EVALUATION OF EFFECTS OF HRHF RESPONSE SPECTRA ON SSCS OF THE APR1400 STANDARD PLANT

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ABSTRACT

This technical report summarizes the methodology and results of the evaluation for the effects of hard rock high frequency (HRHF) input ground motion on structures, systems, and components (SSCs) of the APR1400 standard plant.

The seismic analysis and design of the APR1400 standard plant are based on certified seismic design response spectra. The spectra are based on U.S. Nuclear Regulatory Commision (NRC) Regulatory Guide 1.60 with an enhancement in the high frequency range. However, many of the envelope response spectra of the central and eastern United States rock sites show higher amplitudes at higher frequencies than the certified seismic design response spectra. Response spectra with these characteristics are referred to as HRHF ground motion response spectra.

Based on the 2011 EPRI report “Evaluation of Seismic Hazard at Central and Eastern US Nuclear Power Plant Sites", the APR1400 HRHF response spectra are determined as the 0.8-fractile, 5%-damped, horizontal composite envelope ground motion response spectra for central and eastern United States hard rock sites. The APR1400 HRHF response spectra exceed the certified seismic design response spectra for frequencies above approximately 10 Hz. However, in general, as presented in EPRI Draft White Paper, “Considerations for NPP Equipment and Structures Subjected to Response Levels Caused by High Frequency Ground Motions”, the high frequency input ground motion is regarded as non-damaging.

Confirmation of nondamage from high frequency seismic input motion is needed for the APR1400 structures and equipment qualified by design-basis seismic analyses for the seismic response spectra. The building structures, reactor pressure vessel and internals, primary component supports, primary loop nozzles, piping, and equipment are mentioned in the evaluation of the APR1400 standard plant for HRHF seismic responses to demonstrate that the seismic responses of the SSCs for high frequency input ground motion are non-damaging. In the evaluation, the seismic responses in the high frequency range of the structures due to high frequency input ground motion are reduced first by considering the effects of spatial incoherence of input ground motion.

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List of Acronyms

AB	Auxiliary Building
BLPB	Branch Line Pipe Break
CESMD	Center for Engineering Strong Motion Data
CEUS	Central Eastern United States
COL	Combined License
CSDRS	Certified Seismic Design Response Spectra
EPRI	Electric Power Research Institute
EW	East-West
GMRS	Ground Motion Response Spectra
HRHF	Hard Rock High Frequency
ISRS	In-Structure Response Spectra
ISG	Interim Staff Guidance
NI	Nuclear Island
NS	North-South
PGA	Peak Ground Acceleration
POSRV	Pilot-Operated Safety Relief Valve
PSD	Power Spectral Density
PZR	Pressurizer
RCB	Reactor Containment Building
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RG	Regulatory Guide
RPV	Reactor Pressure Vessel
RV	Reactor Vessel
RVI	Reactor Vessel Internals
SG	Steam Generator
SRP	Standard Review Plan
SRSS	Square-Root-of-the-Sum-of-Squares
SSCs	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake
SSI	Soil-Structure Interaction
WUS	Western United States

1.0 INTRODUCTION

This technical report presents the evaluation of the effects of hard rock high frequency (HRHF) input ground motion on structures, systems, and components (SSCs) of the APR1400 standard plant. The technical report also describes the soil-structure-interaction (SSI) analysis of the nuclear island (NI) structures including the effects of spatial incoherence of seismic ground motions. The analysis procedure is the same as the conventional SSI analysis procedure for coherent input ground motion, using the computer program SASSI, with modifications to allow the program to incorporate the spatial incoherence of ground motion in the input ground motion to the analysis.

The response spectra used in this evaluation are developed for central eastern United States (CEUS) hard rock sites. In this report, response spectra are also called the HRHF response spectra. The HRHF response spectra are higher than the certified seismic design response spectra (CSDRS) in the high frequency range (from approximately 10 to 100 Hz). However, by including the effects of spatial incoherence of seismic ground motions, seismic responses such as in-structure response spectra (ISRS) in the high frequency are reduced.

Since the reactor containment building (RCB) and auxiliary building (AB) share a common basemat, the seismic SSI analysis is performed with the combined NI structures (i.e., the combined RCB and AB supported on a common basemat foundation). The incoherent SSI analysis is performed using the analysis methodology described in Subsection 2.1 with the SASSI computer program. The direct method (or flexible volume method) of SASSI substructuring is used in the SSI analysis.

In addition the evaluations for the APR1400 SSCs are performed to demonstrate that the seismic responses obtained from the design-basis SSI analysis envelop those obtained from the incoherent SSI analysis or to demonstrate that the seismic responses obtained from the incoherent SSI analysis are non-damaging.

This technical report consists of eight sections. Section 1 provides an introduction and background information. Section 2 describes the methodology of the incoherent SSI analysis. Section 3 describes the methodology for generating HRHF ground motion time histories and results. Section 4 describes the ground motion coherency function. Section 5 compares the ISRS based on CSDRS and HRHF response spectra. Section 6 describes the evaluation of HRHF response spectra effects on SSCs of the APR1400 standard plant. Section 7 contains the conclusions from the evaluation. Section 8 is a list of the references cited in the report.

2.0 INCOHERENT SSI ANALYSIS METHODOLOGY AND PROCEDURE

2.1 ANALYSIS METHODOLOGY

The incoherent-motion SSI analysis determines the maximum seismic response of the APR1400 NI structures, taking into account the effects of spatial incoherence of seismic ground motions. The conventional SSI analysis methodology for coherent input ground motion, utilizing the computer program SASSI (Reference 1), is modified to allow the program to incorporate the spatial incoherence of ground motion in the input ground motion to the analysis.

The seismic SSI analysis using SASSI assumes that the seismic motions input to the NI structure SSI system are coherent motions. These input motions result from vertically propagating plane seismic shear (*S*) waves for the horizontal input motion and plane seismic compression (*P*) waves for the vertical input motion. For a horizontally layered free-field soil/rock medium, the idealized plane-wave input ground motions can be derived from horizontal and vertical free-field site response analyses using a one-dimensional elastic wave propagation theory. These analyses are generally performed using the equivalent-linear, free-field site response analysis computer program SHAKE (Reference 2). The free-field input ground motions derived from a one-dimensional elastic wave propagation theory are spatially coherent vertically propagating plane-wave input ground motions. Such motions are used for the conventional SSI analysis without taking into account spatial incoherence of seismic motions.

To incorporate spatial incoherence in the input ground motions for the SSI analysis using SASSI, the methodology developed by Tseng and Lilhanand as described in Electric Power Research Institute (EPRI) Report TR-102631 (Reference 3), is used in the industry.

Following the methodology described in EPRI Report TR-102631, for each of the two horizontal (north-south [NS] and East-West [EW]) and vertical components of input ground motion, the “plane-wave coherency function” $\gamma_{pw}(f, \xi)$ for hard rock described in Section 4 is used to construct a “spatial coherency matrix” $[\gamma]$ for each frequency, f_j, j = 1, 2, 3, …, m, selected for the SASSI response analysis. The set of frequencies f_j, j = 1, 2, 3, …, m is designated as the SASSI calculated frequencies. The matrix $[\gamma]$ to be constructed is generated for the spatial locations of the nodal points on the ground surface of the SASSI finite element model used to model the excavated soil/rock volume. Thus, the matrix $[\gamma]$ is a function of frequency f_j only, i.e., $[\gamma] = [\gamma(f_j)]$, since the spatial separations of the nodal-point locations have been explicitly represented by the elements in the matrix. Each coefficient in this matrix expresses the spatial coherency of the co-directional input ground motions at any two nodal points lying on each horizontal plane of the SASSI finite element mesh, which is used to model the excavated soil/rock volume that corresponds to the embedded portion of the NI structure complex below grade.

Since the coherency functions for characterizing the spatial coherency of seismic motions at different depths are not available, the coherency matrix $[\gamma] = [\gamma(f_j)]$ derived for motions on a horizontal ground surface are assumed to be the same for motions on all other horizontal planes at different depths. This assumption leads to conservative input ground motions to the SSI system, because as a result of this assumption, motions for different horizontal planes at different depths are fully coherent with depth. That is, the variation of input ground motions with depth are fully correlated in the form of vertically propagating plane-wave motions that are derivable from the one-dimensional soil column site response analyses.

The coherency matrix $[\gamma] = [\gamma(f_j)]$ is a symmetrical full matrix with real-valued matrix coefficients with the unit of power (motion-amplitude squared). To incorporate the incoherency of motion into the input ground motion vector for SSI analysis, the square root of the coherency matrix $[\gamma(f_j)]$ is determined. To do this, the coherency matrix $[\gamma]$ is decomposed into two identical but complimentary matrices so that their product gives the coherency matrix $[\gamma]$. To achieve decomposition, it is convenient to decompose the matrix $[\gamma]$ for each calculated frequency f_j into its eigenvalues (principal coherency wave-numbers), λ_i^2, and associated eigenvectors (principal coherency mode shapes), $\{\phi_i\}$, i = 1, 2, 3, …., n, where the number n is the total number of nodal points that lie on each horizontal plane of the finite element model mesh used to model the excavated soil/rock volume of the NI structural foundation below grade (i.e., $[\gamma] = [\phi]^T [\lambda^2] [\phi]$). The matrix $[\phi]$ contains in its columns all Eigen-vectors $\{\phi_i\}$, i = 1, 2, 3, …., n, and $[\phi]^T$ is the transpose of $[\phi]$. The matrix $[\lambda^2]$ is a diagonal matrix containing on its diagonal terms the Eigen-values λ_i^2, i = 1, 2, 3, …., n.

Since the eigenvectors of the coherency matrix $[\gamma]$ are mutually orthogonal to each other, the square root of the coherency matrix $[\gamma]$ can be expressed as the product of $[\lambda]$ and $[\phi]$, in which the diagonal matrix $[\lambda]$ contains on its diagonal terms the square root of the eigenvalues, namely, λ_i. Due to orthogonality of the eigenvectors, construction of the spatially incoherent input ground motion vectors can be carried out independently for each principal coherency mode. In other words, the product $\lambda_i\{\phi_i\}$ for each principal coherency mode i, i = 1, 2, 3, …., n, can be used independently to modify the spatially coherent, co-directional input ground motion vector for each horizontal plane.

The assumption of vertically propagating plane waves for the coherent seismic input motion implies that the spatially coherent, co-directional, seismic input motions for each horizontal plane have identical motion amplitudes and phase angles. Using the product λi{ϕi} to modify the spatially coherent seismic input motions, the identical spatially coherent seismic input motion amplitudes on each horizontal plane are modified to their corresponding non-identical spatially incoherent seismic input motion amplitudes on each horizontal plane. This modification preserves the phase angles associated with the spatially coherent seismic input motions.

By modifying the spatially coherent seismic input motions using the product λi{ϕi} for each principal coherency mode, the SSI analysis for the spatially incoherent seismic input motions constructed for each principal coherency mode is carried out independently in the same manner as the SSI analysis for the conventional, spatially coherent, seismic input motion. The contributions to the SSI response parameters of interest from different principal coherency modes are then combined using the square-root-of-the-sum-of-squares (SRSS) combination rule, which implicitly assumes that the responses of all principal coherency modes are mutually statistically independent (i.e., the phase angles of all principal coherency modes are uncorrelated).

Correlation studies for validating the SSI analysis methodology with spatially incoherent seismic input motions developed as described above have been made as reported in EPRI Report TR-102631 (Reference 3). These studies considered the problems of the SSI response of a flexible structure on a rigid base supported on the surface of an elastic halfspace that was subjected to excitation of a spatially incoherent (random) seismic input motion. These were the same problems studied by Luco and Mita with their analytical solutions (References 4 and 5). The results of the correlation studies, as published in the EPRI report (Reference 3), indicate that to capture the global SSI response due to spatially incoherent seismic input motions adequately, it is only necessary to include a few lower principal coherency modes of the coherency matrix. For each horizontal seismic input, only the first (horizontal translation) and second (twisting) modes are sufficient to capture the global SSI response of the problems studied due to the horizontal incoherent ground motion input. Likewise, for the vertical seismic input, only the first (vertical translation), second (rocking about one horizontal axis), and third (rocking about the other orthogonal horizontal axis) modes are sufficient to capture the global SSI response due to the vertical incoherent ground motion input.

For the incoherent SSI analysis to be carried out for the APR1400 NI structure complex, for each of the two horizontal directions, a minimum of two principal coherency modes, namely, the first (horizontal translation) and second (twisting about the vertical axis) modes, need to be included in the horizontal SSI analysis. For the vertical direction, a minimum of three principal coherency modes, namely, the first (vertical translation), second, and third (rocking about the two orthogonal horizontal axes) modes need to be included in the vertical SSI analysis. Additional parametric studies are to be carried out to demonstrate that inclusion of more principal coherency modes, in addition to those described previously, does not change the SSI response significantly.

2.2 SITE RESPONSE ANALYSIS

The procedure used for performing the site response analysis is described below.

1. Select the soil profile from Reference (6) consistent with the hard rock coherency function.

2. Perform two horizontal (H1H and H2H) site response analyses with equivalent linear iterations on non-linear soil properties using SHAKE (Reference 2) to determine strain-compatible soil properties. The H1H and H2H ground motion time histories for SSE are input motion at El. 98′-6″ (ground surface). The shear-modulus-degradation and damping-value variation curves considered for rock are from Reference 2 and are shown in Table 2-1 and Figure 2-1.

3. Compute the averaged strain-compatible soil properties by averaging the two horizontal strain-compatible soil properties obtained from SHAKE in Step (2) for use as horizontal free-field soil properties in the SASSI soil model for the SSI analysis.

4. Using the averaged strain-compatible soils obtained from Step (3), perform horizontal (H1H and H2H) SHAKE analyses with no iterations on soil properties to determine horizontal free-field soil response motions at other elevations and transfer functions.

5. For vertical site response analyses, use the low-strain compression wave velocities. If the low-strain compression wave velocity is less than 4800 fps, then 4800 fps is used since the groundwater table is at the surface (El. 98′-6″) unless this causes Poisson’s Ratio to exceed 0.48, in which case a compression wave velocity corresponding to a Poisson’s Ratio of 0.48 is used due to limitations in SASSI.

2.3 SSI ANALYSIS

Using the SSI analysis methodology and the associated modified SSI analysis computer program SASSI and INCOH as described previously, the SSI analysis of APR1400 NI structures incorporating effects of spatial incoherence of input ground motion can be performed following the analysis steps described below:

(1) Based on the finite element mesh for the horizontal plane on the ground surface of the finite element model for the excavated soil/rock volume, generate the horizontal and vertical incoherent ground-motion coherency matrices using the horizontal and vertical plane-wave coherency functions for hard rock sites as described in Section 4 of this report.

(2) Perform an eigenvalue analysis of each horizontal and vertical incoherent ground-motion coherency matrix to generate the eigenvalues (principal coherency wave-numbers), λ_i^2, and associated eigenvectors (principal coherency mode shapes), $\{\emptyset_i\}$, i = 1, 2, 3, ., n; where n is the total number of nodal points on the horizontal plane on the ground surface of the finite element mesh used to model the excavated soil/rock volume.

(3) For each principal coherency mode i, compute the product $\lambda_i\{\emptyset_i\}$ and incorporate the product into the horizontal or vertical coherent ground-motion vector, as appropriate, for the "n" nodal points lying on each horizontal plane of the finite element mesh used in modeling the excavated soil/rock volume. This step generates an incoherent seismic input ground-motion vector for each principal coherency mode i to be included in the incoherent-motion SSI analysis, i = 1, 2,..., m, and m << n.

(4) Using the incoherent ground-motion vector generated in Step (3) for each principal coherency mode i for each of the two horizontal or vertical seismic input ground motion, perform a horizontal or vertical SASSI analysis to generate the seismic response transfer functions for all seismic response parameters of interest. Such response parameters may include absolute accelerations, relative displacements, member forces and moments, and in-structure response spectral values, at all designated structure locations.

(5) For each principal coherency mode i included in the analysis of Step (4), perform convolution of the computed seismic response transfer functions with the Fourier spectrum of the prescribed HRHF response spectrum-compatible seismic input time history to generate corresponding frequency-response functions. The resulting frequency response functions are then inverse Fourier-transformed back to the time domain to produce the response time-histories.

(6) For each principal coherency mode i included in the analysis in Step (5), generate the maximum response values from the time histories of seismic response parameters of interest.

(7) For each seismic response parameter of interest, combine the maximum response contributions from all principal coherency modes included in the analysis using the SRSS combination rule.

Steps (3) through (6) described above need to be repeated as many times as the total number of principal coherency modes, m, included in the seismic SSI analysis. As described previously, the minimum number of modes included in the incoherency SSI analysis of the NI structures is two (m = 2) for each of the horizontal NS and EW seismic inputs and three (m = 3) for the vertical seismic input.

3.0 SEISMIC INPUT

In this section the seismic design spectra for the APR1400 and high frequency ground motion response spectra (GMRS) are described.

3.1 EPRI GMRS FOR CEUS ROCK SITES

Following the issuance of NRC RG 1.208 “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion” in March 2007, EPRI undertook seismic hazard studies in 2008 and 2011 for the existing CEUS nuclear power plant sites.

The first EPRI study was documented in an EPRI report published in August 2008. This report, “Assessment of Seismic Hazard at 34 U.S. Nuclear Power Plant Sites” (Reference 7), presents the results of seismic hazard assessment for 34 existing U.S. nuclear power plant sites located in CEUS. The study was performed using the NRC RG 1.208 methodology and guidelines and incorporated the 1989 EPRI seismic source characterization model with updated seismic source characterization information through 2003. The 5%-damped GMRS for 28 of the 34 sites studied were computed and compared with the NRC RG 1.60 design response spectra anchored to a peak ground acceleration (PGA) value of 0.3g. The comparisons indicate that the GMRS for 7 of the 28 sites developed have GMRS exceeding the RG 1.60 design response spectra anchored to 0.3g in the high frequency range of 8 Hz to 50 Hz and higher.

The second EPRI study was documented in the EPRI report, “Evaluation of Seismic Hazard at Central and Eastern US Nuclear Power Plant Sites" (Reference 8). This report presents the results of seismic hazard evaluations performed for 60 U.S. nuclear power plant sites located in CEUS. The 60 sites studied include the 34 sites that were studied in the first EPRI study (Reference 7). This study, like the first EPRI study in 2008, was performed using the methodology and guidelines of NRC RG 1.208 but instead of the 1989 EPRI seismic source characterization model used in the first study, it incorporated the updated 2008 U.S. Geological Survey seismic source characterization model (Reference 9).

Site-specific GMRS for all 60 sites were computed considering their site-specific site conditions. The 60 site conditions were categorized into five site categories, labelled Site 1 through 5. The 5%-damped GMRS for all 60 sites were calculated again for each of the 60 sites by assuming that each site condition of all 60 sites was represented by one of the generic site categories (Sites 1 through 5) plus a hard rock category. The computed GMRS were then enveloped and the maximum (enveloped) 0.95, 0.9, 0.8, 0.7, 0.6, and 0.5 fractiles of the “composite envelope spectra” were computed. These spectra represent that, if any of the 5 generic site conditions (Sites 1 through 5 or rock) exists at a specific plant site, the 0.9 fractile “composite envelop spectrum” will encompass 90 percent of the GMRS computed for the 60 nuclear power plant sites studied. The maximum and fractile “composite envelope spectra” for the CEUS nuclear power plant sites developed in this study are useful for comparison with the CSDRS used for the standard plant design to assess the approximate percentage of sites in the CEUS that will be covered by the CSDRS.

The details of CSDRS and the CSDRS-compatible design time histories are provided in the technical report APR1400-E-S-NR-13001-P (Reference 10).

3.2 HRHF RESPONSE SPECTRA FOR APR1400

In the second EPRI study (Reference 8) described above, the maximum and fractile GMRS for the 60 CEUS nuclear power plant sites were developed, assuming that they are all hard rock sites. These 5%-damped maximum and fractile hard rock horizontal “composite envelope GMRS” are shown in Figure 3-1. The fractile GMRS shown in Figure 3-1 provide a rational basis for determining a suitable HRHF response spectra for applicable to the APR1400. The APR1400 set a goal of the 0.8-fratile for non-exceedance probability. The horizontal “composite envelope GMRS” for CEUS hard rock sites is selected as the 5%-damped target horizontal HRHF response spectra for application to the APR1400 standard plant design as shown in Figure 3-2.

The 5%-damped HRHF vertical target response spectrum is generated from the 5%-damped HRHF horizontal target response spectrum by multiplying the recommended vertical/horizontal (V/H) ratios for CEUS rock sites referred to in NUREG/CR-6728 (Reference 11). The V/H ratios for the 0.2 to 0.5g range of the peak rock-outcrop horizontal acceleration are used. For all needed frequencies not listed in NUREG/CR-6728, the ratios used follow a log-log amplitude-frequency linear interpolation. The resulting 5%-damped HRHF vertical target response spectrum generated are plotted along with the 5%-damped HRHF horizontal target response spectrum in Figure 3-3.

The digitized values of the HRHF horizontal and vertical target response spectra are given in Table 3-1 and 3-2. The V/H ratios are given in Table 3-3 and plotted in Figure 3-4.

The HRHF horizontal response spectra for damping ratios other than 5% (namely, 2%, 3%, 7%, and 10% damping ratios, which are not available from the EPRI study) are generated from the 5%-damped HRHF horizontal response spectrum by multiplying the 5%-damped spectral values by the spectral ratios for CEUS rock sites given in Table 3-4 of Appendix C of SRP 3.7.1 (Reference 12). For spectral frequencies not listed in Table 3-4, the ratios that were used follow a log-log amplitude-frequency linear interpolation. The HRHF horizontal response spectrum for a 4% damping ratio, for which the spectral ratios are not available in Table 3-4, is generated by interpolating between the spectral values for 3% and 5% damping ratios on a log scale for the damping ratio and a linear scale for the spectral acceleration.

The HRHF vertical response spectra for 2%, 3%, 4%, 7%, and 10% damping ratios are generated by multiplying the V/H ratios for the CEUS rock site conditions given in Table 3-3 by the corresponding HRHF horizontal response spectra.

The resulting HRHF horizontal and vertical response spectra for 2%, 3%, 4%, 5%, 7%, and 10% damping ratios developed in the manner described above are shown in Figures 3-5 and 3-6, respectively. The spectrum curves shown in these two figures are the HRHF horizontal and vertical response spectra selected for the APR1400. The numerical values of the HRHF horizontal and vertical response spectra selected are listed in Tables A-1 and A-2 in Appendix A of this report.

Comparisons of the HRHF response spectra with the CSDRS for 5% damping are shown in Figures 3-7 and 3-8 for the horizontal and vertical directions, respectively.

3.3 GENERATION OF HRHF RESPONSE-SPECTRUM-COMPATIBLE TIME HISTORIES

The basic guidelines and criteria to be used for generating a set of three-component design time histories compatible with the HRHF target response spectra follow the guidelines and criteria in NRC SRP Section

3.7.1, Rev. 3, for Option 1 ("single time history option"). Since the HRHF response-spectrum-compatible design time histories are to be used for the evaluation of the APR1400 standard plant design, which involves the plant SSCs with different damping ratios, the recommended approach for generating the spectrum-compatible design time history is Option 1, Approach 1. The requirements of Option 1, Approach 1, are summarized below.

3.3.1 GROUND MOTION TIME HISTORIES

The guidelines and criteria in SRP Section 3.7.1, Rev. 3, for Option 1, Approach 1, and the desirable spectrum-compatible design time histories are as follows:

(a) Design time histories to be generated are based on recorded seed motion time histories.

(b) The set of time histories should consist of time histories in three mutually orthogonal directions - two horizontal and one vertical.

(c) The time interval of time history digitization, t, shall be less than $1/(2\ f_n)$ where f_n is the highest frequency of interest. For the APR1400, the interval of time history digitization shall be 0.005 second, which corresponds to a f_n of 100 Hz.

(d) The minimum acceptable strong-motion duration, which is defined as the time required for the Arias Intensity to rise from 5 to 75 percent, should be 6 seconds.

(e) The three time histories (two horizontal and one vertical) shall be statistically independent from one another. The criterion for statistical independence shall be based on the cross-correlation coefficients computed for any pairs of time histories and these calculated coefficients shall be less than 0.16.

(f) In addition to the duration, the ratios V/A and AD/V^2, where A, V, and D are peak ground acceleration, ground velocity, and ground displacement, respectively, should be consistent with characteristic values determined for the low and high frequency events described in Appendix D of NRC RG 1.208 (Reference 13).

3.3.2 RESPONSE SPECTRUM AND POWER SPECTRAL DENSITY ENVELOPING REQUIREMENTS

In accordance with the guidelines and criteria for Option 1 Approach 1, the response spectrum and power spectral density (PSD) enveloping requirements for design time histories are as follows:

(a) The response spectra from the time history must envelop the target HRHF response spectra for all damping values used in the seismic response analysis.

(b) For each applicable damping value, the response spectrum of the time history shall envelop the target response spectrum with no more than five points falling below the target spectrum by no more than 10 percent of the target spectral values.

(c) In checking spectrum-enveloping, the set of frequencies at which the response spectra are to be calculated shall be the standard set of 92 frequencies from 0.2 Hz to 80 Hz as specified in SRP 3.7.1 Table 3.7.1-1.

(d) The PSD of the time history shall adequately match a target PSD, which is compatible with the target design response spectra. For design response spectra other than the NRC RG 1.60 response spectra, the response spectrum-compatible target PSDs should be generated. In generating the target PSDs, the guidelines and procedures provided in Appendix B to SRP 3.7.1 can be used.

(e) The time history PSDF shall generally envelop the minimum required target PSD, which is set at 80 percent of the target PSD, in the frequency range between 0.3 Hz and 80 Hz.

3.3.3 SELECTION OF INITIAL SEED MOTION TIME HISTORIES

To comply with the SRP 3.7.1 guidelines, design time histories should be generated from the recorded, actual earthquake ground motion called “seed motion”. The selection guidelines of a set of recorded time histories to be used as the seed motion for the generation of the HRHF response spectrum-compatible design time histories are follows:

(a) The three component seed motion time histories, two horizontal and one vertical, should come from the same earthquake event and recording station.

(b) The scaled seed motions should provide a reasonably close match to the target response spectra over the amplified frequency range of the target response spectra to select seed motions that require the least amount of modifications to match the target spectra.

(c) The seed motions should have a reasonable duration of 20 seconds and a strong-motion duration greater than 6 seconds as characterized by and Arias Intensity from 5 to 75 percent. Long-duration seed motions can be truncated to duration of between 20 and 24 seconds.

(d) The seed motions with a PGA value greater than 0.10g are more desirable because they require a scale factor of less than 3.0 to bring them to the 0.3g target PGA value.

(e) Seed motions from an earthquake of magnitude M greater than or equal to 6.5 and less than or equal to 7.3 are more desirable because they tend to generate motions that are sufficiently strong.

(f) Seed motions at recording sites at a distance greater than or equal to 10 but less than or equal to 50 km from the earthquake epicenter are more desirable because they contain distinctive phases of P and S waves and have sufficiently high PGA amplitudes greater than 0.1 g.

(g) Seed motions with broadband and high frequency motion contents are more desirable than those having narrow-band and low frequency motion contents.

(h) Recorded motions from CEUS rock sites, when available, are more desirable than recorded motions from CEUS soil sites or western Inited States (WUS) soil or rock sites because they should have more high frequency motion contents.

(i) The cross-correlation coefficient computed for any pair of the three component time histories of seed motions should be less than 0.16. The modification of seed motion time histories to match the target spectra generally does not change cross-correlation coefficients of the seed motion significantly.

For generation of the horizontal and vertical HRHF response spectrum-compatible time histories, the initial seed motion time histories can be selected from the catalog of recorded actual earthquake ground motion time histories for CEUS rock sites presented in Appendix B of NUREG/CR 6728 (Reference 11).

Based on the selection guidelines described above, a set of three component earthquake motion time histories from magnitude 6.8 Nahanni, Canada, earthquake of December 23, 1985 recorded at Station #3, Mackenzie, Northwest Territories, Canada, is selected as the initial seed time histories. This recording is selected from the catalog of NRC time histories presented on Page B-50 of Appendix B in NUREG/CR 6728. The recording station is located about 16 km from the epicenter of the earthquake. The digitized data of the recording are obtained from the Center for Engineering Strong Motion Data (CESMD) website (Reference 14). The recorded motion consists of time histories for two horizontal (designated as 270 and 360) and one vertical (designated as VT) components. The digitized data of the recorded time history of each component have 3,819 points digitized at 0.005-second time increments giving a total record duration of 19.09 seconds. The plots of acceleration and integrated velocity and displacement time histories of the recorded motion for each component are shown in Figures 3-9 through 3-11 for the 270, 360, and VT components, respectively.

Comparisons of the time history response spectra for the recorded motion scaled to the target PGA value of 0.46g and the corresponding APR1400 HRHF horizontal and vertical target response spectra are shown in Figures 3-12 through 3-14 for the 270, 360, and VT components, respectively. As shown in these comparisons, the recorded time histories scaled to the target PGA value of 0.46g have time history response spectra match the target response spectra over a relatively wide frequency band.

3.3.4 OTHER RELAVANT GROUND MOTION PARAMETERS

To comply with the guidelines and criteria in SRP 3.7.1, Rev. 3, the response-spectrum-compatible time histories to be generated should also be checked for reasonable compliance within the target value of ranges of other associated design ground motion parameters. In addition to the maximum acceleration, A, of the generated time history, the other ground motion parameters to be checked include the maximum velocity, V, maximum displacement, D, and V/A and AD/V^2 ratios.

The target and target ranges of values for these other design ground motion parameters defined to be the median (m) values and median (m) ± one standard deviation (σ), i.e., $m \pm \sigma$, ranges. The target and target ranges of values are determined based on the methodologies and ground motion databases described in SRP 3.7.1 and NUREG/CR-6728.

The peak ground acceleration (PGA) of the selected APR1400 HRHF response spectra is 0.46g for both the horizontal and vertical components of ground motion. Thus, the target maximum acceleration (A) of the HRHF response spectrum-compatible time histories is A = 0.46g.

From the study results presented in NUREG/CR-6728, the target median (m) values of maximum velocity V, maximum displacement, D, V/A and AD/V^2 ratios of the HRHF response spectrum-compatible time histories to be generated, scaled to the target PGA value of A = 0.46g, are given in Table 3-5. The target ranges of V, D, V/A, and AD/V^2 values defined to be the median ± one standard deviation ($m \pm \sigma$) ranges are shown in Table 3-6. The standard deviation (σ) for each parameter is derived from the ground motion databases for CEUS rock sites for earthquake magnitudes of 6.3 to 7.5 and epicentral distance bins 0-100 km, as given in Table 3-6 (on pages 3-14 and 3-15) of NUREG/CR-6728. For conservatism, the smallest of the σ values of each parameter for CEUS rock motions for magnitudes of 6.3 to 7.5 and for epicentral distance 0 to 100 km is used. The smallest σ value leads to the smallest target range of variation for the parameter considered and is therefore, the most conservative.

For the maximum velocity V, the minimum σ-value selected from Table 3-6 of NUREG/CR-6728 is 0.40. Thus, the value for "$m+\sigma$" is computed as $m+\sigma = m \times \exp(\sigma) = 8.53 \times \exp(0.40) = 12.73$ in/sec and the value for "$m-\sigma$" is computed as $m-\sigma = m \times \exp(-\sigma) = 8.53 \times \exp(-0.40) = 5.72$ in/sec.

For the maximum velocity D, the minimum σ-value selected from Table 3-6 of NUREG/CR-6728 is 0.57. Thus, the value for "$m+\sigma$" is computed as $m+\sigma = m\times\exp(\sigma) = 3.63\times\exp(0.57) = 6.42$ in. and the value for "$m-\sigma$" is computed as $m-\sigma = m\times\exp(-\sigma) = 3.63\times\exp(-0.57) = 2.05$ in.

The σ-values of 0.33 and 0.45 for V/A and AD/V², respectively, as given in Table 3-6 are smaller and, hence, more conservative than the corresponding σ-values of 0.48 and 0.54, respectively, given in NUREG-0003 (Reference 15), which are applicable for the NRC RG 1.60 horizontal design response spectra (Reference 16).

3.4 METHOD FOR GENERATING SPECTRUM-COMPATIBLE TIME HISTORIES

Two methods have generally been adopted for the generation of response-spectrum-compatible time histories: (a) the time domain time history adjustment method and (b) the frequency domain time history adjustment method. To generate a time history that is compatible with a set of multiple damping target response spectra based on a recorded actual earthquake seed motion time history, the time domain time history adjustment method is usually adopted because it preserves the motion characteristics of the recorded seed motion.

3.4.1 ANALYTICAL BACKGROUND

The method for generating a design time history with response spectra closely matching a family of target response spectra of multiple damping values is the time domain time history adjustment method. This method was originally developed by Kaul (Reference 17) for matching a single damping target spectrum. It was extended later by Lilhanand and Tseng (References 18 and 19) for matching multiple damping target response spectra. The extended method by Lilhanand and Tseng is implemented into the computer program SYNQKE-R, PC Version 1.0 (Reference 20).

The time domain time history generation method begins with the use of an appropriately selected initial seed motion time history. The seed motion time history is selected to be consistent with the pertinent earthquake source, path, site parameters and the guidelines described previously in Section 3.3.2. Using the time domain time history generation method, the initial time history is modified (adjusted) in an iterative manner to match the time history response spectral values to the target spectral values within a prescribed tolerance. For each selected frequency for which the spectral values of multiple damping are to be matched, only localized adjustment with a wavelet is made to the time history over a short duration centered around the time when the maximum (i.e., spectral) response values occur. As a result, the iterative time history modifications produce not only a close match to the target response spectra but also only small localized perturbations to the initial time history; thus, the final modified time history closely resembles the motion characteristics of the initial seed time history.

3.4.2 ANALYTICAL PROCEDURE

For generating a set of three component design time histories matching the APR1400 HRHF target response spectra, the recommended seed motion time histories recorded from the 1985 Nahanni, Canada, earthquake, as described in Section 3.3.3 are to be used as the initial set of time histories. These initial time histories are first adjusted by (a) scaling to have a maximum acceleration of 0.46g, (b) adding trailing zeros to make the time histories with 4,096 points with a total duration of 20.475 seconds, and (c) modulating the time histories by an intensity envelope function, *g*(*t*) as shown in Figure 3-15. The adjusted initial time histories are then used for time history modifications using the computer program SYNQKE-R.

SYNQKE-R adjusts the initial time history by automated iterations. For each cycle of iteration, the time history response spectra are compared with the target response spectra of corresponding damping values and the necessary time history adjustments to achieve spectrum-matching for the cycle are automatically solved. By repeating this iteration process and constantly monitoring the convergence to within the SRP spectrum-enveloping guidelines, a final modified time history that which has response spectra closely matching with the target multiple damping response spectra and satisfying the SRP spectrum-enveloping guidelines is obtained.

The final modified acceleration time histories, H1H, H2H, and VTH, are integrated to obtain their integrated velocity and displacement time histories. From these results, baseline corrections are performed, as necessary, to minimize the residual velocity and displacement values and, at the same time, produce the desirable time history intensity envelopes and integrated maximum velocity (V) and displacement (D) values, giving the baseline-corrected acceleration time histories.

Time history response spectra of the baseline-corrected time histories are then computed and compared with the target spectra to provide resonable assurance that the SRP spectrum-enveloping guidelines are still satisfied; otherwise, further time history modifications and baseline corrections are performed until the guidelines are satisfied.

3.5 DEVELOPING HRHF RESPONSE-SPECTRUM-COMPATIBLE PSDs

To check the adequacy of the power spectral density (PSD) of each generated response spectrum-compatible time history, horizontal and vertical target PSDs that are compatible with the HRHF horizontal and vertical target response spectra for APR1400 are needed. The development of the horizontal and vertical target PSDs compatible with the APR1400 HRHF horizontal and vertical response spectra is described below.

3.5.1 HRHF RESPONSE SPECTRUM-COMPATIBLE TARGET PSDs

The development of the APR1400-HRHF response spectrum-compatible target PSDs in the frequency range of 0.3 to 80 Hz, the time history simulation method described in NUREG/CR-5347 (Reference 21) is used. Applying this method for developing the target PSD involves the following steps:

(1) An ensemble of 30 artificial time histories is generated using a frequency domain response spectrum-compatible time history generation method developed by Gasparini and Vanmarcke and implemented in SIMQKE (Reference 22). Each time history 30 time history ensemble has a total duration of 20.475 seconds and is modulated by the intensity envelope function shown in Figure 3-16. Each time history generated has a 2%-damped time history response spectrum compatible with the 2%-damped horizontal APR1400 HRHF response spectra.

The SIMQKE frequency domain response spectrum-compatible time history generation method starts with synthesizing pure harmonic waves with white noise random phases and with amplitudes generated from an initial response spectrum-compatible target PSD within the frequency range of interest, which for APR1400 HRHF response spectra is 0.3 to 80 Hz. The initial target PSD at each frequency is derived from the 2%-damped target response spectral value divided by a frequency-dependent “peak factor” derived from the random vibration theory (Reference 22). The peak factor, which relates the target PSD value to the 2%-damped target response spectral value, is a function of frequency and non-exceedance probability of the target response spectra. The initial time history is then modified iteratively by adjusting the initial time history PSD at each frequency using the square of the ratio of the 2%-damped time history response spectral value to the 2%-damped target response spectral value.

The 2%-damped time history response spectra for the ensemble of 30 artificial time histories are computed based on which 2%-damped “ensemble-median” time history response spectrum is derived. This spectrum for the ensemble of 30 artificial time histories is shown in Figure 22 for the horizontal motion and in Figure 3-17 for the vertical motion. The 2%-damped horizontal and vertical “ensemble-median” time history response spectra are then compared with the 2%-damped horizontal and vertical target HRHF response spectra. These comparisons are shown in Figures 3-18 and 3-19.

As indicated in Figures 3-18 and 3-19, the ensemble-median time history response spectra derived from the generated horizontal and vertical 30 time history ensembles compared closely with the horizontal and vertical target horizontal and vertical APR1400 HRHF response spectra. The good comparisons indicate that the ensembles of the 30 generated time histories are compatible with the horizontal and vertical target HRHF response spectra and are therefore representative time history ensembles from which the target PSDs compatible with the horizontal and vertical target APR1400 HRHF response spectra can be developed.

(2) The PSD of each individual time history in each 30 time history ensemble is computed. Because each time history in the ensemble is intensity modulated and is therefore a non-stationary motion, an equivalent stationary duration for the motion must be determined for use in computing the PSD of the individual time history. The PSDs computed for the 30 time history ensemble are shown in Figure 3-20 for the horizontal motion and in Figure 3-21 for the vertical motion.

(3) The “ensemble-average” or “ensemble-mean” PSDs obtained from the horizontal and vertical 30 time history PSDs computed in Step (2) and shown in Figures 3-20 and 3-21 are smoothed in accordance with the PSD smoothing procedure recommended in NUREG/CR-5347 (Reference 21). To simplify the representation of the target PSDs shown in Figures 3-20 and 3-21, the smoothed ensemble-mean PSDs obtained from the PSDs of the 30 time history ensembles are segmentally smoothed using log-log amplitude frequency linear functions for seven frequency bands, namely, (a) $0.3 < f \leq 1.5$ Hz, (b) $1.5 < f \leq 4.0$ Hz, (c) $4.0 < f \leq 19$ Hz, (d) $19 < f \leq 40$ Hz, (e) $40 < f \leq 55$ Hz, (f) $55 < f \leq 70$ Hz, and (g) $70 < f \leq 80$ Hz.

The resulting horizontal and vertical, piecewise log-log linear, ensemble-mean PSDs generated for the seven frequency bands are the target PSDs compatible with the APR1400 HRHF horizontal and vertical response spectra for the frequency range $0.3 \leq f \leq 80$ Hz and are tabulated in Tables 3-7 and 3-8. The smoothed ensemble-mean PSDs and the piecewise log-log linear smoothed PSDs are shown in Figures 3-22 and 3-23 for the horizontal and vertical motions, respectively. The horizontal target PSD is compared with the PSDs for CEUS rock sites for magnitudes of 6 to 7 with epicentral distances of R = 0 to 100 km as given in Table 1 of SRP 3.7.1, Rev. 3, Appendix B, in Figure 3-24. As shown in this figure, the horizontal target PSD generated to be compatible with the APR1400 HRHF horizontal response spectra envelops the PSDs given in Table 1 in SRP 3.7.1, Rev. 3, Appendix B, for magnitudes of M = 6 to 7 and epicentral distances of R = 0 to 100 km.

The target PSDs given in Tables 3-7 and 3-8, which are designated in this report as $S_H(f)$ and $S_V(f)$, respectively, are the target PSDs for checking adequacy of the PSDs as functions of frequency of the generated horizontal and vertical HRHF response spectrum-compatible design time histories.

3.5.2 MINIMUM REQUIRED TARGET PSDs

The minimum required horizontal and vertical target PSDs, designated as $\bar{S}_H(f)$ and $\bar{S}_V(f)$, for checking power adequacy of the horizontal and vertical time histories are obtained as 80 percent of the target PSD, $S_H(f)$ and $S_V(f)$, given in Section 3.5.1:

$$\bar{S}_H(f) = 0.8 \times S_H(f) \quad ; \quad \bar{S}_V(f) = 0.8 \times S_V(f) \tag{3-1}$$

The horizontal and vertical target and minimum required target PSDs are shown in Figures 3-25 and 3-26. The minimum required target PSDs shown in these figures are used to compare the PSDs of the generated horizontal and vertical HRHF response spectrum-compatible time histories to demonstrate adequacy in power density contents.

3.5.3 CALCULATION OF TIME HISTORY PSDs

To obtain the PSDs of the generated spectrum-compatible time histories for comparison with the minimum required horizontal and vertical target PSDs, the following calculation steps are used for each acceleration time history ai(t), i= H1H, H2H, VTH.

(a) Calculate the (equivalent stationary) strong-motion duration T_s^i for the time history $a_i(t)$ using the following equations:

$$E_i\left(t_p^i\right) = \int_0^{t_p^i} a_i^2(t)dt; \qquad i = \text{H1H, H2H, VTH} \tag{3-2}$$

$$T_s^i = \frac{t_{p2}^i - t_{p1}^i}{p_2 - p_1} \tag{3-3}$$

Where P_1 and P_2, $P_1 < P_2$, are the ratio of the cumulative energies $E_i\left(t_{p1}^i\right)$ and $E_i\left(t_{p2}^i\right)$ to the total cumulative energy of the entire time history; and where t_{p1}^i and t_{p2}^i, $t_{p1}^i < t_{p2}^i$, are the times at which the ratios P_1 and P_2 are reached. The ratios P_1 and P_2, and the corresponding over the duration $t_s^i = t_{p2}^i - t_{p1}^i$ can best be fitted by a straight line (i.e., constant energy buildup) having a constant slope $S = \left[E_i\left(t_{p2}^i\right) - E_i\left(t_{p1}^i\right)\right]/(t_{p2}^i - t_{p1}^i)$. The equivalent stationary duration T_s^i for the entire time history as determined from Eq. (3-3) is the duration over which the total energy of the time history is built up from 0 to 100 percent with the constant slope S. This procedure of calculating T_s^i is illustrated in Figure 3-27.

(b) Compute the one-sided PSD, $S_i(f)$ of the time history $a_i(t)$ using the following equations:

$$S_i(f) = \frac{|A_i(f)|^2}{T_s^i} \tag{3-4}$$

Where $|A_i(f)|$ is the amplitude of the Fourier spectrum obtained from the following equation:

$$A_i(f) = \int_0^{T_i} a_i(t) e^{-2\pi f t} dt \tag{3-5}$$

Where T_i is the total duration of the time history $a_i(t)$.

(c) Smooth the time history PSD $S_i(f)$ using the moving average technique over a ±20 percent frequency bandwidth centered at the frequency f, in accordance with the guidelines in NUREG/CR-5347 (Reference 21), to give the smoothed time history PSD $\tilde{S}_i(f)$.

The smoothed time history PSD, $\tilde{S}_i(f)$, obtained from step (c) above is then compared with the minimum required target PSD, $\tilde{S}_i(f)$, to check the adequacy of the power content of the generated time history.

3.6 GENERATION RESULTS

The acceleration time histories consist of two horizontal (H1H and H2H) and one vertical (VTH) components. H1H, H2H, and VTH are applied in the EW direction, NS direction, and vertical direction, respectively. The time interval of time history digitization, Δt, is 0.005 second, which corresponds to the highest frequency of interest of 100 Hz.

The horizontal H1H acceleration time history is plotted along with the integrated velocity and displacement time histories in Figure 3-28. The comparison of the time history response spectra with the corresponding horizontal target HRHF response spectra for the corresponding damping values are shown in Figure 3-29. Similar results for the horizontal H2H time history are shown in Figures 3-30 and 3-31. Similar results for the vertical time history VTH are shown in Figures 3-32 and 3-33.

The maximum acceleration (A), maximum velocity (V), maximum displacement (D) and V/A and AD/V^2 ratios of the generated H1H, H2H, and VTH time histories are listed in Table 3-9

To show the statistical independence of the set of time histories, the cross-correlation coefficients of pairs of the HRHF response spectrum-compatible time histories are given in Table 3-10. The values all are below 0.16, thus satisfying the SRP Section 3.7.1, Revision 3 (Reference 12) threshold for statistical independence.

4.0 GROUND MOTION COHERENCY FUNCTION

Spatial coherency, or simply coherency, of ground motion, designated with the symbol γ, is a measure of the degree of cross-correlation (similarity) between the two motions within a specific frequency band. It is defined mathematically as the normalized cross-power spectral density function of frequency (*f*) of co-directional ground motion time histories at two stations on a horizontal ground surface separated by a distance ξ. Thus, coherency γ is a function of motion frequency *f* and separation distance between two stations on the horizontal ground surface (i.e., $\gamma \equiv \gamma(f, \xi)$). The function $\gamma\ (f,\ \xi)$ is by definition a complex-valued function whose complex conjugate is anti-symmetrical with respect to the origin $(f,\ \xi)$ = (0, 0) (i.e., the function $\gamma\ (f,\ \xi)$ is a Hermitian function).

Coherency function has and amplitude $|\ \gamma\ (f,\ \xi)\ |$ varying between 0 and 1. For the extreme case in which the coherency is 0 at all frequencies, the co-directional motions at the two ground surface stations are statistically independent from each other. For the other extreme case in thich the coherency a the value equal to 1 at all frequencies, the co-directional motions at the two ground stations are completely correlated (i.e., the two motions are identical to each other except by a scalar factor).

The empirical coherency functions for characterizing spatial coherency of seismic ground motions are derived from statistical analyses of amplitudes of coherency functions computed from earthquake data recorded from many instrument arrays and from many recordings of past earthquakes. Such functions reflect the statistical averages of the amplitudes of coherency functions derived from the recorded instrument-array data. Thus, the empirical coherency functions derived from statistical analyses of recorded earthquake data are real-valued functions of frequency and distance.

The coherency functions generally used for characterizing spatial coherence (or incoherence) of co-directional free field seismic motions at any two stations on the ground surface of hard rock sites are empirically derived, horizontal and vertical, “plane-wave coherency functions”, designated by the symbol $\gamma_{pw}\ (f,\ \xi)$. These coherency functions were developed by Abrahamson based on the recorded Pinyon Flat array data and published in the EPRI report “Hard-Rock Coherency Functions Based on the Pinyon Flat Array Data,” (Reference 23). In accordance with the guidance of ISG-01 (Reference 24), these coherency functions are acceptable to the NRC for application to hard rock sites. The mathematical expressions of these horizontal and vertical “plane-wave coherency functions” for hard rock are tabulated in Tables 4-1 and 4-2, respectively. The amplitudes of these functions, plotted as functions of frequency *f* and separation distance ξ, are shown in Figure 4-1 for both the horizontal and vertical ground motions.

5.0 COMPARISON OF ISRS BASED ON CSDRS AND HRHF RESPONSE SPECTRA

To show the significance of the HRHF response spectra, the CSDRS and HRHF seismic responses are compared. Figures 5-1 through 5-15 (5 percent damping) are comparisons of the ISRS with coherent and incoherent considerations at a number of locations in the NI structures. There are some exceedances, mostly above the 10 Hz region. These curves are typical of comparative responses found throughout the plant.

The exceedances of CSDRS-based ISRS by HRHF-based ISRS are addressed as part of the sampling evaluation in this report to confirm that high frequency seismic input has a marginal effect on equivalent piping, and structures qualified by analysis for the APR1400 CSDRS.

6.0 EVALUATION

This section describes the evaluation results of the HRHF response spectra for the SSCs. The HRHF response spectra for the following SSCs are evaluated:

(a) Building structures

- RCB internal structure
- RCB containment structure
- Auxiliary building

(b) Reactor coolant system

- Reactor vessel internals and core
- Reactor coolant system supports
- Reactor coolant system nozzles

(c) Piping systems

(d) Safety-related equipment

6.1 BUILDING STRUCTURES

Maintaining the structural integrity of the NI buildings is important to plant safety. The RCB internal structure, RCB containment structure and auxiliary building are evaluated for the effect of high frequency input ground motion.

The evaluation consists of comparisons of the responses from high frequency input ground motion to those obtained from the APR1400 CSDRS for the building structures.

The comparisons are performed to demonstrate that seismic responses from CSDRS envelop those from the high frequency input motion. The NI structures are considered to be qualified for the high frequency input ground motion if the seismic responses from the CSDRS envelop those from the high frequency input motion.

To evaluate an effect on the RCB internal structures (i.e., PSW, IRWST, and SSW), seismic forces and moments of these structures are compared as shown in Tables 6-1, 6-2, and 6-3. Although the comparisons of forces and moments from high frequency input motion are greater than CSDRS, the arrangements of rebar are not changed due to seismic responses from HRHF seismic input.

Comparisons of the RCB containment structures are presented in Table 6-4. The comparisons of the containment structures show that seismic forces and moments resulting from the CSDRS input motion are greater than forces and moments obtained from high frequency input ground motion.

Equivalent accelerations of auxiliary building to seismic response story forces are evaluated for comparison of equivalent accelerations from CSDRS and HRHF response spectra. The comparisons for the auxiliary building are presented in Table 6-5. Equivalent accelerations from HRHF input ground motion envelop those from CSDRS except the vertical acceleration of Fuel Handling Area 3 (El. 195'-0" to 213'-0"). The effect due to the increment of equivalent acceleration in the global z direction can be absorbed in the design of the shear walls because each wall member has stiffness enough to resist the additional seismic load due to high frequency seismic input in the axial direction.

6.2 REACTOR COOLANT SYSTEM

The reactor vessel internals (RVI) support the core which is important to safety. The RVI consists of complicated components whose natural frequencies are in the relatively high frequency range. The RCS component supports are evaluated because they provide the support for the RCS components to maintain their intended safety-related functions. The nozzles are evaluated because piping failures generally occur at high stress locations such as at nozzles of a component and they represent the sensitivity of the reactor coolant loop piping to high frequency excitation. For selected items, the HRHF response is evaluated by comparing the design loads with the loads obtained from the HRHF incoherent analysis. It is concluded that the supports and nozzles are acceptable for the HRHF seismic loads if the design loads from the CSDRS envelop those from the HRHF input ground motion.

6.2.1 REACTOR VESSEL INTERNALS AND CORE

The RVI and core were selected because they are important to safety and their analyses are representative of major primary components. Because the natural frequencies of the RVI components are in the relatively high frequency range, the RVI may be sensitive to high frequency excitation.

Detailed analyses were performed to obtain the responses of the RVI and core to HRHF loads. The RVI HRHF analysis was done using the HRHF excitation of the reactor vessel (RV) obtained from the response of the RCB and RCS to HRHF loads. Then, the response of the core was calculated using the detailed core model and the core plate motion obtained from the RVI analysis.

The time history analyses of the RVI and core were performed for each HRHF mode, and the responses of all modes were combined for the resultant response. The maximum response of each mode was used for the combination. The broadening of the input excitation was also considered for the RVI and core analyses by frequency variation as implemented for CSDRS loads.

The RVI resultant responses of HRHF loads were compared with those of CSDRS loads. Most forces and moments of the RVI components for HRHF loads were calculated to be less than those for CSDRS loads. It was already determined that the structural integrities of the RVI and core are maintained for the CSDRS loads. The evaluations were performed for RVI components such as the core support barrel flange and cylinder because the forces and moments on the components from HRHF loads exceeded those from CSDRS loads. The results of the evaluations showed that the increases in component loads due to HRHF loads were insignificant for the structural integrity of the components.

The core resultant responses of HRHF loads were compared with those of the CSDRS loads. The resultant responses for the comparison were grid impact forces. Since the natural frequency of the fuel assembly is in the relatively low range, the core responses for the HRHF loads were predicted to be less than those of the CSDRS loads. The resultant grid impact forces of the HRHF loads were calculated to be less than those of CSDRS loads. No grid impact of the fuel assemblies occurs for all the modes except the first mode.

Therefore, the effects of HRHF loads on the structural integrity of the RVI and core are insignificant.

6.2.2 COMPONENT SUPPORTS AND NOZZLES OF RCS

The RCS structural supports support RCS components during normal operation and transients and during SSE and design basis accident conditions. RCS component supports are necessary to preserve the safety function of the RCS components. The arrangement of the RCS, including acronyms of the components, is shown in Figure 6-1. A comparison of the support loads on the RCS supports is provided in Table 6-6. The design loads for the RCS supports and nozzles are bounding at all locations.

The RV is supported by four vertical columns located under the vessel inlet nozzles. The columns are designed to be flexible in the horizontal direction to allow horizontal thermal expansion during heat-up and cool-down. They also support the reactor vessel in the vertical direction.

The steam generator (SG) is supported at the bottom by a sliding base bolted to an integrally attached conical skirt. The sliding base rests on low friction bearings, which allows unrestrained thermal expansion of the RCS. Two keyways in the sliding base mate with embedded keys to guide the movement of the steam generator during expansion and contraction of the RCS and to limit the movement of the bottom of the steam generator during SSE and branch line pipe break (BLPB) events.

The reactor coolant pump (RCP) supports consist of four vertical columns, four horizontal columns and two horizontal snubbers.

The pressurizer (PZR) is supported by a cylindrical skirt which is welded to the pressurizer and bolted to the building structure. Four keys welded to the upper shell of the pressurizer provide additional restraint for an SSE, pressurizer pilot-operated safety and lelief valve (POSRV) actuation and BLPB conditions. The component supports of the RCS are shown in Figure 6-2.

The RCS component nozzles of the RV, SG, and RCP are included in the evaluation since a component nozzle has greater potential for failure than at other locations and the cold leg, hot leg, and crossover leg are relatively sensitive to high frequencies when compared with other components.

The locations and acronyms of the RCS component nozzles are shown in Figure 6-3. A comparison of the component nozzle loads with the design basis loads is provided in Table 6-7. Table 6-7 shows that the nozzle design loads envelop the loads from the HRHF incoherent analysis at all locations.

6.3 PIPING SYSTEMS

Since piping lines and piping supports throughout the plant are designed according to the relevant guidelines, a stress analysis of a sample of lines is representative of all lines in the plant. Evaluating the susceptibility to excitation caused by high frequency seismic input requires the following factors to be present:

- The local HRHF-based ISRS need to have exceedances relative to CSDRS-based ISRS in the high frequency range.

- The system must have modes or natural frequencies in the high frequency range.

- The system layout must include valves or other concentrated masses that would require closely spaced supports and therefore, cause high local natural frequencies. This generally yields significant cumulative mass in the high frequency range.

ASME Class 1, 2, and 3 piping systems are required to be evaluated for the HRHF-based ISRS.

In the APR1400, the design acceptance criteria are applied to the piping design area. The evaluation for the HRHF response spectra is to be accomplished by the combined license (COL) applicant.

6.4 SAFETY-RELATED EQUIPMENT

Safety-related equipment is evaluated for the effect of high frequency input motion for safety of the plant. Representative items are selected for the evaluation because they are susceptible to high frequency seismic inputs. Susceptibility to excitation caused by high frequency input requires the following factors to be present:

- The local HRHF-based ISRS need to exceed CSDRS-based ISRS in the high frequency range.

- Safety-related equipment must have modes or natural frequencies in the high frequency range.

- Safety-related components must have potential failure modes involving change of state, chatter, signal change/drift, or connection problems.

It is expected that equipment with modes in the range of the high frequency response excitation will experience higher loads and amplifications than equipment with modes outside this range. To support this expectation and determine the effect of high frequency input ground motion on the APR1400 safety-related equipment, a review of the equipment configuration, location, stress analysis methodology, and equipment qualification testing procedures is required.

The evaluation of representative items shown in Table 6-8 is to be accomplished by the COL applicant.

7.0 CONCLUSION

Evaluations are performed for portions of structures, components, piping, and systems for the HRHF seismic response. The sample that was evaluated consists of the following:

(a) Building structures

- RCB internal structure
- RCB containment structure
- Auxiliary building

(b) Reactor coolant system

- Reactor vessel internals and core
- Reactor coolant system supports
- Reactor coolant system nozzles

(c) Piping systems

(d) Safety-related equipment

The evaluation of the building structures is performed through a comparison of the seismic responses obtained from HRHF incoherent analysis to those obtained from the design-basis seismic analysis. It is concluded that the existing design for nuclear island structures based on the CSDRS includes the seismic responses considering HRHF input ground motion.

For selected items of the reactor coolant system, the HRHF seismic responses are evaluated by comparing the design loads obtained from design-basis seismic analysis with the loads from the HRHF incoherent analysis. It is concluded that the supports and nozzles are acceptable for the HRHF seismic loads and the design loads from the CSDRS envelop those from the HRHF input ground motion.

The evaluations for HRHF input ground motion on piping systems and safety-related equipment are to be accomplished by the COL applicant.

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Table 2-1 Shear-modulus-degradation and Damping-value Variation Curves for Rock Considered for HRHF

Uniform shear strain, γ (%)	G/Gmax
0.0001	1.0
0.0003	1.0
0.001	0.9875
0.003	0.9525
0.01	0.900
0.03	0.810
0.1	0.725
1.0	0.550

Uniform shear strain, γ (%)	Damping Ratio (%)
0.0001	0.40
0.001	0.80
0.01	1.50
0.1	3.00
1.0	4.60

Table 3-2 5%-damped HRHF Horizontal Target Response Spectrum

5% - Damped Horizontal Response Spectrum			
Frequency (Hz)	**Sa (g)**	**Frequency (Hz)**	**Sa (g)**
0.10	0.0144	8.00	0.8200
0.13	0.0225	8.50	0.8398
0.15	0.0323	9.00	0.8589
0.20	0.0431	9.50	0.8823
0.25	0.0539	10.00	0.9050
0.30	0.0647	10.50	0.9263
0.40	0.0862	11.00	0.9471
0.50	0.1078	11.50	0.9674
0.60	0.1271	12.00	0.9873
0.70	0.1452	12.50	1.0067
0.80	0.1622	13.00	1.0245
0.90	0.1780	13.50	1.0420
1.00	0.1960	14.00	1.0591
1.10	0.2153	14.50	1.0759
1.20	0.2346	15.00	1.0924
1.25	0.2442	16.00	1.1150
1.30	0.2535	17.00	1.1367
1.40	0.2720	18.00	1.1575
1.50	0.2905	20.00	1.1969
1.60	0.3056	22.00	1.2168
1.70	0.3205	25.00	1.2441
1.80	0.3351	28.00	1.2376
1.90	0.3497	30.00	1.2336
2.00	0.3640	31.00	1.2274
2.10	0.3747	34.00	1.2102
2.20	0.3852	35.00	1.2048
2.30	0.3955	37.00	1.1866
2.40	0.4056	40.00	1.1615
2.50	0.4156	43.00	1.1262
2.60	0.4288	45.00	1.1046
2.70	0.4420	46.00	1.0896
2.80	0.4550	49.00	1.0476
2.90	0.4679	50.00	1.0345
3.00	0.4808	52.00	0.9970
3.15	0.4961	55.00	0.9458
3.30	0.5111	58.00	0.8997

5% - Damped Horizontal Response Spectrum			
Frequency (Hz)	**Sa (g)**	**Frequency (Hz)**	**Sa (g)**
3.45	0.5259	60.00	0.8715
3.60	0.5405	61.00	0.8530
3.80	0.5596	64.00	0.8015
4.00	0.5783	65.00	0.7856
4.20	0.5942	67.00	0.7553
4.40	0.6097	70.00	0.7136
4.60	0.6249	73.00	0.6726
4.80	0.6398	75.00	0.6474
5.00	0.6545	76.00	0.6354
5.25	0.6711	79.00	0.6017
5.50	0.6873	80.00	0.5911
5.75	0.7032	82.00	0.5733
6.00	0.7187	85.00	0.5483
6.25	0.7328	88.00	0.5251
6.50	0.7467	90.00	0.5107
6.75	0.7603	91.00	0.5055
7.00	0.7736	94.00	0.4904
7.25	0.7855	97.00	0.4763
7.50	0.7972	100.00	0.4630
7.75	0.8087		

Table 3-2 5%-damped HRHF Vertical Target Response Spectrum

5% - Damped Vertical Response Spectrum			
Frequency (Hz)	Sa (g)	Frequency (Hz)	Sa (g)
0.10	0.0108	8.00	0.6150
0.13	0.0169	8.50	0.6298
0.15	0.0242	9.00	0.6442
0.20	0.0323	9.50	0.6617
0.25	0.0404	10.00	0.6788
0.30	0.0485	10.50	0.6989
0.40	0.0647	11.00	0.7187
0.50	0.0809	11.50	0.7381
0.60	0.0953	12.00	0.7572
0.70	0.1089	12.50	0.7759
0.80	0.1217	13.00	0.7935
0.90	0.1335	13.50	0.8108
1.00	0.1470	14.00	0.8278
1.10	0.1615	14.50	0.8445
1.20	0.1759	15.00	0.8610
1.25	0.1832	16.00	0.8858
1.30	0.1901	17.00	0.9097
1.40	0.2040	18.00	0.9329
1.50	0.2179	20.00	0.9882
1.60	0.2292	22.00	1.0335
1.70	0.2403	25.00	1.0948
1.80	0.2514	28.00	1.1322
1.90	0.2622	30.00	1.1556
2.00	0.2730	31.00	1.1628
2.10	0.2810	34.00	1.1881
2.20	0.2889	35.00	1.1963
2.30	0.2966	37.00	1.2040
2.40	0.3042	40.00	1.2199
2.50	0.3117	43.00	1.2198
2.60	0.3216	45.00	1.2177
2.70	0.3315	46.00	1.2114
2.80	0.3413	49.00	1.1765
2.90	0.3510	50.00	1.1632
3.00	0.3606	52.00	1.1238
3.15	0.3721	55.00	1.0698
3.30	0.3833	58.00	1.0210

5% - Damped Vertical Response Spectrum			
Frequency (Hz)	Sa (g)	Frequency (Hz)	Sa (g)
3.45	0.3944	60.00	0.9910
3.60	0.4054	61.00	0.9710
3.80	0.4197	64.00	0.9116
4.00	0.4337	65.00	0.8922
4.20	0.4456	67.00	0.8553
4.40	0.4573	70.00	0.8046
4.60	0.4687	73.00	0.7553
4.80	0.4799	75.00	0.7251
5.00	0.4909	76.00	0.7077
5.25	0.5033	79.00	0.6594
5.50	0.5155	80.00	0.6444
5.75	0.5274	82.00	0.6185
6.00	0.5390	85.00	0.5827
6.25	0.5496	88.00	0.5500
6.50	0.5600	90.00	0.5299
6.75	0.5702	91.00	0.5221
7.00	0.5802	94.00	0.4998
7.25	0.5892	97.00	0.4808
7.50	0.5979	100.00	0.4630
7.75	0.6065		

Table 3-3 V/H Ratios for CEUS Rock Site Conditions

Table 4-5 (FROM NUREG/CR-6728 OCTOBER 2001) RECOMMENDED V/H RATIOS FOR CEUS ROCK SITE CONDITIONS			
Frequency (Hz)	**0.2g***	**0.2 - 0.5g***	**0.5g***
0.10	0.67	0.75	0.90
10.00	0.67	0.75	0.90
18.75	0.70	0.81	1.01
22.06	0.73	0.85	1.08
25.00	0.75	0.88	1.12
31.25	0.77	0.95	1.25
37.50	0.81	1.02**	1.37
41.67	0.84	1.07	1.44
46.88	0.85	1.12	1.50
62.50	0.90	1.14	1.52
75.00	0.89	1.12	1.48
93.75	0.81	1.02	1.33
100.0	0.78	1.00	1.30

* Range in rock outcrop horizontal component peak acceleration.
**The original Table had 1.00. 1.02 was used to make the curves smoother.

Table 3-4 Scale Factors for Horizontal Response Spectra Damping Ratios Relative to 5%-damped Response Spectrum, CEUS

Scale Factors for Horizontal Response Spectra Damping Ratios (0.5 - 80 Hz) Relative to 5% - Damped Response Spectrum, CEUS				
Frequency (Hz)	**2% Damping**	**3% Damping**	**7% Damping**	**10% Damping**
0.50	1.1588	1.0835	0.9620	0.9500
0.60	1.2038	1.1113	0.9381	0.8927
0.70	1.2299	1.1263	0.9263	0.8651
0.80	1.2487	1.1369	0.9190	0.8480
0.90	1.2631	1.1445	0.9137	0.8359
1.00	1.2749	1.1503	0.9096	0.8266
1.10	1.2836	1.1546	0.9062	0.8193
1.20	1.2889	1.1571	0.9045	0.8147
1.30	1.2914	1.1587	0.9038	0.8121
1.40	1.2941	1.1603	0.9027	0.8096
1.50	1.2991	1.1623	0.9022	0.8084
1.60	1.3060	1.1657	0.9008	0.8059
1.70	1.3099	1.1675	0.9000	0.8041
1.80	1.3145	1.1699	0.8986	0.8017
1.90	1.3173	1.1720	0.8973	0.7993
2.00	1.3215	1.1745	0.8964	0.7980
2.10	1.3287	1.1785	0.8943	0.7947
2.20	1.3355	1.1816	0.8923	0.7912
2.30	1.3388	1.1828	0.8916	0.7902
2.40	1.3400	1.1831	0.8919	0.7908
2.50	1.3391	1.1825	0.8920	0.7909
2.60	1.3392	1.1829	0.8914	0.7902
2.70	1.3392	1.1827	0.8916	0.7902
2.80	1.3386	1.1820	0.8919	0.7908
2.90	1.3354	1.1796	0.8931	0.7925
3.00	1.3330	1.1781	0.8944	0.7945
3.15	1.3330	1.1777	0.8951	0.7959
3.30	1.3341	1.1779	0.8953	0.7964
3.45	1.3309	1.1764	0.8954	0.7965
3.60	1.3279	1.1748	0.8962	0.7980
3.80	1.3238	1.1721	0.8979	0.8004
4.00	1.3238	1.1719	0.8985	0.8014
4.20	1.3238	1.1717	0.8989	0.8016

Scale Factors for Horizontal Response Spectra Damping Ratios (0.5 - 80 Hz) Relative to 5% - Damped Response Spectrum, CEUS				
Frequency (Hz)	**2% Damping**	**3% Damping**	**7% Damping**	**10% Damping**
4.40	1.3308	1.1752	0.8973	0.7989
4.60	1.3357	1.1773	0.8960	0.7964
4.80	1.3387	1.1791	0.8948	0.7938
5.00	1.3427	1.1813	0.8938	0.7915
5.25	1.3512	1.1853	0.8925	0.7889
5.50	1.3596	1.1892	0.8906	0.7852
5.75	1.3726	1.1961	0.8874	0.7804
6.00	1.3800	1.2002	0.8847	0.7764
6.25	1.3856	1.2024	0.8839	0.7751
6.50	1.3838	1.2010	0.8844	0.7760
6.75	1.3815	1.1995	0.8849	0.7775
7.00	1.3776	1.1973	0.8862	0.7800
7.25	1.3723	1.1945	0.8878	0.7835
7.50	1.3662	1.1917	0.8892	0.7867
7.75	1.3605	1.1887	0.8907	0.7895
8.00	1.3574	1.1863	0.8921	0.7921
8.50	1.3566	1.1857	0.8931	0.7940
9.00	1.3600	1.1877	0.8928	0.7942
9.50	1.3625	1.1892	0.8932	0.7953
10.00	1.3653	1.1906	0.8942	0.7972
10.50	1.3668	1.1911	0.8951	0.7993
11.00	1.3690	1.1920	0.8951	0.7994
11.50	1.3735	1.1941	0.8947	0.7989
12.00	1.3761	1.1953	0.8945	0.7988
12.50	1.3758	1.1952	0.8948	0.7994
13.00	1.3758	1.1946	0.8958	0.8011
13.50	1.3722	1.1924	0.8966	0.8029
14.00	1.3682	1.1900	0.8977	0.8049
14.50	1.3622	1.1868	0.8982	0.8058
15.00	1.3614	1.1866	0.8978	0.8053
16.00	1.3583	1.1845	0.8992	0.8079
17.00	1.3536	1.1819	0.9003	0.8098
18.00	1.3501	1.1801	0.9018	0.8127
20.00	1.3490	1.1796	0.9022	0.8135
22.00	1.3456	1.1781	0.9025	0.8142

Scale Factors for Horizontal Response Spectra Damping Ratios (0.5 - 80 Hz) Relative to 5% - Damped Response Spectrum, CEUS				
Frequency (Hz)	**2% Damping**	**3% Damping**	**7% Damping**	**10% Damping**
25.00	1.3413	1.1759	0.9040	0.8168
28.00	1.3402	1.1755	0.9039	0.8166
31.00	1.3412	1.1764	0.9037	0.8165
34.00	1.3386	1.1745	0.9054	0.8196
40.00	1.3344	1.1723	0.9066	0.8219
45.00	1.3240	1.1671	0.9095	0.8274
50.00	1.3089	1.1592	0.9134	0.8350
55.00	1.2851	1.1465	0.9201	0.8473
60.00	1.2566	1.1316	0.9279	0.8621
65.00	1.2289	1.1171	0.9359	0.8771
70.00	1.1980	1.1009	0.9449	0.8944
75.00	1.1670	1.0847	0.9540	0.9119
80.00	1.1361	1.0691	0.9621	0.9274

Table 3-5 Target Median Values for APR1400 HRHF Response-Spectrum-compatible Time Histories

Distance (km)	M	A (2) (g)	A (cm/sec^2)	V (2) (cm/sec)	D (2) (cm)	V/A (2) (cm/sec/g)	AD/V^2 (2)
0-10 rock	6.53	1.16	1138.5	39.74	7.84	34.37	5.63
	7.25	0.89	873.5	58.4	22.33	65.84	5.7
10-50 rock	6.32	0.25	245.4	7.95	1.7	31.75	6.58
	7.38	0.34	333.7	19.85	9.17	58.24	7.78
50-100 rock	6.38	0.09	88.3	2.99	0.46	32.59	4.66
	7.46	0.15	147.2	7.33	3.98	50.29	10.6
	median values =	0.295	289.5	13.90	5.91	42.33	6.14
	target median values =	**0.46**	**451.5**	**21.67**	**9.22**	**42.33**	**6.1**
Distance (km)	M	A (g)	A (in/sec^2)	V (in/sec)	D (in)	V/A (in/sec/g)	AD/V^2
0-100 km	6.3- 7.5	**0.46**	**177.7**	**8.53**	**3.63**	**16.67**	**6.14**

Table 3-6 Target Ranges of V, D, V/A, and AD/V²

Parameter	V (in/sec)	D (in)	V/A (in/sec/g)	AD/V^2
σ(1)	0.40	0.57	0.33	0.45
m- σ (3)	5.72	2.05	11.98	3.92
m (2)	**8.53**	**3.63**	**16.67**	**6.14**
m+ σ (4)	12.73	6.42	23.18	9.63

Notes:

(1) σ values for V, D, V/A and AD/V² are the minimum log-normal standard deviations for CEUS rock motions for M = 6.3 to 7.5, and R = 0-100 km obtained from Ref. (6).

(2) m = median values of V, D, V/A, and AD/V² for given distance and M are obtained from Ref. (6).

(3) m -σ = m×exp(-σ)

(4) m+σ = m×exp(σ).

(5) Median values of V, D, V/A, and AD/V² are obtained from statistics of the values in the columns.

Table 3-7 Target PSD Compatible with APR1400 HRHF Response Spectra – Horizontal

Frequency (f) Range f (Hz or cps)	Piecewise Linear Target PSD $S_H(f)$ (in^2/sec^4/cps)
$0.3 < f \le 1.5$ Hz	$S_0(f) = 2\pi \times 6.85\ (0.3/f)^{-0.4}$
$1.5 < f \le 4.0$ Hz	$S_0(f) = 2\pi \times 13.04\ (1.5/f)^{-0.2}$
$4.0 < f \le 19$ Hz	$S_0(f) = 2\pi \times 15.86\ (4.0/f)^{0.25}$
$19 < f \le 40$ Hz	$S_0(f) = 2\pi \times 10.75\ (19.0/f)^{1.1}$
$40 < f \le 55$ Hz	$S_0(f) = 2\pi \times 4.75\ (40.0/f)^{2.3}$
$55 < f \le 70$ Hz	$S_0(f) = 2\pi \times 2.28\ (55.0/f)^{4.5}$
$70 < f \le 80$ Hz	$S_0(f) = 2\pi \times 0.76\ (70.0/f)^{7.1}$

Notes: The minimum required PSD is obtained by multiplying the target PSD by a factor of 0.8.

Table 3-8 Target PSD Compatible with APR1400 HRHF Response Spectra – Vertical

Frequency (f) Range f (Hz or cps)	Piecewise Linear Target PSD S_V (f) (in^2/sec^4/cps)
$0.3 < f \leq 1.5$ Hz	$S_0(f) = 2\pi \times 3.44\ (0.3/f)^{-0.5}$
$1.5 < f \leq 4.0$ Hz	$S_0(f) = 2\pi \times 7.69\ (1.5/f)^{-0.1}$
$4.0 < f \leq 19$ Hz	$S_0(f) = 2\pi \times 8.49\ (4.0/f)^{0.15}$
$19 < f \leq 40$ Hz	$S_0(f) = 2\pi \times 6.72\ (19.0/f)^{0.3}$
$40 < f \leq 55$ Hz	$S_0(f) = 2\pi \times 5.38\ (40.0/f)^{1.5}$
$55 < f \leq 70$ Hz	$S_0(f) = 2\pi \times 3.34\ (55.0/f)^{3.9}$
$70 < f \leq 80$ Hz	$S_0(f) = 2\pi \times 1.31\ (70.0/f)^{6.2}$

Notes: The minimum required PSD is obtained by multiplying the target PSD by a factor of 0.8.

Table 3-9 Statistics of HRHF Response Spectrum-compatible Time Histories

Com-ponent	A (g)	Target	V (in/sec)	Target Range (in/sec)	D (in)	Target Range (in)	V/A (in/sec/g)	Target Range	AD/V²	Target Range
H1H	0.463	0.463	8.86	5.72 – 12.73	3.63	2.05 – 6.42	19.1	11.98 – 23.18	8.27	3.92 – 9.63
H2H	0.463	0.463	10.50	5.72 – 12.73	3.51	2.05 – 6.42	22.7	11.98 – 23.18	5.70	3.92 – 9.63
VTH	0.463	0.463	9.94	5.72 – 12.73	4.16	2.05 – 6.42	21.5	11.98 – 23.18	7.53	3.92 – 9.63

Table 3-10 Cross-correlation Coefficients of HRHF Response-Spectrum-Compatible Time History Pairs

Components	Cross-Correlation Coefficient
H1H × H2H	0.028
H2H × VTH	0.036
VTH × H1H	0.031

Table 4-1 EPRI (2007) Empirical Plane-Wave Coherency Function for Horizontal Seismic Ground Motions for Hard Rock

The EPRI (2007) empirical plane-wave coherency function for horizontal component of seismic ground motions for hard rock (Reference 4) is given as follows:

$$\gamma_{\mathrm{pw}}(f,\xi) = \left[1 + \left(\frac{f\ Tanh(a_3\xi)}{a_1 f_c(\xi)}\right)^{n_1(\xi)}\right]^{-1/2} \left[1 + \left(\frac{f\ Tanh(a_3\xi)}{a_2}\right)^{n_2}\right]^{-1/2}$$

where *f* = frequency in Hz, and ξ = separation distance in meter.

The coefficients in the function for the horizontal component of ground motion are listed in the following table:

Coefficient	Horizontal Component
a_1	1.0
a_2	40
a_3	0.4
$n_1(\xi)$	3.80 – 0.040*ln(ξ + 1) + 0.0105*[ln(ξ + 1) – 3.6]^2
n_2	16.4
$f_c(\xi)$	27.9 – 4.82*ln(ξ + 1) + 1.24*[ln(ξ + 1) – 3.6]^2

Table 4-2 EPRI (2007) Empirical Plane-Wave Coherency Function for Vertical Seismic Ground Motions for Hard Rock

The equation for EPRI (2007) plane-wave coherency function for vertical component of seismic ground motions for hard rock (Reference 4) is the same as that for the horizontal motion given in Table 4-1, i.e.,

$$\gamma_{pw}(f,\xi) = \left[1 + \left(\frac{f\ Tanh(a_3\xi)}{a_1 f_c(\xi)}\right)^{n_1(\xi)}\right]^{-1/2} \left[1 + \left(\frac{f\ Tanh(a_3\xi)}{a_2}\right)^{n_2}\right]^{-1/2}$$

where f = frequency in Hz, and ξ = separation distance in meter.

The coefficients in the function for the vertical component of ground motion are listed in the table below.

Coefficient	Vertical Component
a_1	1.0
a_2	200
a_3	0.4
$n_1(\xi)$	$2.03 + 0.41*\ln(\xi + 1) - 0.078*[\ln(\xi + 1) - 3.6]^2$
n_2	10
$f_c(\xi)$	$29.2 - 5.20*\ln(\xi + 1) + 1.45*[\ln(\xi + 1) - 3.6]^2$

Table 6-1 Comparison of Design Force and Moment for PSW

Unit: kips/ft, kips-ft/ft

Location	CSDRS				HRHF Response Spectra			
North Wall	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	157.9 (-195.9)	111.3 (-77.9)	26.5	60.0	163.7 (-138.3)	44.5 (-62.6)	28.5	66.8
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	-74.8	-89.2	127.4	-117.6	-77.3	-92.4	144.3	-133.3
East Wall	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	680.7 (-616.1)	352.1 (-351.4)	108.8	184.5	695.0 (-630.4)	419.2 (-423.0)	120.9	221.7
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	-139.7	-135.2	99.6	-213.9	-150.2	-158.0	105.2	-230.6
East Wall	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	162.4 (-144.2)	46.6 (-64.0)	33.0	50.6	182.2 (-146.8)	55.4 (-63.4)	36.2	57.0
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	-76.3	-74.5	108.5	-106.3	-78.5	80.4	122.8	-124.0

Notations :
Mφ - Meridional Moment around Horizontal Axis
Mθ - Hoop Moment around Vertical Axis
Nφ - Meridional Axial Force (+ : Tension, - : Compression)
Nθ - Hoop Axial Force (+ : Tension, - : Compression)
Qφ - Meridional Transverse Shear Force
Qθ - Hoop Transverse Shear Force
Q_T - Tangential Shear Force (In-plane Shear Force)
Mφθ - Torsion Moment

Table 6-2 Comparison of Design Force and Moment for IRWST

Unit: kips/ft, kips-ft/ft

Location	CSDRS				HRHF Response Spectra			
Top Slab	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	60.2 (-19.7)	12.6 (-9.3)	45.5	15.4	60.2 (-20.1)	12.5 (-9.2)	50.0	17.5
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	17.5	15.7	16.3	-5.6	19.1	17.1	19.6	-5.6
Outer wall	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	50.3 (-51.7)	11.6 (-7.5)	-65.3	70.2	50.3 (-51.7)	11.6 (-7.5)	-65.3	70.2
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	47.8	3.7	10.5	-4.0	47.8	4.4	11.7	-4.0

Notations :
Mφ - Meridional Moment around Horizontal Axis
Mθ - Hoop Moment around Vertical Axis
Nφ - Meridional Axial Force (+ : Tension, - : Compression)
Nθ - Hoop Axial Force (+ : Tension, - : Compression)
Qφ - Meridional Transverse Shear Force
Qθ - Hoop Transverse Shear Force
Q_T - Tangential Shear Force (In-plane Shear Force)
Mφθ - Torsion Moment

Table 6-3 Comparison of Design Force and Moment for SSW

Unit: kips/ft, kips-ft/ft

Location	CSDRS				HRHF Response Spectra			
SSW (a)	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	130.9 (-119.8)	240.3 (-130.3)	88.4	154.4	136.5 (-125.4)	265.9 (-155.7)	90.8	159.6
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	-35.3	54.0	-128.2	-71.2	-36.5	59.1	-136.1	-78.3
RFP (b)	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	1521.6 (-1304.2)	949.7 (-1038.2)	215.6	344.1	1389.5 (-1165.9)	897.3 (-978.6)	222.4	319.7
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	232.5	415.5	-158.8	673.6	213.8	377.2	-165.8	633.4
RFP (c)	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	89.1 (-74.3)	306.8 (-255.6)	40.4	365.6	105.7 (-90.6)	295.7 (-244.5)	43.7	366.3
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	32.7	-72.3	-108.9	53.5	31.5	-71.0	-105.7	51.7
S/G (d)	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	430.3 (-335.7)	492.3 (-407.3)	399.2	199.4	407.5 (-313.6)	513.1 (-421.7)	379.6	208.6
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	114.1	92.2	61.7(g) -111.4(h)	-220.2(g) 280.3(h)	111.7	92.3	58.1(g) -108.3(h)	-221.5(g) 275.1(h)

Location	CSDRS				HRHF Response Spectra			
S/G (e)	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	743.5 (-685.3)	703.4 (-603.5)	85.1	211.5	895.1 (-784.0)	610.1 (-713.0)	20.5	168.7
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	-171.4	-149.5	57.2(g) 116.5(h)	-446.0(g) -324.0(h)	-158.9	-140.5	71.7(g) -131.6(h)	-362.4(g) -346.9(h)
PZR (f)	Mφ	Mθ	Nφ	Nθ	Mφ	Mθ	Nφ	Nθ
	21.2 (-15.7)	178.8 (-244.7)	173.7	89.6	21.5 (-16.5)	197.5 (-205.0)	177.9	169.2
	Qφ	Qθ	QT	Mφθ	Qφ	Qθ	QT	Mφθ
	-1.2	-92.3	135.7(g) 95.2(h)	16.3(g) -69.7(h)	-1.3	-96.3	138.9(g) 118.7(h)	-17.1(g) -26.6(h)

Notations :
Mφ - Meridional Moment around Horizontal Axis
Mθ - Hoop Moment around Vertical Axis
Nφ - Meridional Axial Force (+ : Tension, - : Compression)
Nθ - Hoop Axial Force (+ : Tension, - : Compression)
Qφ - Meridional Transverse Shear Force
Qθ - Hoop Transverse Shear Force
Q_T - Tangential Shear Force (In-plane Shear Force)
Mφθ - Torsion Moment
Note :
(a) Secondary Shield Wall (Thickness 4 feet)
(b) South/North Wall of Refueling pool (Thickness 6 feet 2 inches)
(c) West Wall of Refueling pool (Thickness 5 feet)
(d) Circular Wall of Steam Generator (S/G) Enclosure (Thickness 4 feet)
(e) Straight Wall of Steam Generator (S/G) Enclosure (Thickness 5 feet)
(f) Pressurizer (PZR) Enclosure Wall (Thickness 2 feet 9 inches)
(g) These forces are considered with Nφ and Mφ when designing vertical re-bar
(h) These forces are considered with Nθ and Mθ when designing horizontal re-bar

Table 6-4 Comparison of Design Force and Moment for Containment Structure

Location	Elevation		CSDRS				HRHF Response Spectra			
	Bottom (ft)	Top (ft)	N_ϕ (kip/ft)	M_ϕ (kip-ft/ft)	N_θ (kip/ft)	M_θ (kip-ft/ft)	N_ϕ (kip/ft)	M_ϕ (kip-ft/ft)	N_θ (kip/ft)	M_θ (kip-ft/ft)
RCB-1	78′-0″	103′-0″	694.33	254.56	306.00	50.42	462.93	167.78	212.05	34.27
RCB-2	103′-0″	143′-0″	598.84	64.69	300.47	40.56	400.43	44.94	209.42	38.69
RCB-3	143′-0″	157′-6″	503.42	158.60	280.95	85.44	342.62	112.57	203.42	51.43
RCB-4	157′-6″	197′-6″	471.44	117.51	272.82	47.37	317.36	79.04	191.96	31.65
RCB-5	197′-6″	228′-0″	305.13	55.19	221.56	52.64	216.83	36.39	148.83	28.71
RCB-6	228′-0″	254′-6″	272.38	126.76	223.21	144.11	196.83	94.80	156.34	95.69

Notations :
N_ϕ - Meridional Force
M_ϕ - Meridional Moment
N_θ - Hoop Force
M_θ - Hoop Moment

Table 6-5 Comparison of Equivalent Accelerations for Auxiliary Building

Location	Elevation (ft)		CSDRS			HRHF Response Spectra		
	Bottom	Top	Acc. X (g)	Acc. Y (g)	Acc. Z (g)	Acc. X (g)	Acc. Y (g)	Acc. Z (g)
AB-FHA: 1	213′-6″	226′-6″	1.39	1.84	0.75	1.04	1.50	0.73
AB-FHA: 2	213′-0″	213′-6″	1.60	1.05	0.61	1.02	0.83	0.44
AB-FHA: 3	195′-0″	213′-0″	1.33	1.27	0.34	0.86	0.96	0.47
AB-MCR: 1	195′-0″	213′-0″	1.48	1.12	0.77	1.34	0.90	0.61
AB: 1	174′-0″	195′-0″	1.00	1.07	0.49	0.58	0.69	0.39
AB: 2	156′-0″	174′-0″	0.71	0.96	0.51	0.54	0.69	0.42
AB: 3	137′-6″	156′-0″	0.60	0.77	0.50	0.45	0.46	0.41
AB: 4	120′-0″	137′-6″	0.62	0.71	0.45	0.39	0.50	0.41
AB: 5	98′-6″	120′-0″	0.51	0.64	0.42	0.33	0.45	0.33
AB: 6	77′-0″	98′-6″	0.33	0.47	0.34	0.25	0.33	0.30
AB: 7	67′-0″	77′-0″	0.27	0.31	0.31	0.23	0.27	0.27
AB: 8	55′-0″	67′-0″	0.26	0.26	0.31	0.23	0.23	0.24

Table 6-6 Comparison of Design Force and Moment for RCS Component Supports

Load Interface(3)		Description	HRHF(1)(2)	Design Loads(2)
RV	H	Upper Lateral Support	1160	3190
	Fa	Column Base	11	30
	Fb		946	1900
	Fc		288	390
	Ma		250	400
	Mb		632	970
	Mc		115	280
SG	Y1	Sliding Vertical Pad	620	880
	Y2		1146	1610
	Y3		820	1170
	Y4		1201	1610
	Z11	Lower Key	737	950
	Z12		737	950
	X	Snubber Assembly (per Snubber)	1055	1910
	S		228	400
	Z1	Upper Key	1048	1500
	Z2		1048	1500
RCP	V1	Vertical Column Support	134	200
	V2		134	200
	V3		134	200
	V4		134	200
	R1	Lower Horizontal Column Support	98	150
	R2		98	150
	R3	Upper Horizontal Column Support	220	410
	R4		220	410
	P	Snubber (Pair)	502	810
PZR	Fv	Skirt Flange	258	380
	Fh		314	410
	Mt		1160	1750
	Mb		6224	8880
	Fk	Key	389	570

Note : 1. The maximum loads from HRHF seismic analyses are as-calculated values.
2. Units are [kips] for forces and [ft-kips] for moments.
3. For load designation, refer to Figures 6-4 ~ 6-7.

Table 6-7 Comparison of Design Force and Moment RCS Component Nozzles

Location	Case(1)	Nozzle Loads(2) (3)					
		Fa	Fb	Fc	Ma	Mb	Mc
RV Inlet	HRHF	131	41	120	250	164	186
	Design Loads	180	80	170	530	480	340
RV outlet	HRHF	725	324	85	218	553	1907
	Design Loads	1500	540	340	680	2600	3700
SG Inlet	HRHF	759	84	237	375	2339	571
	Design Loads	1500	360	480	1600	3400	1800
SG outlet	HRHF	22	95	21	286	162	380
	Design Loads	30	130	40	390	230	490
RCP Inlet	HRHF	27	71	75	129	262	296
	Design Loads	40	90	100	190	370	410
RCP outlet	HRHF	171	38	10	105	135	547
	Design Loads	240	70	20	130	210	880

Note : 1. The maximum loads from HRHF seismic analyses are as-calculated values.
2. Units are [kips] for forces and [ft-kips] for moments.
3. For load designation, refer to Figures 6-8 ~ 6-10.

Table 6-8 Equipment List of Evaluation for High Frequency Seismic Input

Equipment	Description
125V DC 1E Battery	Battery
1E Battery Charger	Battery Charger
1E DC Control Center	Distribution Panels
Non-1E DC Control Center	
Ground Fault Monitoring Cabinet	
125V DC Distr. PNL	
480V 1E MCC	Motor Control Center
1E Regulating TR.	Transformer
1E Inverter	Inverter
1E AB 4.16KV SWGR	Switchgear
Spent Fuel Pool Level	Level Switches and Transfer
Floor Drain Sump Flooding Level	
CCW Sump Flooding Level	
SI Pump Room Flooding Level	
SC Pump Room Flooding Level	
CS Pump Room Flooding Level	
BOP RMS Cabinet (SRDC)	Radiation Monitor
MMIS-BOP MCR Consoles	Main Control Room
MMIS-BOP ESF-CCS (LCC & GCC)	
MMIS-BOP QIAS-N	
Flexible Hose	Active Hose
Reactor Trip Switchgear	Switchgear
RCP Pump Speed	Speed Sensor
RCS Hot Leg Water Level	Transmitters
PZR Level	
PZR Wide Range Pressure	
PZR Narrow Range Pressure	
POSRV Motor Operated Isolation Valve	Active Valves
Pilot Operated Safety Relief Valve	
SIT Discharge Isolation	
PZR Level Reference Leg Temperature	Resistance Temperture Detector
SIT N2 Vent	Non Active Valve
SCS Heat Exchanger	Heat Exchanger
Safety Injection Tank	Tank