level 3), and numerous seismic hazard studies for recent ESP and COL applications to the NRC. In addition, he has conducted numerous seismic hazard studies for bridges, nuclear-fuel facilities, industrial facilities, and USGS-sponsored regional studies in the central United States. Dr. Toro has developed ground motion prediction equations for intraplate regions, where strong-motion data are limited and simplified physical models must be used. His ground motion prediction equations for the CEUS have been widely used. He was a member of the expert panel in the EPRI (2004) ground motion study (SSHAC Level 3), was the TI Lead for the recently completed EPRI (2013) ground motion study (SSHAC Level 2), and is the PPRP Chair for the ongoing NGA-East ground motion study (SSHAC Level 3). Dr. Toro is a member of the SSC TI Team for the PSHA for the Palo Verde Nuclear Generating Station in Arizona (SSHAC Level 3), and is a Resource Expert in the ongoing SWUS ground motion study (SSHAC Level 3). Dr. Toro also developed a widely used probabilistic model for the variation of shear-wave velocity as a function of depth, for the purpose of calculating the effect of uncertainty in site effects on earthquake ground motions. He and others have applied this model in most recent ESP and COL applications, and he has performed the subsequent site-response analysis for a number of them. He has served as peer reviewer for seismic hazard and loss studies in the United States, Malaysia, Bolivia, Guatemala, Jamaica, and Perú.

Dr. Toro has a civil engineering degree (with Honors) from the National University of Colombia, and Master's and PhD degrees in civil engineering from the Massachusetts Institute of Technology. He has published more than 40 papers in peer-reviewed journals and conference proceedings, and numerous technical reports to clients and funding agencies. His research and publications have earned him a Thesis of Merit recognition from the National University of Colombia in 1979, the OMAE Award from ASME in 1994, and the EERI Outstanding Paper Award in 2001.

Robert R. Youngs, PhD, a Principal Engineer at AMEC Environment & Infrastructure, Inc. Oakland California, has more than 35 years of consulting experience, with primary emphasis in hazard and decision analysis. He has pioneered approaches for incorporating earth sciences data and their associated uncertainties into probabilistic hazard analyses. The focus of this work has been on developing quantitative evaluations of hazard by combining statistical data and expert judgment. Dr. Youngs has considerable experience in assessing earthquake hazards in central and eastern North America and implementing SSHAC processes. He was a member of the research teams that developed EPRI's seismic hazard assessment for nuclear power plants in the CEUS, as well as EPRI-sponsored research projects to assess ground motions (1993) and maximum magnitudes (1994) for the CEUS. He was also a member of the project team for the NRC project to develop response spectral shapes for analysis of nuclear facilities (NUREG/CR-6728) in 2001, and for the EPRI project to characterize ground motions in the CEUS for analysis of nuclear facilities in 2004. Dr. Youngs has completed seismic hazard analyses of existing and proposed nuclear power plants throughout the United States (including in Alabama, Florida, Louisiana, Michigan, and North Carolina) and internationally, including in Ontario, Canada, and Switzerland (PEGASOS project). He earned his BS in civil engineering at California State Polytechnical University, Pomona (1969), and his MS and PhD in geotechnical engineering at the University of California, Berkeley (1982).

A.4 Hazard Calculation Team

Valentina Montaldo Falero, PhD, a Seismologist with AMEC Environment & Infrastructure, Inc., is the Seismic Hazard Analyst for the Hanford PSHA project. She has 14 years of research and consulting experience in PSHA, earthquake catalog development and analysis, and ground motion simulation.

Dr. Montaldo Falero's experience in SSHAC Level 3 projects includes the Central and Eastern United States Seismic Source Characterization for Nuclear Facilities project, for which she contributed to the preparation and analysis of the earthquake catalog, and the BC Hydro SSHAC Level 3 study, for which she prepared and analyzed the uniform earthquake catalog and performed seismic hazard calculations at 42 dam sites. She also contributed to the PEGASOS Refinement Project by testing alternative ways to compute maximum magnitude distributions (bootstrap technique and generalized extreme value approach), by calculating probability distributions of earthquake inter-arrival times and verifying earthquake recurrence calculations.

Dr. Montaldo Falero has participated in a number of probabilistic seismic hazard studies for nuclear power plants and nuclear repositories in the United States, Canada, and the UK, including five COL application studies for proposed nuclear sites in the United States (DTE Fermi, River Bend, Turkey Point, Levy, and Harris nuclear power plants). Her responsibilities included preparing or verifying calculation packages on earthquake catalog and earthquake recurrence analysis, PSHA, site-response analysis, and preparing sections of the Final Safety Analysis Report. As part of these studies, Dr. Montaldo Falero has tested and documented the use of AMEC in-house probabilistic seismic hazard software, for which she obtained commercial grade dedication under NQA-1 requirements. In addition, she performed PSHAs and sensitivity studies for two facilities within the Idaho National Laboratory, and various dams in Oregon, Washington, and Kentucky.

Prior to joining AMEC, Dr. Montaldo Falero was a researcher at the Italian Institute for Geophysics and Volcanology (INGV) in Milan, Italy. Her research focused on ground motion simulation and seismic hazard analysis. Dr. Montaldo Falero collaborated in developing the Italian national seismic hazard map currently in use and participated in projects funded by the Italian Civil Defense Agency. She has co-authored several papers about aspects of PSHA, ground motion simulation, and the compilation of earthquake catalogs. Dr. Montaldo Falero received her MS (Laurea) in geology from Universita' degli Studi di Milano (Italy) in 2000, and her PhD from Universita' degli Studi di Milano-Bicocca (Italy) in 2006.

Robert Youngs (see GMC Team)

A.5 Participatory Peer Review Panel

Ken Campbell, PhD, (PPRP Chairperson) is Vice President of CoreLogic EQECAT Inc. and Sole Proprietor of Kenneth W Campbell Consulting providing consulting services in the fields of ground motion and seismic hazard assessment. He received a MS in engineering from the University of Los Angeles (UCLA) in 1972 with a thesis that applied linear system theory to the estimation of seismic site response and a PhD in geotechnical engineering from UCLA in 1977 with a dissertation that applied Bayesian probability techniques to the estimation of earthquake recurrence frequency in terms of fault slip rate and characteristic magnitude. Dr. Campbell has more than 40 years of professional experience in technical management, engineering, consulting, and research in the areas of engineering seismology, strong ground motion, seismic hazard evaluation, and geotechnical earthquake engineering. Seven of these years were spent as a Project Engineer with the U.S. Geological Survey National Hazards Mapping Program. Dr. Campbell is responsible for directing the development of seismic hazard models and seismic input for EQECAT's global risk-assessment software, portfolio loss studies, and securitization risk analyses for the insurance and financial industries. As a leading expert in strong ground motion estimation and seismic hazard assessment, he also provides consulting expertise for seismic hazard studies of critical facilities worldwide. His consulting and research have led to the authorship of more than 135 publications, many of which have been published in international books and peer-reviewed journals.

Dr. Campbell’s experience in earthquake ground motion characterization and seismic hazard analysis related to nuclear facilities includes being a member of the PPRPs for the SSHAC Level 3 BC Hydro PSHA Project (43 dams in British Columbia) and the SSHAC Level 3 Southwest United States Ground Motion Project (ground motion characterization for the Diablo Canyon and Palo Verde nuclear power plants), and an Expert Evaluator on Ground Motion for the SSHAC Level 4 PEGASOS Refinement Project (five nuclear power plants in Switzerland). He participated as a Ground Motion Expert on the Yucca Mountain PSHA Project (high-level nuclear waste repository in Nevada), which many consider to be equivalent to a SSHAC Level 4 project, and on the SSHAC Level 3 CEUS Ground Motion Project (sponsored by EPRI). He also participated as a Ground Motion Expert on the original SSHAC study in 1997 and the Trial Implementation Project (southeastern United States), which was meant to serve as the first implementation of the 1997 SSHAC Level 4 recommended guidelines. He has also participated as an Expert Proponent of the Hybrid Empirical Method of ground motion simulation for the SSHAC Level 3 Thyspunt PSHA Project (nuclear power plant in South Africa), the SSHAC Level 3 Blue Castle PSHA Project (nuclear power plant in Utah), and the SSHAC Level 3 Next-Generation Attenuation (NGA-East) Project (CEUS). He also serves as a member of the Coordination Committee and as a Ground Motion Prediction Equation Developer on the NGA-West and NGA-East Projects. He has served on the DOE Savannah River Advisory Board and as a seismic hazard expert on nuclear facility review missions of the IAEA.

Brian S.-J. Chiou, PhD, is Senior Seismologist at the California Department of Transportation where he has worked since 2000. From 1992 to 2000, he was an engineering seismologist at Geomatrix Consultants, Inc. He has more than 20 years of professional experience in applied research and consulting in strong-motion seismology and earthquake hazard assessment. He is also a member of the PPRP for the Southwest United States Ground Motion Characterization Project and the Hanford Probabilistic Seismic Hazard Analysis Project, both of which are SSHAC Level 3 studies.

Between 2002 and 2007, Dr. Chiou participated in the planning, management, and execution of the NGA Model program, a major collaborative research initiative between the Pacific Earthquake Engineering Research Center, USGS, and Southern California Earthquake Center. He was a developer of the NGA model and is currently working on an update of his model in the Phase 2 of the NGA program. In addition, during the last 10 years, Dr. Chiou has participated in several other research projects, including the development of single-station/single-path standard deviation of ground motions, development of predictive models of directivity and polarization effects, fault rupture hazard methodology, and a design ground motion library. Dr. Chiou earned a BS in geology from National Taiwan University (1981), an MS in geophysics from Saint Louis University (1986), and a PhD in geophysics from the University of California, Berkeley (1991).

William R. Lettis, PhD, is Senior Principal Geologist of Lettis Consultants International, Inc. He has more than 30 years of experience performing regional and site investigations to assess geologic and seismic hazards for large engineered facilities, including bridges, dams, nuclear and fossil fuel plants, pipelines, and liquid natural gas terminals. With more than 100 publications, he is a recognized authority on the assessment of seismic hazards, both in the United States and throughout the world. Dr. Lettis has served as a TI Lead or TI Team member on five SSHAC Level 3 studies (CEUS SSC, BC Hydro, Blue Castle, Diablo Canyon, and Palo Verde) and 18 SSHAC Level 2 studies for new nuclear COL applications. He has worked extensively on geologic and seismic hazard assessments for nuclear facilities both domestically and abroad, including the United Arab Emirates, Israel, Switzerland, Korea, Taiwan, Australia (HIFAR), Turkey, and the United Kingdom. He is the author or co-author of several NRC NUREG volumes, American Nuclear Society Standard NS 2.27 on “Criteria for investigations of nuclear facility sites for Seismic hazard assessment,” and the IAEA training manual on “Seismology and Seismic Ground Motion.” Dr. Lettis earned his BS in geology from Humboldt State University (1977) and his MS (1979) and PhD (1982) in geology from the University of California, Berkeley.

William Underwood Savage, PhD, is an independent consultant in seismology and seismotectonic interpretation living in Las Vegas, Nevada. During his professional career Dr. Savage has applied his research training and professional experience to seismic safety analyses, focusing on assessing earthquake hazards for the design of critical facilities such as nuclear power plants and major dams and developing and implementing strategies for reducing earthquake vulnerabilities of natural gas and electric power facilities and systems. He has held senior positions with the USGS in Menlo Park, California, and Las Vegas, Nevada, as well as senior positions with Pacific Gas and Electric Company and Woodward-Clyde Consultants. He is an Emeritus Geophysicist at the USGS Earthquake Science Center, Menlo Park, California, and an Adjunct Professor in the Departments of Geoscience and Civil Engineering at the University of Nevada, Las Vegas.

In recent years, Dr. Savage served as the USGS seismologist for the Yucca Mountain Project, where he addressed technical issues associated with the license submittal as well as issues related to nuclear quality assurance. He also recently served as a reviewer of information about the Shoreline fault and related features just offshore of the Diablo Canyon nuclear power plant that was developed for submittal to the NRC as part of an assessment related to future operation of the plant. Dr. Savage was a consultant to Southern California Edison in support of the earthquake safety evaluation of the San Onofre Nuclear Generating Station.

He holds a BS degree in physics from the University of Oregon Honors College, and MS and PhD degrees in seismology from the University of Nevada in Reno. He was a post-doctoral researcher at the USGS in Menlo Park.

J. Carl Stepp, PhD, is currently Sole Proprietor of J. Carl Stepp Consulting providing consulting services in the fields of seismic hazard and risk assessment. His distinguished contributions to nuclear facility regulation focusing on development and worldwide application of seismic hazard and seismic design bases ground motion assessment technologies span more than 40 years. He spent more than 20 years in nuclear plant regulation first with the NRC as chief of the Geosciences Branch, then with EPRI, as director of the Seismic Center. At the NRC he managed the reviews of seismic and geotechnical engineering aspects of safety applications for nuclear plant licenses. With experience gained from these reviews he led the development of the Chapter 2.5 of NRC's Standard Review Plan, NUREG 0800, which established technical and procedural guidance for satisfying the requirements of geologic and seismic safety regulation 10 CFR 100, Appendix A. This experience led him to develop recommendations for revision of the geologic and seismic regulation to provide greater clarity, to reflect evolved seismic hazard assessment technologies, and to permit periodic future updating of guidance as warranted by evolving seismic hazard assessment technologies.

As director of the Seismic Center at EPRI, Dr. Stepp planned and managed a broad seismic and seismic engineering research and technology development program. A key element of the program focused on development of probabilistic seismic hazard assessment methodology to incorporate methodological, data, modeling, and scientific uncertainties. The product of this effort was a regional SSC model for the Central and Eastern United States (the EPRI-SOG CEUS SSC model), which developed and implemented a structured evaluation and assessment of uncertainty in existing geological, geophysical, and seismological data, methods and models. The EPRI-SOG CEUS SSC model provided the primary technical basis for NRC's Regulatory Guide 1.165, which in turn provided procedures accepted by NRC for satisfying the requirements of the newly revised seismic and geologic regulation 10 CFR 100.23. The later formalization of the procedural process implemented for development of the EPRI-SOG model evolved into the now well-established SSHAC Methodology, which is the currently accepted procedure for development of SSC as well as GMC models. As an independent consultant, Dr. Stepp has continued to support the development of seismic hazard technologies and implementation guidance. He is a co-author of the IAEA seismic hazard evaluation guideline and has participated in updating the guideline to keep pace with evolving seismic hazard assessment technologies. He has conducted training courses on the implementation of the IAEA seismic guideline in a number of regions of the world and has provided expert assistance to the IAEA in applying the guideline to evaluate the seismic safety of approximately 15 nuclear plant sites located throughout the world. He chaired the task group that developed the Seismic Topical Report II, Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain, and directed the probabilistic seismic hazard evaluation for the facility site. He subsequently served as Chairman of the Yucca Mountain Project Seismic Advisory Panel. He has continued to support the nuclear utility industry as a member of the Nuclear Energy Institute's New Plant Seismic Issues Resolution Program, which developed technologies for updating the NRC's seismic regulatory guidance: Regulatory Guide 1.208 and the Standard Review Plan, NUREG-0800. He more recently has served as chairman of PPRPs for more than 20 SSHAC studies.

Appendix B

PPRP Closure Letter

Appendix B

PPRP Closure Letter

November 15, 2014

Mr. Robert W. Bryce
Hanford PSHA Project Manager
Pacific Northwest National Laboratory
902 Battelle Boulevard
P.O. Box 999, MSIN K6-75
Richland, WA 99352

Subject: Hanford Site-Wide Probabilistic Seismic Hazard Analysis Participatory Peer Review Panel Closure Letter

Dear Mr. Bryce:

Consistent with the requirements for a SSHAC[1] Level 3 study, the Hanford Site-Wide (HSW) Probabilistic Seismic Hazard Analysis (PSHA) Participatory Peer Review Panel (hereafter "PPRP" and "Panel") is pleased to issue this PPRP Closure Letter containing our findings with respect to the HSW PSHA SSHAC Level 3 project. The Panel participated in the study following implementation guidance for a SSHAC Level 3[2] study. The Panel was actively engaged in all phases and activities of the Project's implementation, including final development of the Project Plan and planning of the evaluation and integration activities, which are the core of the SSHAC assessment process.

Consistent with regulatory guidance for SSHAC projects, the role of the PPRP is to conduct a review of both the *process* followed and the *technical* assessments made by the Technical Integration (TI) Teams. Accordingly, this letter documents the activities that the PPRP has undertaken in its review of the PSHA, its review of the adequacy of the process followed, and its findings relative to the technical adequacy of the PSHA.

PPRP Activities for the PSHA Review

The notion of a participatory peer review process entails the continual review of a project from its start to its completion. Thus, proper implementation requires adequate opportunities during the conduct of the study for the PPRP to understand the data being used, the analyses performed for the study, the TI Team's evaluations and integration of the technical bases for its assessments, and the completeness and clarity of the

[1]Budnitz, R.J., G. Apostolakis, D.M. Boore, L.S. Cluff, K.L. Coppersmith, C.A. Cornell, and P.A. Morris (1997). *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and the Use of Experts (known as the "Senior Seismic Hazard Analysis Committee Report", or "SSHAC Guideline"),* NUREG/CR-6372, U.S. Nuclear Regulatory Commission, TIC; 235076, Washington, D.C.

[2]USNRC (2012). *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*, NUREG-2117, U.S. Nuclear Regulatory Commission, Washington, D.C.

documentation. Participatory review also involves opportunities for the PPRP to provide its reviews and comments in written form during the conduct of the project, such that the suggestions and recommendations made by the Panel can be considered by the TI Teams in a timely fashion prior to completion of the work. Written comments by the PPRP serve to document the review process and provide a vehicle for ensuring that all aspects of the SSHAC process have been adequately conducted.

The activities of the PPRP for the HSW PSHA are summarized in the table below, which include written reviews during various stages of the project.

Date	PPRP Activity
April 23, 2012	Kick-off Meeting and Site Tour: All PPRP members attended in person
May 25, 2012	Submittal of PPRP written review comments on Kick-off Meeting
July 23-27, 2012	SSHAC Workshop No. 1: All PPRP members attended in person as observers
August 11, 2012	Submittal of PPRP written review comments on SSHAC Workshop No. 1
September 11, 2012	GMC Working Meeting No. 1a: PPRP representative attended via teleconference as an observer
September 17-19, 2012	SSC Working Meeting No. 1: PPRP representatives attended in person as observers
October 24, 2012	GMC Working Meeting No. 1b: PPRP representatives attended via teleconference as observers
December 3-8, 2012	SSHAC Workshop No. 2: All PPRP members attended in person as observers
January 3, 2013	Submittal of PPRP written review comments on SSHAC Workshop No. 2
February 18-21, 2013	GMC Working Meeting No. 2: PPRP representatives attended in person as observers
February 25-28, 2013	SSC Working Meeting No. 2: PPRP representatives attended in person as observers
August 13-16, 2013	GMC and SSC Working Meetings No. 3: PPRP representatives attended via teleconference and in person as observers
September 17, 2013	Quaternary Geologic Studies Field Trip: PPRP representative attended in person as an observer
November 11-15, 2013	SSHAC Workshop No. 3: All PPRP members attended in person as active participants
December 7, 2014	Submittal of PPRP written review comments on SSHAC Workshop No. 3
January 13-16, 2014	SSC Working Meeting No. 4: PPRP representatives attended via teleconference and in person as observers
January 13-17, 2014	GMC Working Meeting No. 4: PPRP representative attended in person as an observer
March 6-7, 2014	PPRP Briefing Meeting on changes made to the GMC and SSC models following Workshop No. 3 and on the PPRP written review comments on Workshop No. 3: All PRPP members attended in person as active participants
June 16, 2014	Submittal of PPRP written review comments on HSW PSHA Draft Report No. 1
June 18, 2014	Teleconference with TI Teams to discuss PPRP written review comments on partially complete HSW PSHA draft report: All PRPP members attended

June 30, 2014	Submittal of PPRP written review comments on HSW PSHA Draft Report No. 2 and on TI Teams' responses to PPRP written review comments on PSHA Draft Report No. 1
October 23, 2014	Submittal of PPRP written review comments on HSW PSHA Draft Report No. 3 and on TI Teams' responses to PPRP written review comments on PSHA Draft Report No. 2
November 11, 2014	Submittal of PPRP written review comments on HSW PSHA Draft Report No. 4 and on TI Teams' responses to PPRP written review comments on PSHA Draft Report No. 3
November 16, 2014	Submittal of HSW PSHA PPRP Closure Letter

The activities listed above are those that were related directly to the conduct of the HSW PSHA and the development of the HSW PSHA report. Prior to the HSW PSHA work activities, the Panel was provided with the Mid-Columbia Project PSHA report and other documents related to Hanford Site seismic hazards. Although those documents provided a useful background for the Panel, this letter does not address these activities, because they lie outside of the SSHAC Level 3 process for the new HSW PSHA.

The Panel concludes that its ongoing review and feedback interactions with the TI Teams during the conduct the HSW 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 Teams provided written responses to PPRP comments documenting that all comments had been adequately considered during the conduct of the work and its documentation.

SSHAC *Process* Review

As explained in NUREG-2117 (USNRC, 2012), the SSHAC process consists of two important activities, described as follows:

> "The fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration, defined as:
>
> - *Evaluation*: The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.
> - *Integration*: Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods)."

These activities are essential to any SSHAC Level study and to both refinements to existing studies as well as new PSHAs (such as the HSW PSHA).

During the *Evaluation* phase of the HSW PSHA, the TI Teams considered new data, models, and methods that have become available in the technical community since the previous HSW PSHA project was completed in 1995. Importantly, the TI Teams also evaluated new site-specific data and methods for conducting site-response analysis, which is included as part of the HWS PSHA project as guidelines that ensure that there is a proper interface between the reference-rock hazard and the site-response analyses that will be conducted by the engineering consultants. The Panel concludes that the TI Teams conducted an adequate evaluation process and that this process has been sufficiently documented in the PSHA report.

During the *Integration* phase of the project, SSC and GMC models and site-response methodological guidance were developed for purposes of the HSW-specific PSHA. SSHAC guidelines require that the technical bases for the PSHA model be documented thoroughly in the PSHA report. The PSHA document demonstrates the consideration by the TI Teams of the existence of seismic-source and ground-motion data and models that have become available since the previous HSW PSHA model was developed. The site-response guidelines entailed developing shear-wave velocity profiles for the Saddle Mountain Basalts and conducting a site-response analysis in light of models and methods that have been identified by the U.S. Nuclear Regulatory Agency and used in recent analyses for nuclear facilities. Documentation in the PSHA report confirms that the GMC TI Team was aware of the applicable site-specific data, as well as models and methods for building the profiles, accounting for uncertainties, and carrying out the site-response analysis in order to develop these guidelines.

Based on the review of the *Evaluation* and *Integration* activities conducted by the TI Teams, as well as the documentation of these activities in the PSHA report, the PPRP concludes that the SSHAC process has been adequately conducted.

SSHAC *Technical* Review

The role of the PPRP in the review of the technical aspects of the project is specified in NUREG-2117 (USNRC, 2012) as follows:

> "The PPRP fulfills two parallel roles, the first being technical review. This means that the PPRP is charged with ensuring that the full range of data, models, and methods have been duly considered in the assessment and also that all technical decisions are adequately justified and documented.
>
> The responsibility of the PPRP is to provide clear and timely feedback to the TI/TFI and project manager to ensure that any technical or process deficiencies are identified at the earliest possible stage so that they can be corrected. More commonly, the PPRP provides its perspectives and advice regarding the manner in which ongoing activities can be improved or carried out more effectively. In terms of technical review, a key responsibility of the PPRP is to highlight any data, models or proponents that have not been

> considered. Beyond completeness, it is not within the remit of the PPRP to judge the weighting of the logic-trees in detail but rather to judge the justification provided for the models included or excluded, and for the weights applied to the logic-tree branches."

Consistent with this USNRC guidance, the PPRP reviewed at multiple times during the project the TI Teams' analyses and evaluations of data, models, and methods. These reviews included conference calls, post-workshop meetings, written comments, and the review of drafts of the PSHA report. Through these reviews, the PPRP communicated feedback to the TI Teams regarding data and approaches that did not appear to have been considered, suggestions for methods being used within the technical community, and recommendations for ways that the documentation could be improved to include more discussion of the technical bases for the assessments.

Examples of PPRP feedback regarding the technical aspects of the project can be found in the written comments provided at various times to the TI Teams.

The TI Teams were responsive to the questions, comments, and suggestions made by the PPRP relative to the technical aspects of the project. Therefore, the Panel concludes that the technical aspects of the projects have been adequately addressed.

Conclusion

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.

We appreciate the opportunity to provide our review of the project.

Sincerely,

HSW PSHA PPRP Members

Kenneth W. Campbell
Chair

Brian S.-J. Chiou

William R. Lettis

William U. Savage

J. Carl Stepp

Pacific Northwest
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

Proudly Operated by **Battelle** *Since 1965*

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

www.pnnl.gov