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High Frequency Program

Application Guidance for Functional Confirmation and Fragility Evaluation

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High Frequency Program

Application Guidance for Functional Confirmation and Fragility Evaluation

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Product Description

Following the accident at the Fukushima Daiichi nuclear power plant resulting from the March 11, 2011, Great Tohoku Earthquake and subsequent tsunami, various reviews were undertaken, including examinations of the seismic safety of nuclear power plants. In the United States, the Nuclear Regulatory Commission (NRC) established a Near-Term Task Force (NTTF) to conduct a systematic review of NRC processes and regulations.

Background

New assessments of seismic hazard are performed for nuclear power plants around the world from time to time. In some cases, updated information has led to an assessment that the seismic hazard is higher than had been previously understood. Such a situation developed in the United States when a new catalog of seismic sources was compiled for plants in the central and eastern portion of the country and this catalog was used to develop updated estimates of seismic hazard. Subsequently, the NRC issued a letter that requested information to ensure that all U.S. nuclear power plants address these recommendations.

EPRI 1025287 provided guidance for conducting seismic evaluations, including those requested in the NRC's letter, which asks that plants reevaluate the seismic hazards at their sites against present-day NRC requirements and guidance. One conclusion in EPRI 1025287 was that there was a limited need to evaluate components such as relays, switches, and other contact devices to determine their potential vulnerability to high-frequency ground motions. To support the seismic evaluations, EPRI conducted high-frequency seismic testing of a diverse set of typical plant control components. The results of this test program were documented in EPRI 3002002997.

Objective

The objective of this report is to provide guidance for applying the high-frequency seismic testing results to support plant-specific analyses of potential high frequency effects. Guidance is provided for plants performing a limited-scope high frequency confirmation and for plants performing seismic probabilistic risk assessments (SPRAs).

Approach

The report first provides a review of the device high-frequency test results. The report also establishes supplemental criteria for determining which sites require a high frequency confirmation evaluation. For plants performing a high frequency confirmation, a scope of components is defined, and procedures for component

evaluations using deterministic high confidence of low probability of failure (HCLPF) capacity, conservative deterministic failure margin (CDFM) demand measures, and the ground motion response spectra (GMRS) as the review level ground motion are developed. For those sites performing an SPRA, additional fragility methodology guidance is provided for the estimation of in-cabinet median demand and median component capacity using the high-frequency test results.

Results
This report provides guidance for performing a high frequency confirmation including identification of the equipment scope to be evaluated, methods for estimating the component demand, and procedures for evaluating the capacity-to-demand ratio. A procedure for estimating the vertical GMRS component is also developed. The horizontal in-structure response spectra (ISRS) are estimated from the GMRS based on procedures described in EPRI NP-6041, and a new procedure is developed for estimating the vertical ISRS.

The horizontal in-cabinet response spectra are estimated using amplification factors from EPRI NP-6041, and a new procedure is developed for estimating a vertical in-cabinet amplification factor, consistent with the CDFM philosophy. Component adequacy is evaluated using the HCLPF capacity to demand ratio.

For plants performing SPRAs, supplemental guidance is provided for applying the seismic fragility methodology provided in EPRI TR-103959 to account for high-frequency input motions, given the median ISRS for the cabinet location. Guidance is also provided on the use of low-frequency and high-frequency test capacities and recommendations provided for the application of broad frequency input device capacity factors to cover both the low- and high-frequency regions.

Applications, Value, and Use
The data presented in this report will support high frequency confirmation evaluations as identified in EPRI 1025287, as well as high frequency considerations in fragility calculations for SPRAs.

Keywords
Earthquakes
Fragilities
Fukushima
High-frequency
Relay
Seismic probabilistic risk assessment

Acronyms and Symbols

A	Acceleration
AC	alternating current
AF_c	cabinet amplification factor (CDFM)
$\breve{AF}_c$	cabinet amplification factor (median)
AF_{cH}	CDFM cabinet amplification factor - horizontal direction
AF_{cV}	CDFM cabinet amplification factor - vertical direction
AF_{SH}	structural amplification factor in the horizontal direction (CDFM)
AF_{SV}	structural amplification factor in the vertical direction (CDFM)
ANSI	American National Standards Institute
β_R	random variability
β_U	Uncertainty
$\beta_{r,RS}$	variability of the response factor
$\beta_{u,RS}$	random uncertainty of the response factor
B	bandwidth to central frequency ratio
BWR	boiling water reactor
C_c	clipping factor (CDFM)
$\breve{C}_c$	clipping factor (median)
$\breve{C}_I$	capacity increase factor (median)
CDFM	conservative deterministic failure margin
CEUS	Central and Eastern United States
ΔSA	increment of test spectral acceleration
$\Delta f_{0.8}$	total frequency range over which the spectral amplitudes exceed 80% of the peak spectral amplitude
d_i	layer thickness
$\breve{D}_R$	demand reduction factor (median)
DC	direct current
(EA)	effective area times the elastic modulus
EDG	emergency diesel generator
EPRI	Electric Power Research Institute

ESEP	Expedited Seismic Evaluation Process
ESP	early site permit
f_c	central frequency
FIRS	foundation input response spectrum
$\breve{F}_D$	broad frequency input spectrum device capacity factor (median)
F_K	knockdown factor (CDFM)
F_{MS}	multi-axis to single-axis correction factor (CDFM)
$\breve{F}_{MS}$	multi-axis to single-axis correction factor (median)
$\breve{F}_{RS}$	response factor for building (structure) (median)
FRMF	filtered random multi-frequency
GERS	generic equipment ruggedness spectrum
GMI	ground motion incoherency
GMRS	ground motion response spectrum
H	Height
HCLPF	high confidence of low probability of failure
HPCI	high pressure coolant injection
HPCS	high pressure core spray
IC	isolation condenser
ICRS	in-cabinet response spectra (CDFM)
$\widetilde{ICRS}$	in-cabinet response spectra (median)
$ICRS_c$	clipped in-cabinet response spectra (CDFM)
$\widetilde{ICRS}_c$	clipped in-cabinet response spectra (median)
IEEE	Institute of Electrical and Electronics Engineers
IHS	IPEEE HCLPF spectrum
IPEEE	Individual Plant Examination of External Events
ISRS	in-structure response spectra
$ISRS_c$	clipped in-structure response spectra
K_B	stiffness of a concrete insert anchor
K_{LP}	load path stiffness of the cabinet base
m	Mass
M	Magnitude, earthquake
MCCB	molded case circuit breaker
NC	normally closed
NEP	non-exceedance probability
NO	normally open
NPP	nuclear power plant

NRC	Nuclear Regulatory Commission
NTTF	Near-Term Task Force
OBE	operating basis earthquake
PGA	peak ground acceleration
PWR	pressurized water reactor
R	Distance, hypocenter
RCIC	reactor core isolation cooling
RIM	required input motion
RLE	review level earthquake
RLGM	review level ground motion
RMF	random multi-frequency
RMS	root-mean-square
SA	spectral acceleration
SA*	test capacity acceleration
SA_{cH}	spectral acceleration, clipped horizontal
SA_{cV}	spectral acceleration, clipped vertical
SA_{GERS}	spectral acceleration, GERS
SA_{GMRS}	spectral acceleration, GMRS
SA_{mp}	spectral acceleration, peak mounting point demand
SA_{pi}	spectral acceleration, ISRS peak value at frequency f_i
SA_T	spectral acceleration, effective spectral test capacity
SA_{VGMRS}	spectral acceleration, vertical GMRS
SDOF	single degree of freedom
SMA	seismic margin assessment
SPID	screening, prioritization, and implementation details
SPRA	seismic probabilistic risk assessment
SQURTS	Seismic Qualification Reporting and Testing Standardization
SSC	structures, systems, and components
SSE	safe-shutdown earthquake
SSI	soil-structure interaction
$\widetilde{TRS}$	effective wide-band component capacity acceleration
UHS	uniform hazard spectrum
V/H	vertical-to-horizontal
Vs30	average shear-velocity down to 30 meters of soil or rock
Vs_i	shear wave velocity for layer i
ZPA	zero period acceleration

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Section 1: Introduction and Purpose

Ground motion studies have indicated that seismic hazard-consistent ground motion for sites in the Central and Eastern United States (CEUS) often contains significant amounts of high-frequency vibratory motion. The ability of some power plant components to function properly during these high-frequency motions has been considered in prior studies but only in a limited manner. This report provides evaluation guidance for the effects of high-frequency ground motion on power plant systems based on the results of shake table testing of a diverse set of common plant components.

1.1 NRC NTTF Recommendations

Following the accident at the Fukushima Daiichi Nuclear Power Plant (NPP) resulting from the March 11, 2011 Great Tohoku Earthquake and subsequent tsunami, the U.S. Nuclear Regulatory Commission (NRC) established the Near Term Task Force (NTTF) in response to Commission direction. The NTTF issued a report with a series of recommendations, some of which were to be acted upon "without unnecessary delay," concerned with the capability of NPPs to deal with extreme events. NTTF Recommendation 2.1 instructed NRC staff to issue requests for licensees to re-evaluate the seismic hazards at their sites, using present-day NRC requirements and guidance, and to identify and address any plant-specific vulnerabilities associated with the updated seismic hazards. Subsequently in 2012, the NRC issued a 50.54(f) letter [1] that requested information to ensure that these recommendations were addressed by all operating U.S. NPPs.

The NRC requested that each plant provide information about the updated hazard on an accelerated schedule and proposed a progressive screening/evaluation approach to evaluate the potential risk posed by future seismic events. While the full seismic hazard studies were requested, the measure of the re-evaluated seismic hazard for a given site was provided by a new horizontal ground motion response spectrum (GMRS) developed using updated uniform hazard spectra (UHS) [2]. Depending on the comparison between the GMRS and the current design basis spectrum, the plants either were screened-out from further evaluation or were required to perform a seismic risk assessment using the updated seismic hazard. However, in all cases, high-frequency motions that exceed the plant design basis were to be addressed.

1.2 Industry Response

EPRI 1025287, *Seismic Evaluation Guidance, Screening, Prioritization and Implementation Details (SPID) for the resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic* [3] provided screening, prioritization, and implementation details to the U.S. nuclear utility industry for the resolution of NTTF Recommendation 2.1: Seismic. This report was developed with NRC participation and was subsequently endorsed by the NRC. The SPID [3] provided screening guidance for the comparison of site-specific horizontal GMRS, developed from the new seismic hazard evaluations, with the site safe-shutdown earthquake (SSE). As an alternate screening approach, the Individual Plant Examination of External Events (IPEEE) high confidence of low probability of failure (HCLPF) spectrum (IHS) could be used in lieu of the SSE for comparison to the GMRS if certain conditions were satisfied. Use of the IHS for the high frequency confirmation is appropriate for those plants for which the licensee demonstrated that the IPEEE program meets the SPID screening criteria, as determined by the NRC in the screening determination. The new GMRS were submitted to the NRC, and plants with SSE (or IHS if justified) exceedances in the 1 to 10 Hz range were screened-in to perform a seismic risk evaluation using either a Seismic Probabilistic Risk Assessment (SPRA) or a risk-based Seismic Margin Assessment (SMA) based on the new hazard curves. Plants that did not have GMRS exceedances of the site SSE (IHS, if appropriate) in the 1 to 10 Hz range were screened from performing risk evaluations. However, consistent with the SPID [3], plants not performing a risk evaluation but with GMRS exceedances above 10 Hz need to provide confirmation that structures, systems, and components (SSCs) that may be affected by high-frequency ground motion will maintain their functions important to safety.

Some of the new GMRS have peak spectral accelerations above 10 Hz, which may produce significant high-frequency in-structure or in-cabinet motions. Figure 1-1 compares an example site ground motion design spectrum with a corresponding GMRS for a rock site. This is an example of a site that would screen out of a risk evaluation based on the GMRS-to-SSE comparison in the 1 to 10 Hz range but would screen in for a confirmation of high-frequency functionality. It is apparent that consideration of the updated CEUS hazard has shifted the dominant frequency content of the design input motion at this rock site to a frequency range where high-frequency motions may be significant.

The EPRI SPID [3] includes general criteria for new tests to characterize the seismic capacity of components with unknown high-frequency sensitivity. These high-frequency tests have two objectives within the EPRI program to resolve NTTF Recommendation 2.1:

- Provide data to evaluate high-frequency capacity of selected components for those plants that were screened from further risk reviews using the SPID screening criteria.
- Determine the fragility of selected high-frequency sensitive components for those plants that are required to perform SPRA or SMA evaluations.

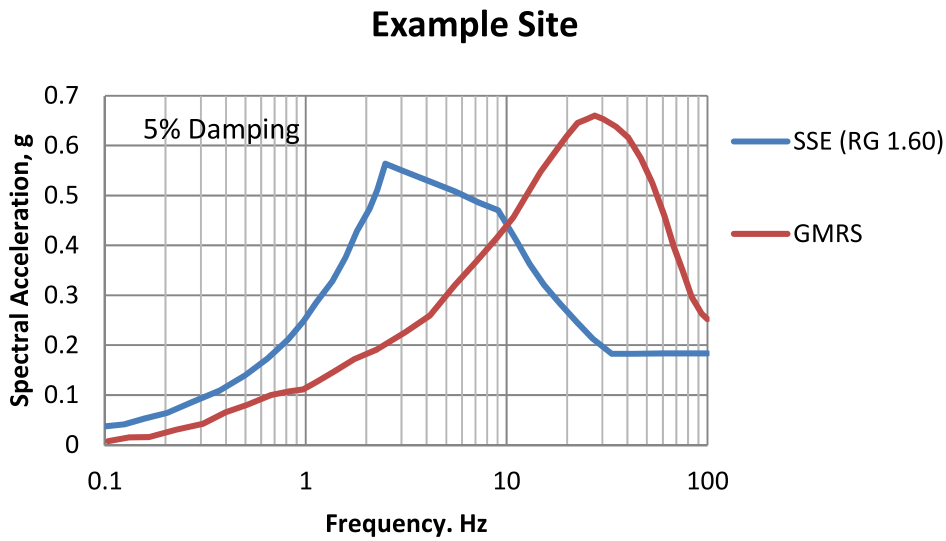

Figure 1-1
Example Horizontal High-Frequency Ground Motion Response Spectrum

1.3 Consideration of Potential High-Frequency Vulnerability

The risk posed by seismic events to NPPs operating in the United States has been the subject of several studies conducted over the past three decades. The prerequisite for any plant seismic risk study is the determination of the seismic hazard associated with a given plant site. Hazard studies for the operating plant sites conducted during the late 1980s concluded that, despite a large uncertainty in the seismic hazard results, there was increased high-frequency content in the resulting seismic motions for the CEUS when compared to the SSE response spectrum used for the design of many plants.

Equipment items important to safety within operating NPPs were seismically qualified for the in-structure or in-cabinet motions consistent with the SSE defined for each plant. The equipment was also evaluated, in general, for a review level earthquake (RLE) under each plant's IPEEE Program. The SSE and RLE ground motions, however, do not typically include significant frequency content above 10 Hz. Studies conducted in the late 1980s provided guidance concerning the hazard-consistent ground motions for the CEUS that had maximum spectral values occurring in the 20 to 30 Hz range. EPRI NP-7498, *Industry Approach to Severe Accident Policy Implementation* [4] includes an appendix titled "Recommended Procedures to Address High-Frequency Ground Motions in Seismic Margin Assessment for Severe Accident Policy Resolution." This appendix reviewed the bases for concluding that high-frequency motions were, in general, non-damaging to components and structures that have strain- or stress-based potential failures modes. However, it concluded that components, such as relays and other devices subject to electrical functionality failure modes, have unknown acceleration sensitivity for frequencies greater than 16 Hz. Thus, the evaluation of high-frequency vulnerability was limited to components that are subject to intermittent states.

In 1991, the NRC requested that each NPP conduct an IPEEE evaluation [5] to identify and report to the NRC all plant-specific vulnerabilities to severe accidents caused by external events. This program, referred to as the IPEEE Program, included seismic events and required that each plant conduct either an SMA (approximately 60% of operating units used this approach) or an SPRA (approximately 40% of operating units used this approach) to address the issue of seismic motions greater than considered in the original design basis. For those plants that used the SMA approach, the RLE (greater than the plant SSE) was chosen to have the low-frequency spectral characteristics similar to the design SSEs. Most plants conducting SPRAs used median spectral shapes that had low frequency characteristics anchored to the peak ground acceleration (PGA) hazard curve for the site.

For the IPEEE Program, the issue of high frequencies was addressed in an indirect manner, focusing on a list of low ruggedness relays mutually agreed to by the industry and the NRC, with known earthquake or shock sensitivity [6]. These specific model relays, designated as "bad actor" relays were identified in EPRI NP-7148, *Procedure for Evaluating Nuclear Power Plant Relay Seismic Functionality* [7]. Rather than considering high-frequency capacity vs. demand screening, relays on this list were considered program outliers and were evaluated using circuit analysis, operator actions, component replacements, or site-specific testing.

During the initial new plant licensing activities, EPRI published two reports to provide additional information regarding the potential high-frequency vulnerability of NPP SSCs. EPRI 1015108 [8] summarizes a significant amount of empirical and theoretical evidence, as well as regulatory precedents, that support the conclusion that high-frequency vibratory motions above about 10 Hz are not damaging to the large majority of NPP structures, components, and equipment. A potential exception to this was the functional performance of vibration-sensitive components, such as relays and other electrical and instrumentation devices whose output signals could be affected by high-frequency excitation. EPRI 1015109 [9] provides guidance for identifying and evaluating potentially high-frequency sensitive components for plant applications that may be subject to possible high-frequency motions. The evaluation of potentially high-frequency sensitive components in plants was therefore directed to mechanically actuated bi-state control devices (such as relays, contactors, switches, potentiometers, and similar devices) and those components whose output signal or settings (set-points) could be changed by high-frequency vibratory motion.

The SPID [3] summarized the consideration of these previous evaluations as well as information from the AP1000 NRC licensing application reviews. Table 1-1 shows the items identified in the SPID as the potentially high-frequency-sensitive component types to be evaluated in the High Frequency Program.

Table 1-1
EPRI 1025287 High Frequency Confirmation Component Types

• Electro-mechanical relays (e.g., control relays, time delay relays, protective relays) • Circuit breakers (e.g., molded case and power breakers – low and medium voltage) • Control switches (e.g., benchboard, panel, operator switches) • Process switches and sensors (e.g., pressure, temperature, flow, limit/position)	• Electro-mechanical contactors (e.g., motor control center starters) • Auxiliary contacts (e.g., for molded case circuit breakers, fused disconnects, contactors/starters) • Transfer switches (e.g., low and medium voltage switches with instrumentation) • Potentiometers (without locking devices)

To support the seismic evaluations, EPRI developed a High Frequency Program that conducted high-frequency seismic testing of a diverse set of common plant control components. The test program used a common test protocol for three-axis high-frequency input motion and a common protocol for monitoring of device state. The results of this test program are documented in EPRI 3002002997, *High Frequency Program: High Frequency Testing Summary*, September 2014 [10].

1.4 Purpose of Report

The purpose of this report is to provide guidance for the use of the results of the high-frequency seismic testing of devices to support the high frequency confirmation identified in EPRI 1025287 [3] for plant sites that screen out of risk evaluations. Specifically, those plants for which the GMRS exceeds the safe shutdown earthquake (or the IHS, as appropriate) in the frequency range above 10Hz (box 3f of Figure 3-1). This report also provides guidance for the use of the high frequency test results in fragility calculations at plants that are performing SPRAs.

Figure 1-2 shows which sections of the report would be used by plants screened-in to perform high frequency confirmations and by plants performing SPRAs.

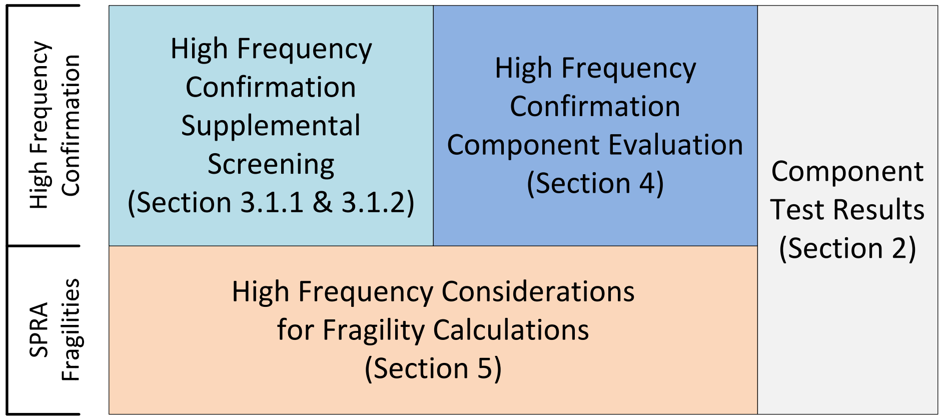

Figure 1-2
High Frequency Confirmation and SPRA Fragility Calculation Applicability

Section 2 provides a review and summary of the results of the High Frequency Program. The primary result of the High Frequency Program was the general conclusion that, while some components are sensitive to vibration, there was no unique high-frequency sensitivity identified for the diverse set of components tested. Many of the components sustained the full table limits (>20g) without contact chatter. Since many of the tested components were subjected to prior low-frequency input test motion, those test results were used to compare to those components that did experience chatter during the high-frequency tests. In all cases where chatter occurred in a high frequency test, chatter also occurred in the low-frequency test at an equal or lower input motion level. There were no cases where a component experienced chatter in a high-frequency test at an acceleration level which was less than the acceleration level at which chatter occurred in a low-frequency test.

Section 3 provides guidance for reviewing results of the GMRS screening of operating NPP sites and establishes criteria for determining which sites should perform a confirmation of high-frequency functionality. Section 3 also provides a procedure for estimating the vertical GMRS component for those sites requiring confirmation, since the vertical GMRS was not previously estimated at those sites.

Section 4 provides guidance for performing a high frequency confirmation for sites that are not performing a full risk evaluation (SPRA or SMA). This includes criteria for:

- Identifying the appropriate equipment scope for the high frequency confirmation.
- Performing simplified estimates of high-frequency in-structure and in-cabinet demand response spectra.
- Performing capacity to demand evaluations of the selected equipment using HCLPF methods.
- Reporting the results to the NRC.

Section 5 provides guidance for applying the high-frequency component capacity information in component fragility evaluations for SPRAs. The general methodology conforms to the criteria provided in EPRI TR-103959 [11] for the development of the seismic fragility of in-cabinet mounted components. Additional guidance is provided for estimating median component capacity using both the low-frequency and high-frequency test capacities.

Appendices provide the bases for the vertical GMRS estimates, the high-frequency in-structure amplification factor estimates, and the high-frequency in-cabinet amplification factor estimates.

Section 2: High Frequency Testing Program Review

Section 1 of this report provides the background on the prior seismic studies that addressed seismic motions of CEUS rock sites with significant high-frequency content. Resolution of the NTTF 2.1 seismic issue requires that the updated seismic hazard of each plant site be evaluated, and that each plant either satisfies certain screening criteria or conducts a new assessment of seismic risk. In either case, plants with GMRS high-frequency content exceeding the SSE are expected to perform functional confirmation evaluations as noted in EPRI 1025287 [3].

It is recognized that the function of complex electro-mechanical components subjected to a given dynamic environment can best be verified by subjecting the components to a realistic test simulation of the motion representative of the environment. Since NPP equipment components have not been routinely subjected to high-frequency seismic motion in the greater than 16 Hz range, the high-frequency seismic vulnerability of NPP components has been essentially unknown. To address this potential component vulnerability to high-frequency motion, EPRI performed a high frequency test program as part of the NTTF 2.1 resolution.

The EPRI high frequency test program was performed in two phases. The Phase 1 effort subjected a small sample of the general component types identified in Table 1-1 to several different types of high-frequency input motion in order to ascertain which test motion type and test procedure would provide the best test protocol to be used in the Phase 2 test program. The Phase 2 effort then used the selected input motion type and procedure to test a large diverse sample of the general component types identified in Table 1-1 to provide the high-frequency fragility information for use in the resolution of the NTTF 2.1 seismic issue.

A complete report of the Phase 1 testing effort is provided in EPRI 3002000706, *High Frequency Program, Phase 1 Seismic Test Summary* [12]. The Phase 2 testing program is documented in EPRI 3002002997, *High Frequency Program, High Frequency Testing Summary* [10].

2.1 Overview of Phase 1 Testing

The focus of the Phase 1 test series was to determine the optimal testing protocol to be used for subsequent fragility testing of selected components. A secondary objective of the Phase 1 pilot effort was to acquire sufficient data to allow development of criteria for comparison of fragility levels obtained using high-frequency wide-band and narrow-band motions.

For the Phase 1 testing effort, eleven test samples were selected as representative of the component types identified in the SPID [3]. In general, the selected components were chosen to investigate contact chatter as the potential high-frequency sensitive failure mode. The components were then sequentially subjected to different types of input motions. Three types of test input motions were investigated in Phase 1: (1) sine sweeps, (2) random multi-frequency (RMF) motions, and (3) filtered random multi-frequency (FRMF) motions. In each case, the input motions were increased in amplitude until either the components failed the acceptance criteria (2 millisecond contact chatter per American National Standards Institute (ANSI) C37.98-1987 [13]), or had anomalous behavior, or the test machine limits were reached.

2.1.1 Phase 1 Sine Sweep Testing

The sine sweep test series subjected the mounted components to constant acceleration single-axis sine sweep input motions over the 16 to 64 Hz frequency range. Testing was conducted using a single-axis high capacity electro-magnetic shake table typically used to conduct sine sweep required input motion (RIM) qualification testing of line-mounted components in the high-frequency range. The mounted components were tested in each primary direction (i.e., front-to-back, side-to-side, and vertical) in the de-energized (non-operate) state and the energized (operate) state. Each mounted component was subjected to an increasing or decreasing frequency sine sweep at each chosen constant acceleration level in each direction, conducted at a one octave per minute rate. Each individual sine sweep test required 2 minutes to complete. The acceleration level of successive sine sweeps were incrementally increased until contact chatter on all instrumented component channels was reached or table motion limits were reached.

2.1.2 Phase 1 Random Multi-Frequency Testing

The RMF test series subjected the same mounted components used in the sine sweep testing to independent tri-axial, random multi-frequency input test motions. The strong motion duration of each input motion was approximately 13 seconds. Each axis of motion was independent but had the same general response spectrum shape and amplitude.

Phase 1 of the EPRI High Frequency Program focused on testing selected components with multi-frequency input motion in the 16 to 48 Hz amplified high-frequency range. Since high frequency testing had not been performed previously, input motions with different frequency ranges were evaluated to

determine the test protocol to be used for the Phase 2 effort. Motions with three types of different spectral frequency content were developed: (1) 16 to 32 Hz broadband motion, (2) 24 to 48 Hz broadband motion, and (3) 20 to 40 Hz broadband motion.

2.1.3 Phase 1 Filtered Random Multi-Frequency Testing

The FRMF test series subjected each test sample of mounted components to independent tri-axial, random multi-frequency input test motions with a uniaxial narrow-band beating motion superimposed in one of the horizontal directions. The testing was conducted using the same test components and test fixture that was used for the RMF testing.

The FRMF test series used wide-band multi-frequency independent random input motions along two primary axes (horizontal and vertical) with a set of narrow-band filtered motions along the third axis (other horizontal). The FRMF testing was intended to simulate either in-structure response or high-frequency local panel in-cabinet response, which is the result of front-to-back or side-to-side response motion; therefore, the filtered motions were limited to those horizontal two directions. Additionally, comparison of the fragility response spectra for both the FRMF and RMF motion allows a high-frequency "clipping factor" to be defined that can be used to convert an in-structure or in-cabinet demand (response spectrum) to an equivalent wide band motion for comparison to a RMF fragility test spectrum.

The FRMF testing demonstrated that the tested components can sustain a narrow-band motion with a peak spectral value that greatly exceeds the RMF fragility levels. In general, narrow-band motion is not as functionally damaging as is wide-band motion, and a "clipping" procedure developed in EPRI TR-103959 [11] can be used to convert a narrow-band in-structure or in-cabinet demand (response spectrum) to an equivalent wide-band motion for comparison to a RMF fragility test spectrum. This procedure is a key tool for component fragility evaluations using RMF component test data. The FRMF test data in EPRI 3002000706 [12] validated the procedure in the high-frequency range.

2.1.4 Phase 1 Conclusions and Insights

The Phase 1 study confirmed that the high-frequency chatter of contact devices was model-specific. Some of the components sustained the full test machine limits without contact chatter. Other components had contact chatter occur in one type of test motion and not in another type of test motion. Thus, the best means to identify any frequency sensitivity is to test a device for an input motion that can be directly related to the expected frequency content of the component mounting point motion.

The 20 to 40 Hz RMF input motion was determined to be the best motion to conduct the multi-axis testing. The use of other input motions required considerable effort and did not provide better information for determining if high-frequency sensitivity existed for a given component.

Sine sweep testing demonstrated conclusively that for most relay models, contact chatter is more prone to occur in the low-frequency region of the sine sweep rather than within a high-frequency region.

Filtered multi-frequency narrow-band inputs resulted in peak spectral fragility values that were two to three times the fragilities obtained using wide-band multi-frequency input motions. The application of the relations used in EPRI TR-103959 [11] for clipping of a narrow-band spectrum to obtain an estimate of an equivalent wide-band spectral level was validated. Thus, the clipping factor used for low-frequency fragility evaluations is also valid for high-frequency fragility evaluations.

2.2 Selection of Phase 2 Components

Test samples were selected to be representative of component types listed in Table 1-1 and which are actually installed in operating nuclear power plants. The test sample selection was based on review of the most common utility components tested in the EPRI Generic Equipment Ruggedness Spectra (GERS) [14] and Seismic Qualification Reporting and Testing Standardization (SQURTS) [15] programs. Selection was made by judgment to include commonly qualified and dedicated items, different manufacturers, model configurations, subcomponents present, voltage/current rating, and a diverse but representative sample of components, and a variety of expected seismic capacity levels.

Overall, 153 components were selected, which are representative of bi-state devices found in operating nuclear plants such as relays, contactors, switches, and other similar devices whose output signal or set-points could be potentially changed by high-frequency vibratory motion. The largest category was control relays since older plants were designed using relay logic for system control and thus have extensive numbers of control relays used for both control logic and terminal device control.

This distribution of test samples is graphically presented in Figure 2-1.

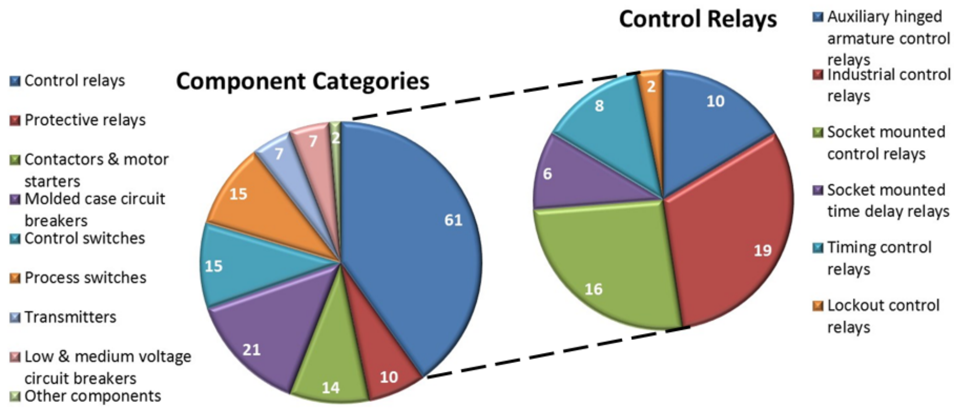

Figure 2-1
Distribution of Tested Components

2.3 Phase 2 Component Testing

The physical testing effort of the selected 153 component items was accomplished in nine separate test weeks spaced out over a ten-month period. Approximately fourteen to twenty items were tested during each test week. Within each test week, the items under test were further divided into groups of one to five components mounted on a common test fixture and subjected to increasing levels of input motion until a discontinuity (contact chatter, voltage, or current output) in the monitoring circuit was observed for each component or the limiting table motion was reached.

2.3.1 Random Multi-Frequency Test Configuration and Setup

For eight of the test weeks, the RMF testing was conducted using a tri-axial servo-motor-driven table, as shown in Figure 2-2. The figure also shows a test fixture mounted to the table to achieve simultaneous independent vibration of the attached components under test.

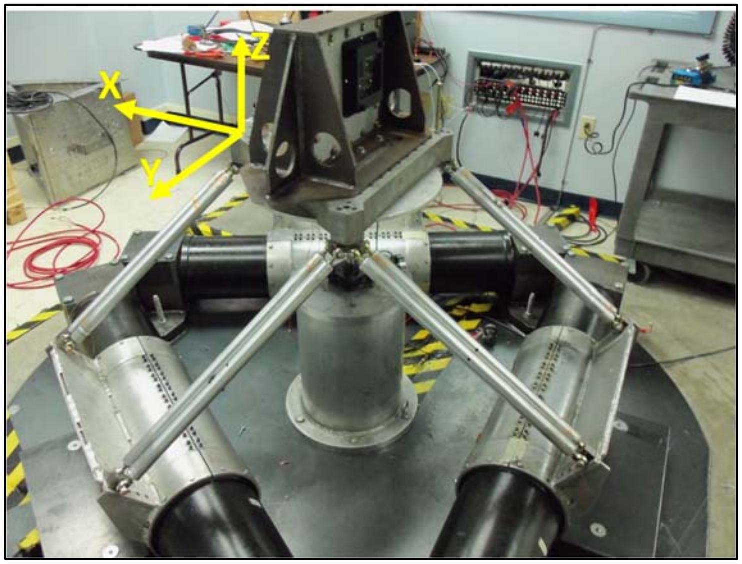

Figure 2-2
Tri-Axial Servo-Motor-Driven Shake Table with Mounted Test Fixture and Identification of Principal Motion Axes

One test week was used for testing larger components using a 10 ft x 10 ft tri-axial table with motion control provided by servo-hydraulic actuators. Being a larger table with greater mass, the RMF acceleration level is limited to a spectral level of about 14g. Figure 2-3 shows a test fixture with attached components mounted to the table to achieve simultaneous independent front-to-back, side-to-side, and vertical vibration of the components under test.

Figure 2-3
Large Servo-Hydraulic Shake Table with Mounted Components and Identification of Principal Motion Axes

The target 20 to 40 Hz broadband table motion was characterized by the normalized shape labeled RMF3 in Figure 2-4. The general shape of the amplified spectral region was patterned after the normalized test shape from ANSI C37.98-1987 [13] with the peak spectral acceleration region being 2.5 times the zero period acceleration (ZPA), but with the frequency ranges shifted as shown in Figure 2-4. The normalized shape defined the frequency content of the motion in each horizontal direction and in the vertical direction (equal spectra in each direction) as well.

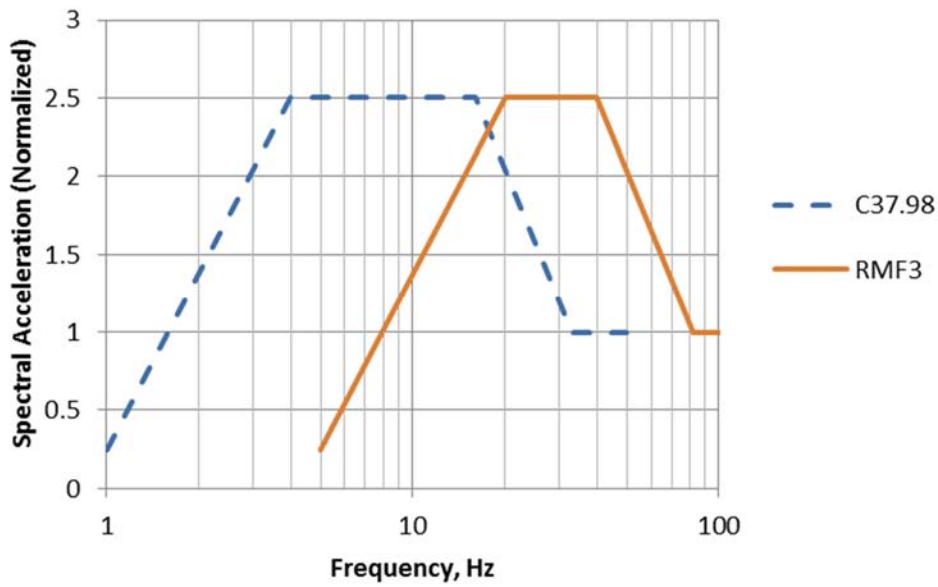

Figure 2-4
Normalized 20 to 40 Hz Wide-Band RMF Input Spectrum (5% Damping)

Input time-history motions were generated to have an overall duration of 15 seconds in accordance with the ANSI C37.98-1987 [13] recommendation for minimum test duration with an approximate 1 second rise time and an approximate 1 second ending decay time. The strong motion duration of each input motion was approximately 13 seconds, which is approximately twice the expected duration of CEUS earthquake high-frequency motions on hard rock [28].

2.3.2 Functional Data Acquisition

Each group of electrical components under test was wired to off-table power supplies and was provided with switched nominal (or rated) operating voltage during the conduct of each test series. Pressure transmitters and process switches used nitrogen gas as the activation source. Temperature transmitters and switches were tested at ambient temperature. In general, each component had a single normally closed (NC) and single normally open (NO) contact selected for independent monitoring during each test run conducted at a given input motion level. Some components also required additional monitoring of main pole and auxiliary or overload contacts. The outermost contacts on the components were

chosen for monitoring when multiple contacts were present. For some components, the current through an external load resistor or the component output voltage was directly monitored. Protective relay seal-in contacts were an exception to the electrical monitoring scheme. Seal-in contacts were wired in series with the operating relay coil with sufficient applied voltage to draw twice the rated seal-in or holding current from the power source.

The 2 millisecond contact chatter acceptance criterion, as described in ANSI C37.98-1987 [13], was used. For this criterion, contact chatter (or a disruption in the monitored contact voltage) is considered a malfunction when the change in voltage is greater than 50% of the closed contact voltage level and persists for more than 2 milliseconds.

2.3.3 Post-Processing of Data

In order to have a single measure of component capacity, a procedure was developed to determine an average estimate of the independent three-axis motion. This procedure can best be described by considering an example. Figure 2-5 shows the set of three-axis time-history test motions and the corresponding response spectra for a typical test run identified as a component test capacity level. Each test response spectrum was averaged over the plateau region of the test RMF spectrum shape (20 to 40 Hz band) to obtain an effective constant spectral level, which served to anchor the target RMF spectrum shape achieved in each direction during the test run. In order to have a single measure of device capacity, the overall effective spectral level achieved during the run was then estimated by the geometric average of the spectral levels achieved in each direction.

Thus, for the example test run shown in Figure 2-5, the 20 to 40 Hz spectral accelerations are 11.93g in the x-direction, 12.63g in the y-direction, and 11.80g in the z-direction. The final component test capacity level is given by:

$$SA^* = [(11.93)(12.63)(11.80)]^{1/3} = 12.11g$$

This acceleration level was used to scale the target RMF spectral shape to yield the effective component test capacity spectrum.

This same procedure was used to determine each component's test capacity level.

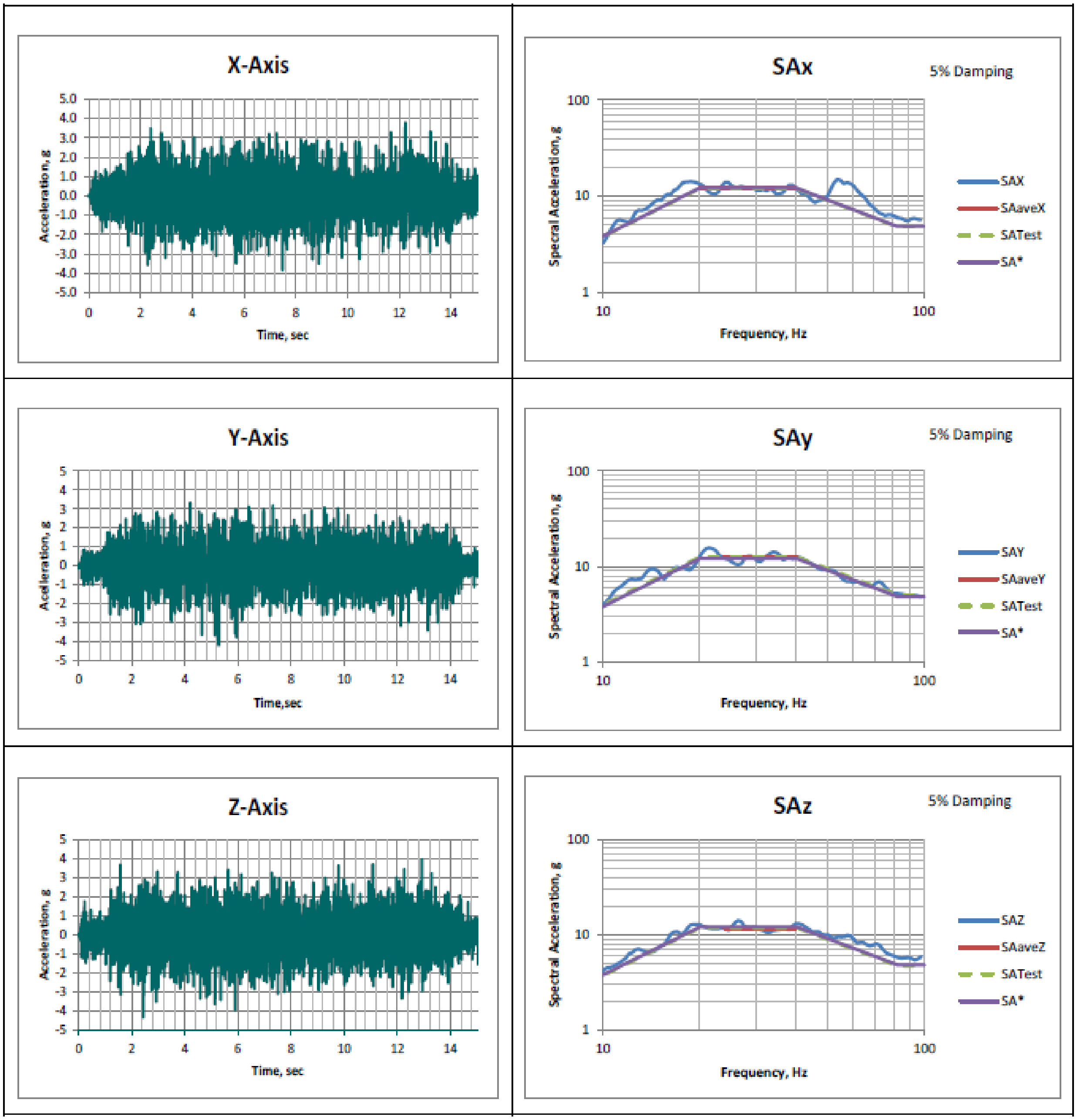

Figure 2-5
Three-Axis Acceleration Time Histories with Corresponding Response Spectra for a Typical Test

2.3.4 Comparison with Low Frequency Test Capacity Results

If the achieved high-frequency capacity for a component was less than 10g spectra acceleration in the 20 to 40 Hz range, a review was performed to determine if that capacity was greater than or less than the capacity achieved in a typical lower frequency test. This comparison was used to determine if the component had unique high-frequency sensitivity, or a more general sensitivity to overall earthquake motions.

The majority of the test components were obtained from the inventory of components maintained by the SQURTS program. These components had been tested with tri-axial independent, random multi-frequency input test motions similar to the ANSI C37.98-1987 [13] spectral shape with broadband motion in the 4.5 to 16 Hz frequency range. Many, but not all, had a capacity test level determined for this low-frequency motion. Usually, the capacity level was found only for the contact state having the lowest chatter threshold. The SQURTS capacity test levels are shown in Figure 2-6 for the same part as used in the example above for the high frequency capacity. Using the same procedure as described above and averaging each axis motion over the 4.5 to 16 Hz range, the component test capacity level for the low-frequency range is 10.58g, which is less than the high frequency test capacity determined above.

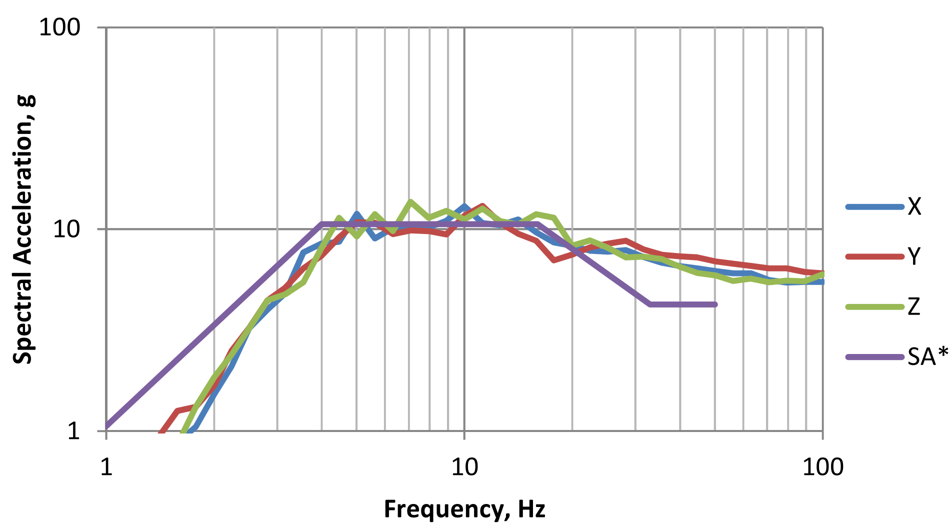

Figure 2-6
SQURTS Capacity Test Spectra

2.4 Summary of Phase 2 Test Results

The Phase 2 testing effort considered the capacity testing of a diverse sample of 153 power plant components selected to be representative of control switches, transmitters, molded case circuit breakers (MCCBs), process switches, contactors and motor starters, transfer switches, low and medium voltage circuit breakers, protective relays, and control relays. These components were chosen from an inventory of items previously tested in low-frequency qualification test programs.

Most of the components were tested in the High Frequency Program to the shake table limits (>14g to >20g spectral acceleration, 5% damping, 20 to 40 Hz range) without chatter or malfunction. Some components did have chatter occur at lower levels of high-frequency table motion. Since many of the tested components were subjected to prior low-frequency input test input motion, those test results were used to compare with the high-frequency chatter results. In all cases where chatter occurred in a high frequency test, chatter also occurred in the low frequency test at an equal or lower input motion level.

Overall conclusions relative to the classes of equipment tested are summarized below. Figures 2-7 through 2-17 show the limiting capacity for each component contact configuration, which is typically a normally closed contact on a deenergized component. Complete test results for all contact configurations are provided in EPRI 3002002997 [10].

- Control switches (sixteen components), transmitters (seven components), and MCCBs (twenty-one components) were shown to be rugged in the high-frequency region. Each tested component sustained the table limit motions without chatter or other discontinuity anomalies. The summary of the test capacity levels achieved for these components is presented in Figures 2-7 through 2-9. Components tested on the smaller shake table had table limiting spectral acceleration values (20 to 40 Hz) in excess of 20g while components tested on the large shake table had table limiting spectral acceleration values (20 to 40 Hz) in excess of 14g.
- Process switches were generally shown to be rugged in the high-frequency region. Twelve of the fifteen process switches tested sustained the table limit motions without anomalies. Three process switches exhibited chatter in the high-frequency range but the test capacities were greater than the levels shown to exist in prior low frequency testing of the components. The Solon pressure switch had different test capacities depending on the component set point. Figure 2-10 presents spectral acceleration values (20 to 40 Hz) achieved for the tested components.
- The example potentiometer tested and additional potentiometers included as subcomponents (such as in timing relays) were shown to be rugged in the high-frequency region and are judged to be representative of other potentiometers. Transfer switches were also shown to be rugged in the high-frequency region. Each transfer switch sustained the table limit motions without anomalies. A tested proximity switch was rugged in the high-frequency region for the non-operate mode but exhibited chatter in the high-frequency range for the operate mode. Low voltage/medium voltage/ insulated case circuit breakers (switchgear) had test capacities that were less than the table limit motions. As such, specific capacity levels were established for each breaker configuration. In general, the high-frequency capacity was greater than generic capacity levels used for switchgear in the low-frequency range. Figure 2-11 presents spectral acceleration values (20 to 40 Hz) achieved for the tested components.

- Contactors and motor starters were generally shown to be rugged in the high-frequency region. The majority of the tested components in this category sustained the table limit motions tested without anomalies. However, certain contactors and starters had test capacities below this table limit value and have capacities (for both main and auxiliary contacts) in the 6g to 12g range, depending on the configuration and model. These capacities were still higher or equal to those obtained in the low-frequency range. Figure 2-12 presents spectral acceleration values (20 to 40 Hz) achieved for the tested contactors and motor starters.
- Protective relays have different operating mechanisms and configurations that lead to a wide range of test capacity. The solid state types with relay output were shown to be rugged in the high-frequency region. The induction disk types with seal-in units had high frequency capacities that varied from 9g to 19g depending on the operating mode and sub-component monitored. The hinged armature telephone type relay had high non-operate test capacities but a wide range of operate test capacity. In general, the high-frequency capacity for one operation mode was low but was greater than the capacity levels obtained in the low-frequency range. The vertical plunger type of relay also had a wide range of high-frequency test capacity but was always greater than the capacity levels obtained in the low-frequency range. Figure 2-13 presents spectral acceleration values (20 to 40 Hz) achieved for the tested solid state, induction disk, hinged armature telephone, and vertical plunger protective relays.
- The group of tested control relays had a broad range of high-frequency capacities.
  - Lockout relays were shown to be rugged in the high-frequency region. Industrial control relays had high frequency test capacities that ranged from over 20g down to 9g. The summary of the test capacity levels achieved for the tested lockout and industrial control relays is presented in Figure 2-14. At the lower end of the test capacities, the high-frequency test capacity was greater than the capacity levels obtained for the same component in the low-frequency range.
  - Socket-mounted control relays had high frequency test capacities that ranged from over 20g to 11g. The summary of the test capacity levels achieved for the tested socket mounted control relays is shown in Figure 2-15.
  - Timing control relays (both socket and panel mounted) socket-mounted control relays had high frequency test capacities that ranged from over 20g to 12g. The summary of the test capacity levels achieved for timing control relays is shown in Figure 2-16.

- Auxiliary hinged armature relays exhibited chatter in the high-frequency range for all tested units. In general, the test capacities were greater than the levels found in prior low frequency testing of the same components. It should be noted that the relays at the lower end of the high frequency test capacities (SG and HGA relay models) are designated as low ruggedness relays in EPRI NP-7148 [7] for the NC contact in the de-energized state since they have been shown to have negligible test capacity for low frequency motions.

The primary result of the High Frequency Program is the general conclusion that while some components are sensitive to vibration, there was no unique high-frequency sensitivity identified. Some components are simply sensitive to vibration in general, but that sensitivity is not increased in the high-frequency region.

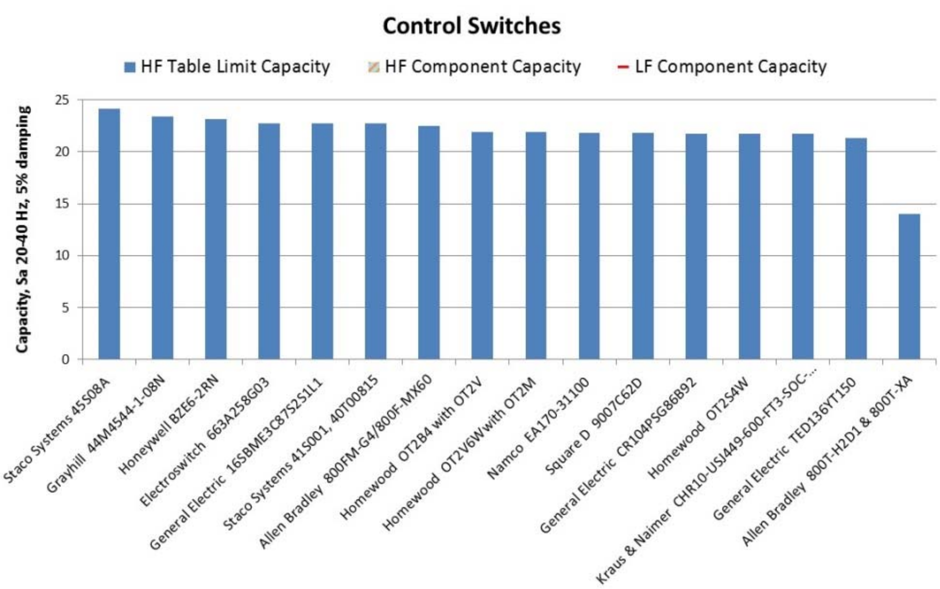

Figure 2-7
Capacity Test Spectral Acceleration Values Achieved for Tested Control Switches (5% Damping, 20-40 Hz)

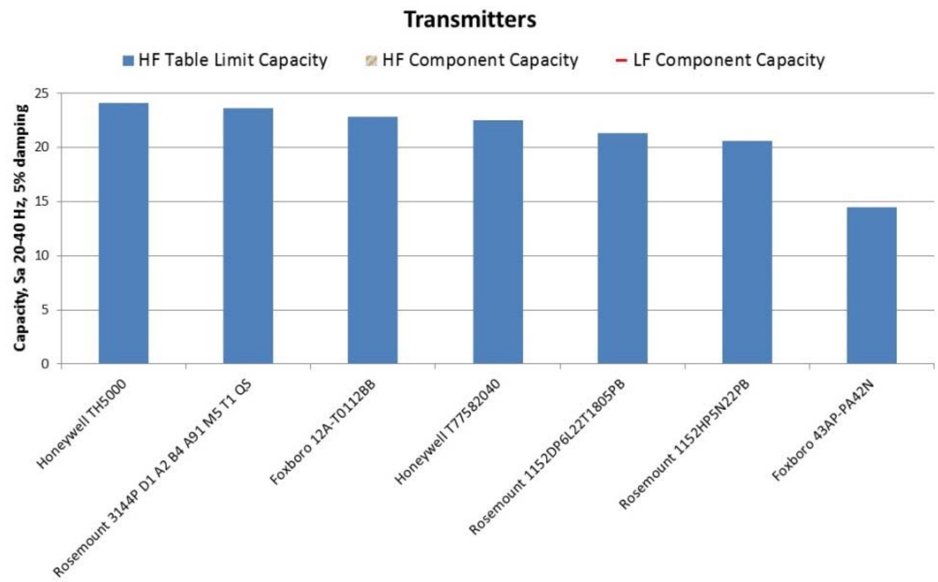

Figure 2-8
Capacity Test Spectral Acceleration Values Achieved for Tested Transmitters (5% Damping, 20-40 Hz)

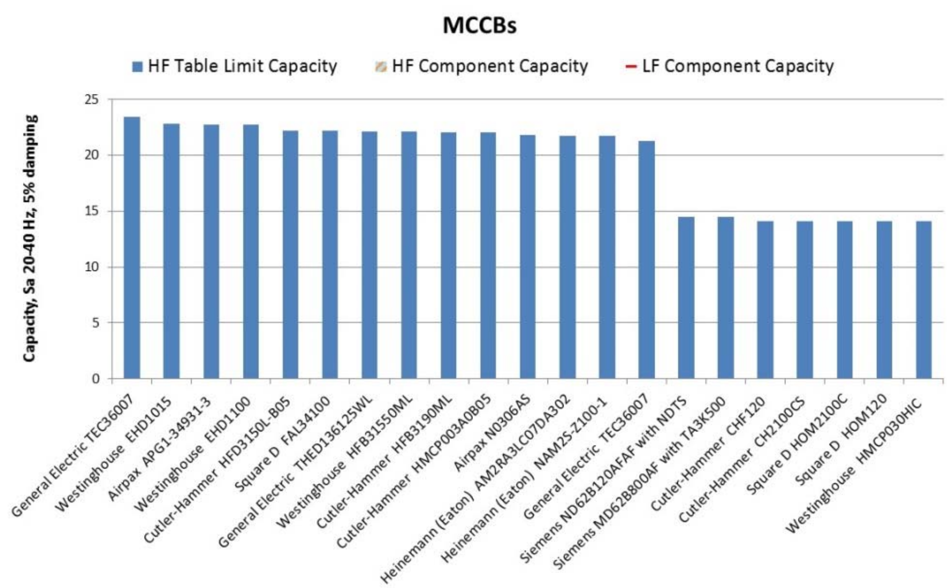

Figure 2-9
Capacity Test Spectral Acceleration Values Achieved for Tested Molded Case Circuit Breakers (5% Damping, 20-40 Hz)

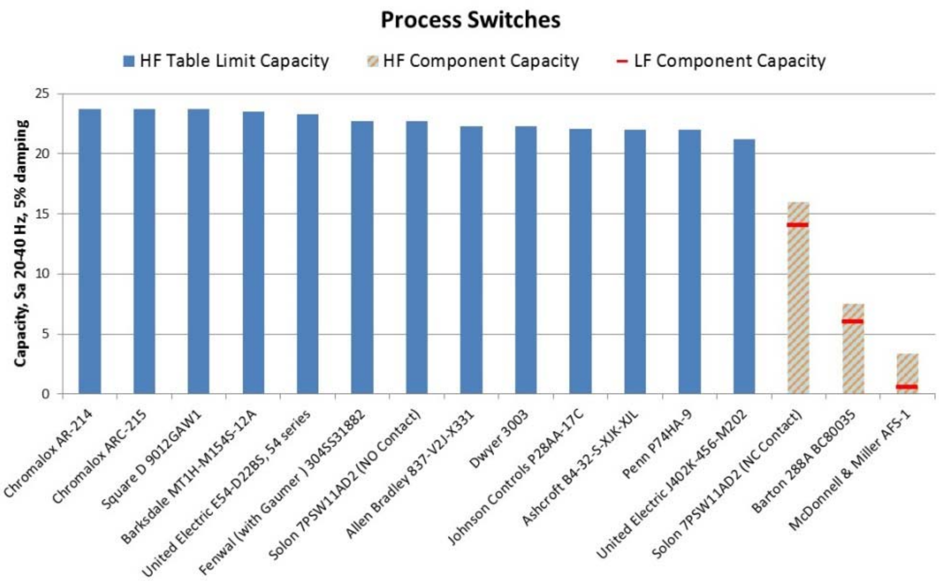

Figure 2-10
Capacity Test Spectral Acceleration Values Achieved for Tested Process Switches (5% Damping, 20-40 Hz)

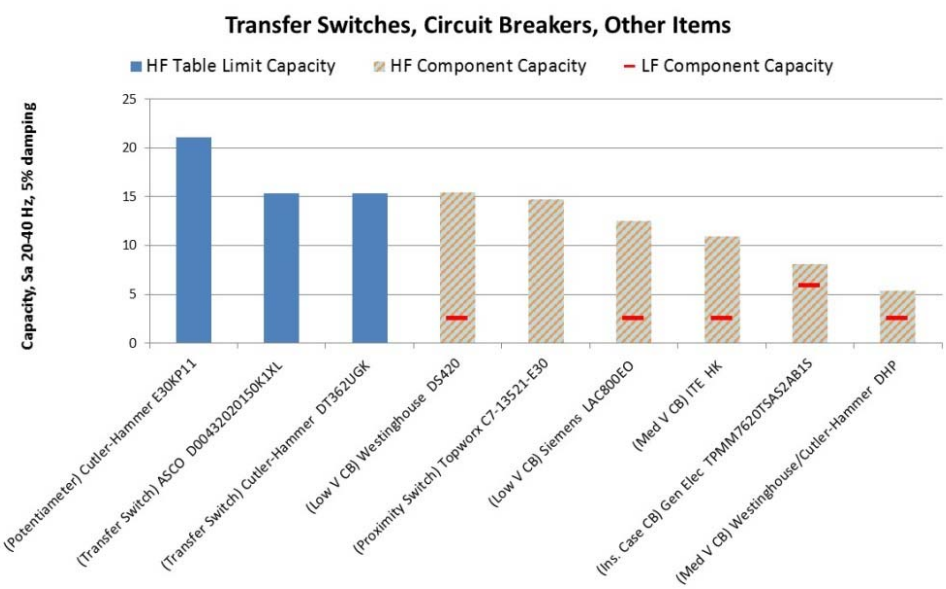

Figure 2-11
Capacity Test Spectral Acceleration Values Achieved for Tested Potentiometers, Transfer Switches, Proximity Switches, Low-Voltage Circuit Breakers, Medium-Voltage Circuit Breakers, and Insulated Case Circuit Breakers (5% Damping, 20-40 Hz)

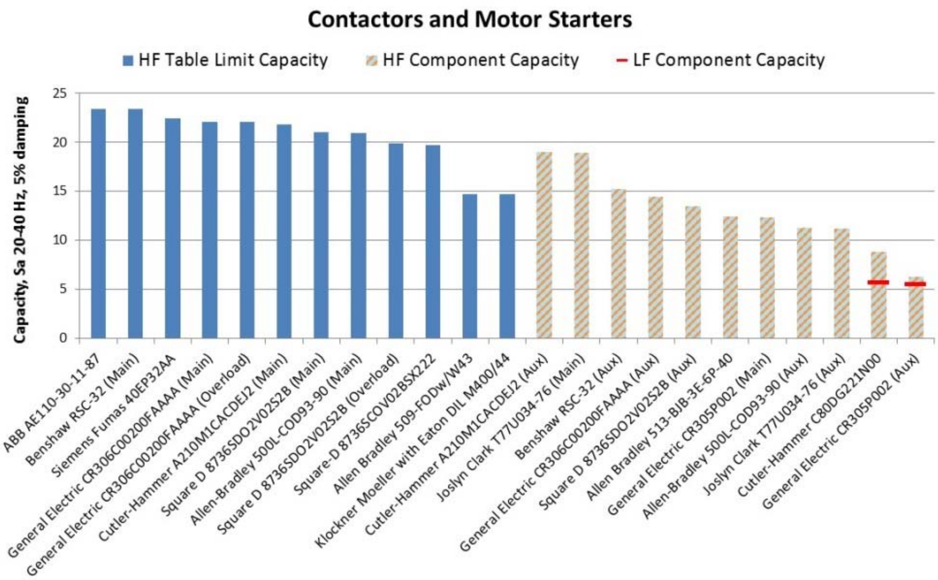

Figure 2-12
Capacity Test Spectral Acceleration Values Achieved for Tested Contactors and Motor Starters (5% Damping, 20-40 Hz)

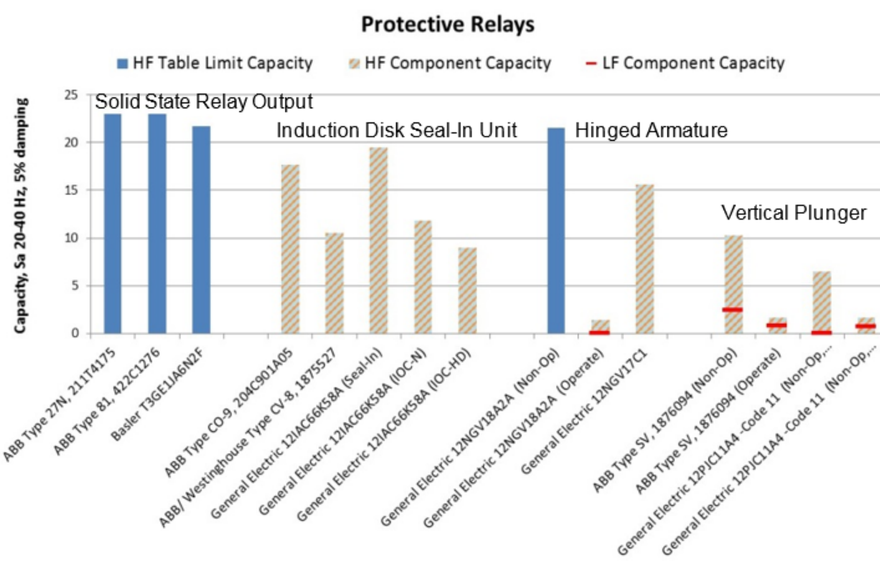

Figure 2-13
Capacity Test Spectral Acceleration Values Achieved for Tested Solid State, Induction Disk, hinged Armature Telephone, and Vertical Plunger Protective Relays (5% Damping, 20-40 Hz)

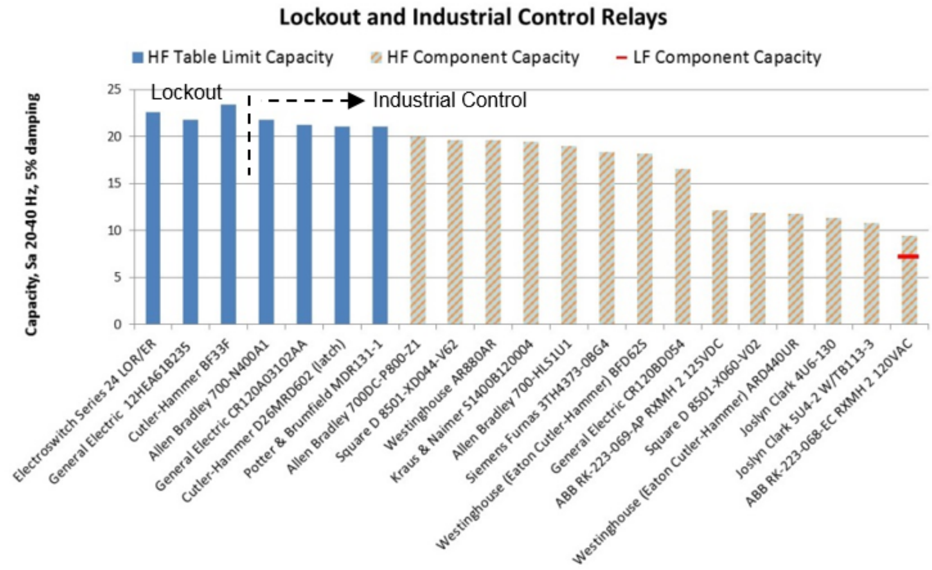

Figure 2-14
Capacity Test Spectral Acceleration Values Achieved for Tested Lockout and Industrial Control Relays (5% Damping, 20-40 Hz)

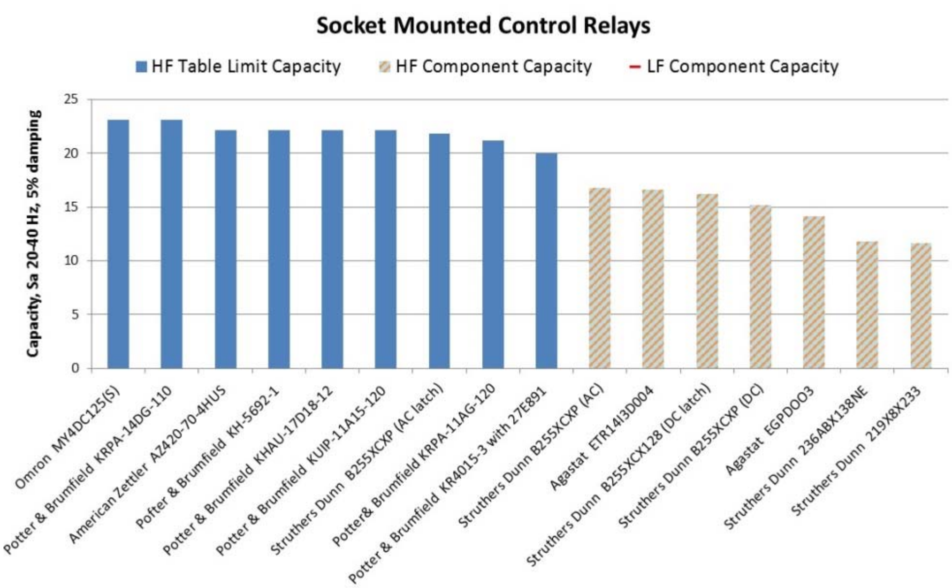

Figure 2-15
Capacity Test Spectral Acceleration Values Achieved for Tested Socket-Mounted Control Relays (5% Damping, 20-40 Hz)

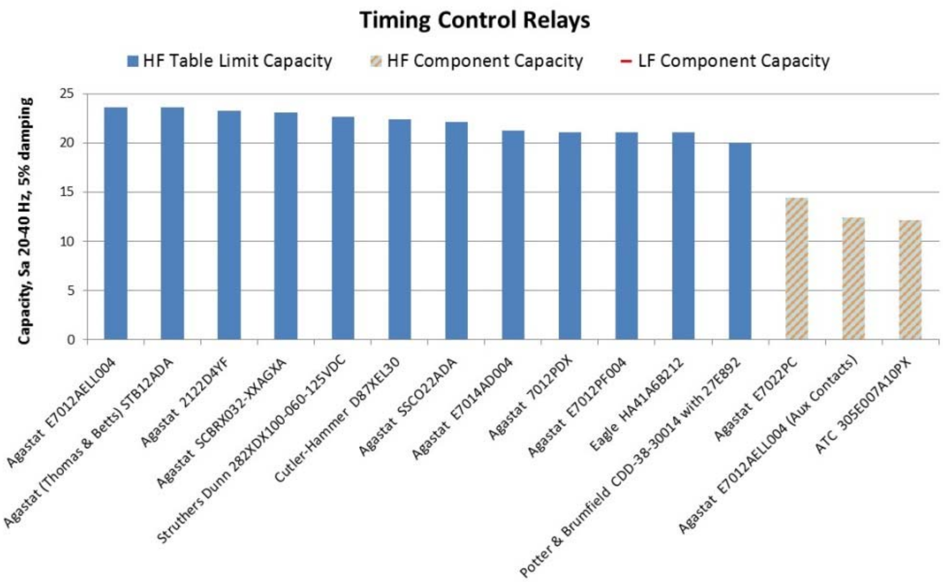

Figure 2-16
Capacity Test Spectral Acceleration Values Achieved for Tested Timing Control Relays (5% Damping, 20-40 Hz)

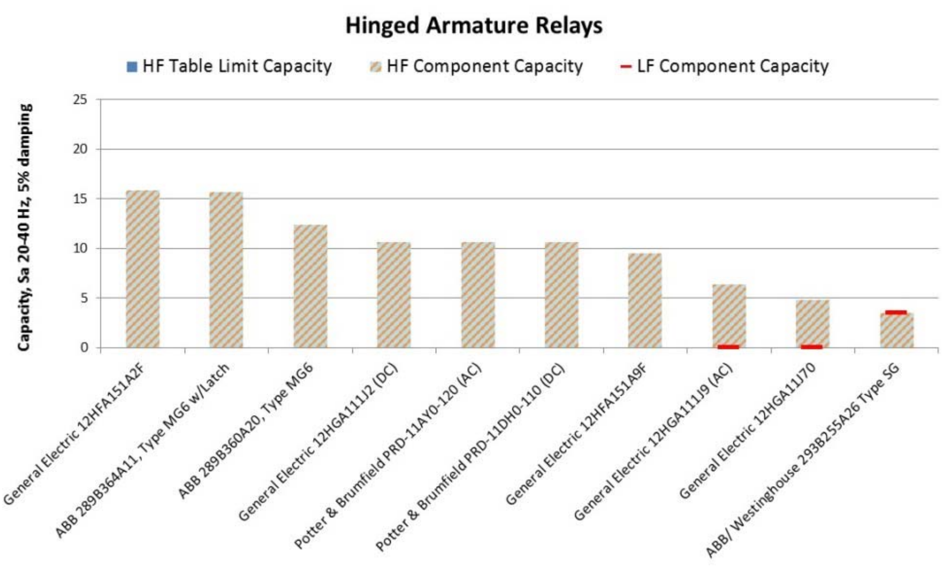

Figure 2-17
Capacity Test Spectral Acceleration Values Achieved for Tested Auxiliary Hinged Armature Relays (5% Damping, 20-40 Hz)

Section 3: CEUS Site GMRS and Screening Results

This section reviews the results of the updated GMRS screening of operating NPP sites. Specific criteria are established for determining which sites should perform a confirmation of high-frequency functionality. A procedure is also included for estimating the vertical GMRS component since plants performing a high frequency confirmation may not otherwise have a vertical GMRS. In addition, this section also includes a discussion of foundation input response spectrum (FIRS) considerations associated with the control point of the seismic input for the high frequency confirmation.

3.1 Review of GMRS Screening Results

Each operating NPP in the United States has conducted a probabilistic seismic hazard analysis in accordance with the guidance contained in the EPRI SPID [3] and has submitted the horizontal GMRS and supporting updated hazard results to the NRC. In accordance with the SPID [3] criteria, sites are either screened-out of a risk evaluation or are required to perform a risk evaluation (SPRA or SMA) using the new hazard result. The comparison of the plant SSE (or IHS as appropriate) in the 1 to 10 Hz range is the deciding action. Use of the IHS for the high frequency confirmation would be appropriate for those plants for which the licensee demonstrated that the IPEEE program met the SPID screening criteria, as determined by the NRC. This includes the completion of the IPEEE full scope relay review. Plants whose SSE (or IHS as appropriate[1]) is exceeded in the 1 to 10 Hz range screen in to perform a seismic risk evaluation. Sites whose SSE (or IHS as appropriate) completely envelope the GMRS are screened-out of further evaluation. Sites, whose SSE (or IHS) screen out from the risk evaluation but have GMRS exceedances above 10 Hz, are screened-in to perform a High Frequency Confirmation. These screening concepts are shown in Figure 3-1, which shows a subset of the screening flowchart from the SPID.

[1] To screen out of a seismic risk evaluation using the IHS, the licensees have to perform the IPEEE full-scope relay review as described in Section 3.3.1 of Ref. 3. The particular screening described in section 3.1.2 of this report is used only to determine whether an additional high frequency confirmation is also needed or not.

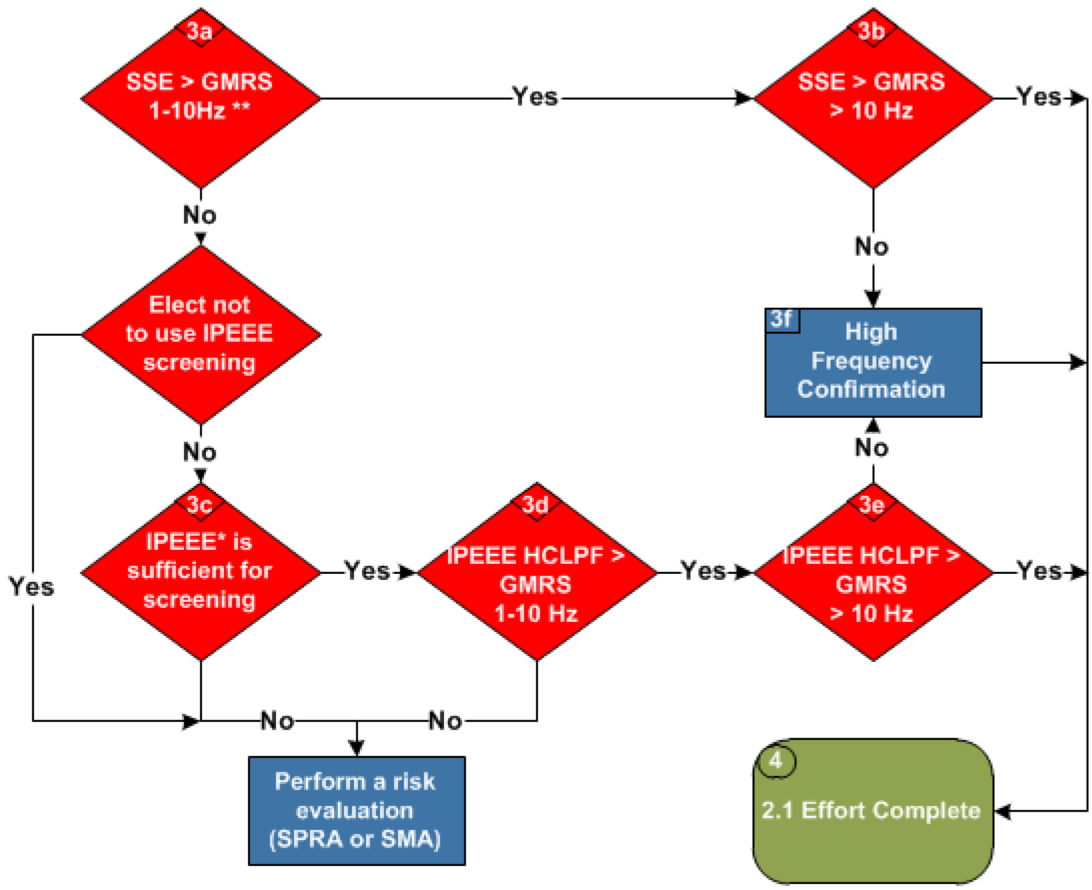

Figure 3-1
High Frequency Confirmation Screening (Subset of SPID Figure 1-1)

A review of the site-specific GMRS indicates that a number of the sites that screen in for performing the High Frequency Confirmation have only nominal exceedances of the SSE (or IHS) in the greater than 10 Hz range. The horizontal GMRS for these sites are characterized by either, (1) a maximum spectral acceleration less than 0.2g, or (2) a small spectral acceleration exceedance over a very limited frequency band in the high-frequency range. A supplemental high frequency screening criteria for these two conditions is provided below.

3.1.1 Low Spectral Acceleration Screening

Figure 3-2 shows an example GMRS where the plant would screen in for the High Frequency Confirmation, but the high-frequency spectral accelerations above 10 Hz are very low. A spectral acceleration up to 0.2g has been determined to be non-damaging in a number of previous EPRI reports and regulatory guidance documents. The 0.2g bound for spectral acceleration is incorporated in EPRI Report 3002000720 [16], *Guidelines for Nuclear Plant Response to an Earthquake*, as part of the criteria governing plant shutdown following an earthquake exceeding the plant operating basis earthquake (OBE). If the instrument-measured site spectral acceleration is 0.2g or less in the 2 to 10 Hz range, then plant shutdown is not required. This threshold is also included in

NRC Regulatory Guide (RG) 1.166, *Pre-Earthquake Planning and Immediate Nuclear Power Plant Operator Postearthquake Actions* [17]. The basis for this criterion is the lack of any damage or other issues observed in actual earthquakes with observed spectral accelerations less than 0.2g in the 2 to 10 Hz range. For the greater than 10 Hz range, there is no spectral bound due to the lack of damage caused by high-frequency motion. However, it is recognized that while relay chatter is possible, it is unlikely at this low motion level. The EPRI High Frequency Program [12] has shown that shake table testing in the 20 to 40 Hz frequency range, in general, yields a higher test capacity than testing in the 4 to 16 Hz range for tests of the same control component. Even low-ruggedness relays, excluded as having negligible capacity in the low-frequency IPEEE evaluations, have finite high-frequency test capacities. Therefore, sites with a horizontal GMRS high frequency peak spectral acceleration ≤ 0.2g do not need to confirm the functionality of control devices in the high frequency range and can be screened-out from the High Frequency Confirmation.

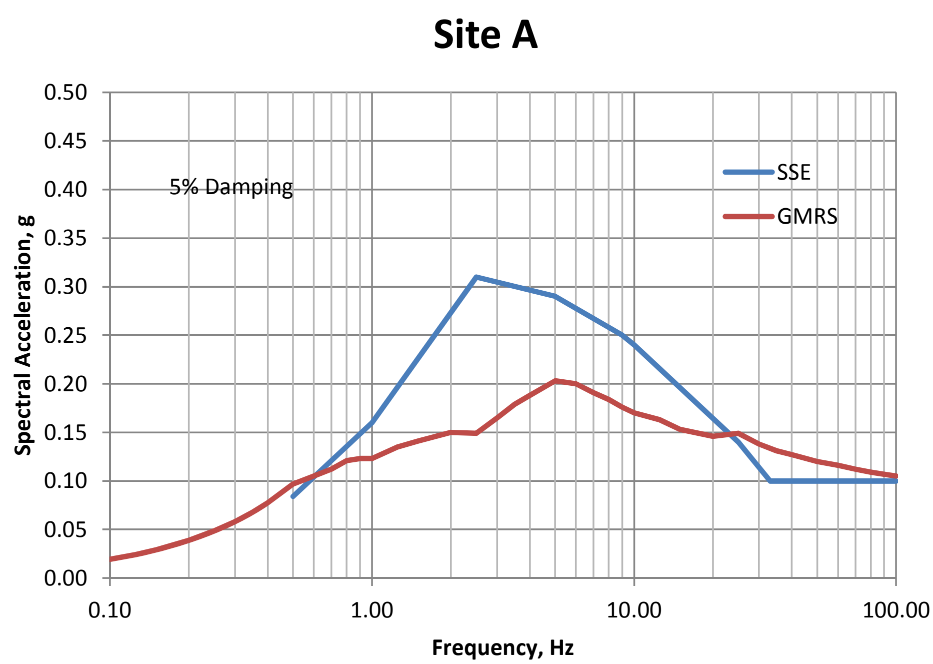

Figure 3-2
Example Site with High Frequency Horizontal GMRS ≤ 0.2g

3.1.2 Limited High Frequency Exceedance Screening

A number of sites have very small exceedances of their respective GMRS over a limited high frequency range. In general, this exceedance occurs when the GMRS traverses the frequency region near the 33 Hz cutoff frequency used to indicate the PGA as part of the SSE or IHS[2] (whichever was used for screening in the plant Seismic Hazard submittal). The discontinuity associated with the PGA cutoff frequency is an artificial byproduct of the simplified SSE response spectra shape in NRC RG 1.60 [18] or the IHS shape used for IPEEE rather than a representation of actual earthquake ground motions. Figure 3-3 shows the small exceedance that can occur for the GMRS near the 33 Hz "notch" in the IHS shape used for a particular site.

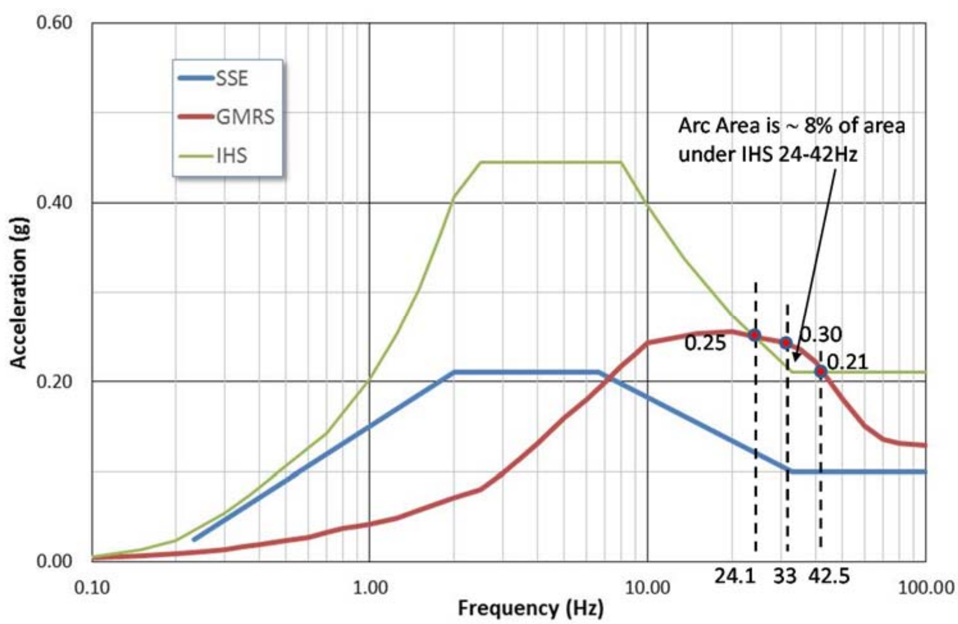

Figure 3-3
Site with Horizontal GMRS with a Small IHS Exceedance while transitioning to the PGA of the GMRS at 100 Hz

In order to quantify the largest exceedance considered as nominal, the increment in area between the SSE or IHS and the GMRS over the frequency band with an exceedance can be computed. Figure 3-3 shows the limits for an example case of nominal exceedance. The resulting area between the two curves is about 8% of the area under the IHS in the same frequency band. The motivation for this procedure is the concept of Spectrum Intensity first used by Housner [19]. While Housner used the area under the pseudo-velocity spectrum for his measure, Arias [20] has noted that the choice of response spectrum is arbitrary and that

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[2] To screen out of a seismic risk evaluation using the IHS, the licensees have to perform the IPEEE full-scope relay review as described in Section 3.3.1 of Ref. 3. The particular screening described in section 3.1.2 of this report is used only to determine whether an additional high frequency confirmation is also needed or not.

the area under the absolute acceleration spectrum could be a preferred intensity measure for certain situations. Pseudo-velocity is proportional to stress and thus is a stress-based damage measure. Since the focus of the high frequency confirmation is the acceleration response of devices, it is logical to consider the area under the absolute acceleration spectrum as an alternate intensity measure of device capacity. Therefore, sites where the GMRS exceedance area between the GMRS and SSE (or IHS) is on the order of 10% or less of the area under the SSE (or IHS) over the frequency range of exceedance, can be screened-out from the High Frequency Confirmation. For the High Frequency Confirmation, these types of minor exceedances over limited frequency ranges evaluated using the above exceedance area criteria, do not represent a significant high frequency concern and can be screened from further component evaluations.

3.2 Guidance for Estimating Vertical GMRS

A procedure for estimating the vertical GMRS component for those sites requiring confirmation is developed in Appendix A. The procedure outlined in Appendix A consists of four steps:

1. Estimate the value of "Vs30" for the profile used to obtain the site GMRS. The site classification measure, Vs30, is defined [44] by the time required for a shear wave to travel from a depth of 30 meters (98.4 ft.) within the site geologic profile to the ground surface. This results in a measure that is not the arithmetic average of the shear wave velocity (Vs) for all layers to a depth of 30 m. As shown in Equation (3-1), the time-averaged Vs30 is calculated as 30 m divided by the sum of the travel times for shear waves to travel through each layer. The travel time for each layer is calculated as the layer thickness (d_i) divided by Vs_i for the respective layer.

   $$Vs30 = (30\text{ m})/\Sigma_i[(d_i/Vs_i)] \qquad \textit{Eq. 3-1}$$

   For example, the Vs30 for a soil profile containing 18 m of soft clay (Vs = 90 m/sec) over 12 m of stiff clay (Vs = 260 m/sec) would be calculated: 30/(18/90 + 12/260) = 122 m/sec.

2. Identify the site Class from Table 3-1 using the Vs30 and the approximate horizontal peak ground acceleration from the Control Point horizontal GMRS. Select the site Class with the Vs30 and horizontal PGA closest to the site-specific values.

3. Select the respective vertical-to-horizontal (V/H) function (column) from Table 3-2 corresponding to the site Class.

4. Use the selected V/H ratio to obtain the vertical GMRS by multiplying the horizontal GMRS value at each frequency by the corresponding V/H value at that frequency.

Table 3-1
Classes of Sites Identified for Characterization

Class	Horizontal PGA	Vs30, mps (ft/sec)
A-Hard	• 0.20g	• 700 (2300)
B-Hard	~ 0.25g	• 1000 (3280)
C-Hard	~ 0.30g	• 1000 (3280)
D-Hard	~ 0.45g	• 1000 (3280)
A-Intermediate	• 0.20g	~ 400 (1310)
A-Soft	• 0.20g	~250 (820)
C-Soft	• 0.30g	~250 (820)

Table 3-2
Mean V/H Ratios by Frequency for Different Site Classes

Freq.	A-Hard	B-Hard	C-Hard	D-Hard	A-Intermediate	A-Soft	C-Soft
100	0.78	0.80	0.81	0.85	0.78	0.86	0.94
90	0.81	0.82	0.84	0.88	0.82	0.92	1.01
80	0.85	0.87	0.88	0.93	0.86	0.99	1.09
70	0.89	0.91	0.93	0.98	0.91	1.08	1.18
60	0.90	0.92	0.94	0.99	0.93	1.13	1.24
50	0.88	0.90	0.92	0.98	0.95	1.15	1.28
45	0.87	0.89	0.91	0.97	0.96	1.17	1.30
40	0.84	0.86	0.87	0.92	0.91	1.10	1.23
35	0.79	0.81	0.82	0.87	0.86	1.01	1.13
30	0.74	0.75	0.77	0.80	0.79	0.92	1.03
25	0.69	0.70	0.71	0.74	0.72	0.81	0.91
20	0.67	0.68	0.70	0.74	0.67	0.70	0.79
15	0.67	0.68	0.70	0.74	0.67	0.67	0.70
10	0.67	0.68	0.70	0.74	0.67	0.67	0.70
0.1	0.67	0.68	0.70	0.74	0.67	0.67	0.70

Note: V/H ratios are constant between 10 Hz and 0.1 Hz.

The resulting factored horizontal GMRS values make up the vertical GMRS. Figure 3-4 shows the resulting vertical GMRS obtained for an example D-hard site.

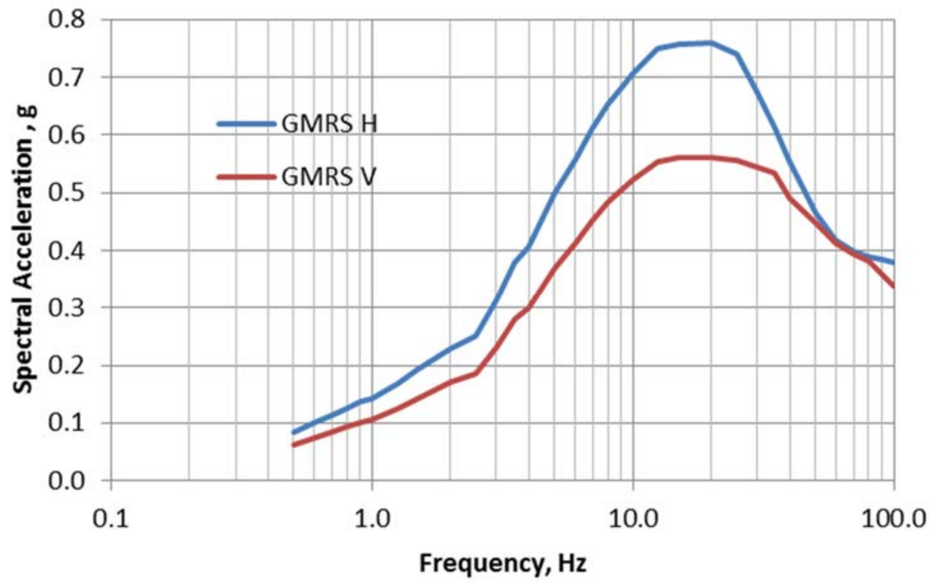

Figure 3-4
Vertical GMRS Compared to the horizontal GMRS of an Example Class D-Hard site (Vs30 > 1000 m/s, PGA (Horizontal) ~0.45g)

3.3 Guidance on GMRS, FIRS, and Control Point

The high frequency confirmation process outlined in this report requires three elements in order to estimate the demand at the component mounting location:

- Review level earthquake
- Structural amplification factor
- In-cabinet amplification factor

The RLE for the purposes of the high frequency confirmation process has been defined as the GMRS. The GMRS is the reference motion level at the Control Point chosen to compare to the site SSE. Plants performing SPRAs would perform detailed calculations to estimate the in-structure building response. However, for the high-frequency confirmation described in Section 4 of this report, the Control Point GMRS is recommended as a representative input to the buildings and amplified to yield in-structure motion, as described in Section 4.3. In some cases, the Control Point is chosen as the free-field surface at the elevation of reactor containment foundation, and the soil profile under the reactor containment is considered in the GMRS determination. However, other buildings on the site can be supported at different elevations and can have different underlying soil profiles. For these buildings, a foundation input response spectrum (FIRS) would normally be defined, which could be different from the GMRS for the site. For sites requiring high-frequency confirmation and that have only the Control Point GMRS defined, the estimation of motion within buildings should consider the possibility that a FIRS for that building can be different from the site GMRS. To aid in that consideration, the following is provided.

The plants, which have screened-in for a high frequency confirmation (box 3f in Figure 3-1), typically have GMRS exceedances in the high frequency portion of the spectrum. These sites are predominantly rock sites. The Control Point GMRS developed for these rock sites are typically appropriate for all rock-founded structures and additional FIRS estimates are not deemed necessary for the high frequency confirmation effort.

For soil sites, or for buildings on shallow soil layers at rock sites, the overall building seismic response can be higher or lower depending on the frequency range of interest and soil-structure interaction (SSI) considerations, such as the presence of embedment. The soil layers typically shift the frequency range of the input toward the lower frequency part of the spectrum. As such, the use of the GMRS as a surrogate site motion may be justified for high frequency confirmation efforts at soil sites.

Section 4: High Frequency Functional Confirmation Guidance

The prior section reviewed the results of the updated GMRS screening of sites and established criteria for determining which sites should perform a confirmation of high-frequency functionality.

This section defines the process for performing a confirmation of high-frequency functionality (box 3f in Figure 3-1). Given that the High Frequency Program testing described in Section 2 did not identify any unique high frequency component sensitivities, the high frequency confirmation identified in the 50.54(f) letter [1] and SPID [3] can be accomplished using a focused set of critical equipment. For the selected set of equipment, the recommended evaluation process uses deterministic HCLPF capacity and Conservative Deterministic Failure Margin (CDFM) demand measures derived from the SMA relay evaluation in EPRI NP-6041 [21]. The GMRS is recommended as the appropriate Review Level Ground Motion (RLGM) for purposes of this CDFM demand characterization.

Guidance is provided for estimating the horizontal and vertical in-structure response in the high frequency range (> 15 Hz) using the GMRS input motion. For seismic evaluation of devices, the clipped ISRS demand is appropriate and is determined using the procedures given in EPRI NP-6041 [21]. In-cabinet amplification factors are also presented in EPRI NP-6041 [21] for horizontal cabinet response, but the vertical amplification is not discussed. A vertical in-cabinet amplification factor (consistent with the CDFM philosophy) is developed herein. Recommendations for determination of HCLPF capacity values from the high-frequency device test capacities are then provided. The seismic margin is provided by the capacity/ demand ratio.

4.1 High Frequency Confirmation Concepts

In 2012, the NRC issued a 50.54(f) letter [1] requesting that each plant provide specific information about the updated seismic hazard for the plant site on an accelerated schedule and proposing a progressive screening/evaluation approach to evaluate the potential risk posed by future seismic events. While the full hazard studies were requested, the measure of the re-evaluated seismic hazard for a given site was provided by a new GMRS, which is developed using the updated UHS [2]. Depending on the comparison between the GMRS and the current

design basis spectrum, the plants were ether screened-out from or required to perform a seismic risk assessment using the updated seismic hazard. This screening process focused on comparing the existing SSE used for plant design to the new GMRS in the 1 to 10 Hz frequency range. However, in all cases, a confirmation was required that SSCs subjected to high-frequency motions exceeding the plant design basis would remain functional. The 50.54(f) letter did not indicate what process constituted a functional confirmation for those plants that were required to evaluate the high frequency ground motions.

Subsequently, EPRI 1025287 (the SPID) [3] was issued to provide screening, prioritization, and implementation details to the U.S. nuclear utility industry to address the seismic portions of the 50.54(f) letter. This report was developed with NRC participation and was subsequently endorsed by the NRC. The SPID [3] maintained, based on prior EPRI studies, that the only plant components that had potential high-frequency sensitivities were control components, such as relays, process switches, and other devices that are subject to intermittent states. The SPID also maintained the requirement that, for plants screening-out of a risk evaluation but with high-frequency ground motion exceedance above 10 Hz, a high frequency confirmation should be performed.

The EPRI High Frequency Program was organized to test a diverse set of bi-state devices to ascertain if any unique high-frequency sensitivity could be identified. The primary result of the High Frequency Program was that, while some components were sensitive to vibration in general, such sensitivity was not increased in the high-frequency region. In fact, the high-frequency test capacities of the devices were greater than the capacity determined in prior low frequency testing. This result indicated that such devices do not have any unique high-frequency vulnerability. Further, the High Frequency Program showed that components such as control switches, transmitters, MCCBs, lockout relays, and potentiometers have table-limiting test capacities and can be screened-out of the high frequency evaluation.

The positive test results from the high frequency testing program allow a focused review of a critical set of equipment to confirm that SSCs that may be affected by high-frequency ground motion will maintain their functions important to safety. The evaluation process employs the same procedures developed for relay (and other devices) evaluation in the IPEEE programs [5, 21]. These relay evaluation procedures have been vetted in past NRC programs, as achieving acceptable confidence (or assurance) that there are no significant control malfunctions caused by seismic ground motions.

The procedures developed for SMA relay evaluation in EPRI NP-6041 [21] use both system consequence screening and deterministic HCLPF capacity and CDFM demand comparisons. These procedures are recommended for the high frequency confirmation using the GMRS as the RLGM. The high frequency confirmation component evaluation follows the steps below.

1. Identify the applicable equipment scope (Section 4.2)
2. Identify seal-in and lockout circuits within the equipment scope (Section 4.2)

3. Identify the contact control devices and contact configurations (normally open, normally closed, energized, de-energized) within the seal-in and lockout circuits
4. Identify the locations (buildings, electrical cabinets) of the contact control devices
5. Estimate the high frequency contact control device mounting point seismic demands using
   - The applicable vertical and horizontal ground motions estimates (Sections 3.2 and 3.3),
   - The applicable in-structure and in-cabinet amplification factors (Sections 4.3 and 4.4), and
   - The CDFM calculation process (Section 4.5.1)
6. Determine the component high frequency capacity using EPRI high frequency test results (Section 2) or estimates based on other available component seismic test data (Section 4.5.2)
7. Compare the component high frequency mounting point seismic demand to the component high frequency seismic capacity (Section 4.5.2)

Within the steps above, it is acceptable to group components to provide a more efficient evaluation process. For example, components on a particular floor could be evaluated by using the in-structure and bounding in-cabinet amplification factors and establishing that as a component screening level for that floor.

Figure 4-1 shows the approach for performing the high frequency confirmation. The figure also identifies the applicable sections of this report where guidance is provided for each step.

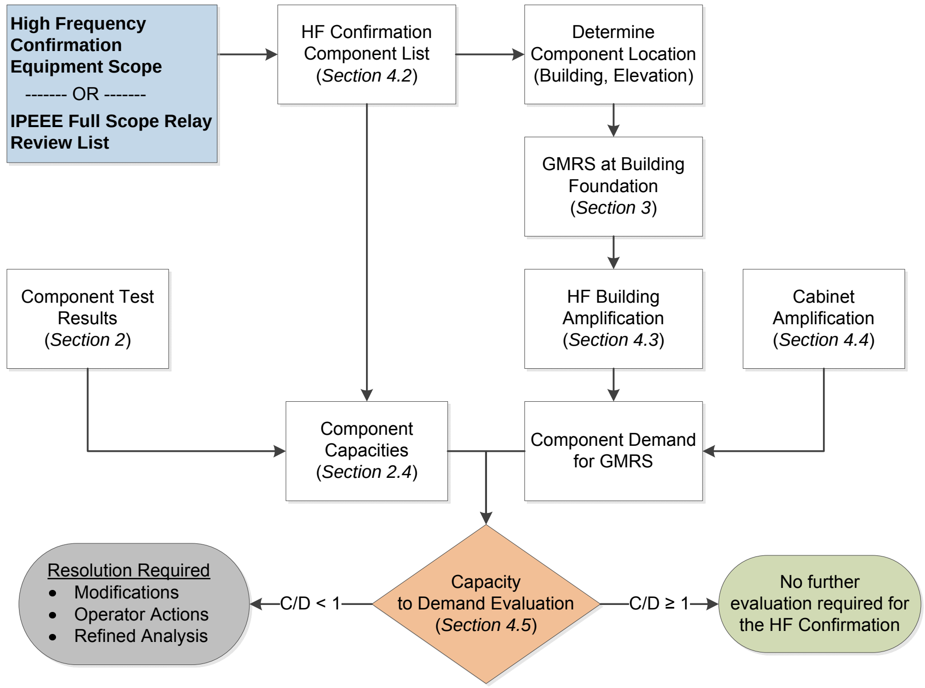

Figure 4-1
High Frequency Confirmation Approach for Control Components Subject to Intermittent States

4.2 High Frequency Confirmation Equipment Selection

In defining the scope of equipment for high frequency confirmation, an optimized evaluation process is applied that focuses on achieving a safe and stable plant state following a seismic event. The objective of this approach is to provide reasonable assurance that key plant safety functions that are critical immediately following a trip/scram are preserved and thereby achieve this stable condition. Additional actions then can be implemented to restore plant equipment functionality, as necessary, to ultimately bring the plant to a cold shutdown state. Based on this concept, the critical functions to be included in the High Frequency Confirmation are:

- Reactor Trip/Scram
- RCS/Reactor Vessel Inventory Control
- RCS/Reactor Vessel Pressure Control
- Core Cooling
- AC/DC Power Support Systems

In all cases, the focus of the high frequency evaluation would be to determine whether the consequences could disable any of the critical functions listed above. If the functions are not adversely impacted then it can be reasonably concluded that the plant would be able to achieve a stable condition and maintain that condition to allow various recovery actions following the seismic event to be performed, which may include resetting devices and/or use of alternate equipment and/or equipment alignments.

4.2.1 High Frequency Component Review Approach

The fundamental objective of the high frequency confirmation review is to determine whether the occurrence of a seismic event could cause credited equipment to fail to respond/perform as necessary. The seismic event could cause normally open contacts to intermittently close or normally closed contacts to intermittently open. The intermittent change in state of electrical contacts can cause operation of plant equipment. This seismic-induced equipment actuation could be 1) inconsequential, 2) could require operator intervention to realign (restore) equipment status, or 3) could render the equipment or related system function unavailable and non-recoverable. The objective of the component review is to identify cases involving the latter two outcomes.

Within the applicable functions, the components that would need a High Frequency Confirmation are contact control devices subject to intermittent states in seal-in or lockout circuits. As noted earlier in Section 4.1, the high frequency test program showed that control switches, transmitters, MCCBs, lockout relays, and potentiometers have table-limiting test capacities and can be screened-out of the high frequency evaluation as no plant demands are expected to exceed these capacities.

The objective of the review is to determine if seismic induced high frequency relay chatter would prevent the completion of the following key functions.

- Reactor Trip/Scram
- RCS/Reactor Vessel Inventory Control
- RCS/Reactor Vessel Pressure Control
- Core Cooling
- AC/DC Power Support Systems

Reactor Trip/Scram – the design requirements for the reactor trip/scram function are such that seal-in or lockout features that would prevent or block it do not exist. There are also multiple signal paths and controls available to initiate this function. The inherent design of this function is such that relay chatter consequences would not prevent or otherwise preclude the tripping of the reactor following a seismic event. These design attributes obviate the need for any specific review or examination to identify high frequency component chatter concerns for this function.

RCS/Reactor Vessel Inventory Control – the scope of treatment for this function is limited to actuation of those valves that effectively can create loss of coolant type events. These would include the PORVs for PWR plants and the SRVs for BWR plants. The focus of the review is to determine if the circuit design for these types of valves are such that seal-in or latching circuits exists that would maintain the valves in an undesired open state following the seismic event. As an example, if non-throttling motor operated valves are applied to provide a flow isolation function, the associated valve control circuits typically include a seal-in feature such that once energized would remain energized until the valve stroke is completed. It is anticipated that a limited number of components (valves) will require plant-specific circuit review to confirm that no seal-in or latching circuits exist.

RCS/Reactor Vessel Pressure Control – the required post event pressure control is typically provided by passive devices and consequently, no specific high frequency component chatter review is required for this function.

Core Cooling – the initial need for decay heat removal and the related scope of consideration varies based on the plant's NSSS system. For PWR plants, it is expected that the availability of an AC-independent (steam or diesel driven) alternate/emergency feedwater pump to supply water to at least one steam generator will be sufficient to satisfy the immediate decay heat removal needs. The relay chatter impacts that could affect this function would be those that would cause the flow control valves to close and remain closed. For example, some PWR plants have circuitry to detect and isolate flow to a faulted steam generator. If such circuitry exists and can isolate flow to all steam generators, then some level of detailed review would be required to assess the likelihood of such an occurrence. For BWR plants, the decay heat removal mechanism involves the transfer of mass and energy from the reactor vessel to the suppression pool. This requires the replacement of that mass to the reactor vessel via some core cooling system, e.g., reactor core isolation cooling (RCIC), high pressure coolant injection (HPCI), high pressure core spray (HPCS), or isolation condenser (IC). The cooling of the suppression pool, while ultimately required, is not an immediate need, so assessment of component chatter effects on systems supporting suppression pool cooling or other core cooling systems is not required. A plant-specific review should be performed to identify seal-in and lockout circuits that are essential for a single AC-independent train to provide decay heat removal.

AC/DC Power Support Systems –The ability to achieve and maintain a stable condition requires the availability of electrical supplies – typically DC. The DC system relies on battery chargers to maintain system functionality which relies on the availability of AC power. In the context of maintaining AC power, the lockout relays that are expected to exist for the emergency diesel generator (EDG) and the safety related switchgears are of particular concern. The resetting of a lockout device is expected to require some level of electrical system diagnostic testing to confirm that an upset state (fault) on the system does not exist. The completion of this diagnostic testing could significantly delay the restoration of power to the plant electrical distribution system. While the lockout

relay itself should be expected to be robust with respect to high frequency and not susceptible to relay chatter, the contacts that are used to energize it could be. The application of lockout relays on the key plant medium voltage switchgear buses and the EDG should be the focus of a plant-specific review of relay chatter consequences. The scope of evaluation should also include key EDG support systems such as cooling water, ventilation (including consideration of combustion air intake), and fuel supply to determine if seal-in or lockout circuits that could disable these functions are present.

Table 4-1 provides a summary of the types of components used in each function in the high frequency confirmation scope. An example characterization of the seal-in and lockout impacts to be assessed is included in Appendix D.

Table 4-1
High Frequency Confirmation Equipment Scope Summary

Function	Component Scope
Reactor Trip/Scram	Design requirements preclude the application of seal-in or lockout circuits that prevent reactor trip/SCRAM functions. No review necessary.
RCS/Reactor Vessel Inventory Control	Contact control devices in seal-in and lockout circuits that would create LOCAs • PWR – PORV function • BWR – SRV function • PWR & BWR – valves that could inadvertently lead to LOCA
RCS/Reactor Vessel Pressure Control	These are typically passive control systems. No review necessary.
Core Cooling	Contact control devices in seal-in and lockout circuits that would prevent at least a single train of non-AC power driven decay heat removal from functioning (i.e., show at least one train will function). • PWR – Steam or diesel driven feedwater function, including flow to the Steam Generator • BWR – RCIC, HPIC, HPCS, or IC function
AC/DC Power Support Systems	Contact control devices in seal-in and lockout circuits that prevent the availability of DC and AC power sources. • DC – Battery charging and inverter functions • AC – EDG start and operate functions, including necessary EDG support systems such as fuel supply, combustible air, ventilation air, and cooling water functions

4.2.2 Alternate High Frequency Component Review Approach for Plants Performing an IPEEE Relay Review

Alternatively, if a plant has performed a full scope relay evaluation for IPEEE (or A-46) or performs a relay evaluation to substantiate IPEEE adequacy for screening (GMRS/IHS comparison), that scope of relays could be used for confirming the functions required following a beyond design basis earthquake. In general, this list is expected to be larger than the scope identified in Section 4.2.1. However, evaluating this scope of equipment would also provide an acceptable confirmation that SSCs that may be affected by high-frequency ground motion will maintain their functions important to safety.

4.3 Estimating High Frequency In-Structure Response Spectra

As described in Section 4.1, the high frequency confirmation process consists of developing deterministic HCLPF capacity and CDFM demand for the selected set of equipment that ultimately need to be evaluated for functional confirmation (per Section 4.2). The GMRS is recommended as the appropriate RLGM for purposes of this CDFM demand characterization. However, the plants that screened-out of the SPRA but require high frequency confirmation do not, in general, have ISRS consistent with the GMRS. Development of new seismic response consistent with the new GMRS can be a very large effort, and this effort is not judged cost-beneficial given the relatively high capacities shown for the devices tested to the high frequency motions (Section 2). As such, guidance is provided in this section for estimating the horizontal and vertical ISRS in the high frequency (≥ 15 Hz) part of the spectrum using the GMRS (or FIRS) input motion alone. These high-frequency ISRS are estimated using structure amplification factors derived from the review of an available set of recent response analyses of nuclear structures that have been evaluated for high frequency input motions. Appendix B contains a more detailed description of the data assessment for structural response that was the basis for these recommended amplification factors.

4.3.1 Seismic Response Data Reviewed for High Frequency Amplification Study

The seismic response analyses that were reviewed as part of this effort to define the high frequency structural response of nuclear structures included:

- Westinghouse AP 1000 analyses to support the Lee Site new plant licensing application
  - Nuclear Island Structure
- Pressurized Water Reactor (PWR) Plant "A" seismic response analyses to support a recent SPRA
  - Auxiliary Building 1
  - Auxiliary Building 2

- Boiling Water Reactor (BWR) Plant "B" seismic response analyses to support a recent SPRA
  - Auxiliary Building
  - Control Building

The two studies (labeled PWR A and BWR B) have not been publically documented but were made available to EPRI for purposes of this study to estimate high-frequency amplification factors.

Each of these three sites are characterized as being "firm rock" sites (see definitions in Appendix A), with site Vs30 values greater than or equal to 490 mps (1,608 ft/sec). As such, their corresponding seismic hazards are appropriately rich in the desired high frequency part of the response spectra, as shown in the example GMRS in Figure 4-2 (all three site GMRS motions are presented in Appendix B). The amplification values recommended in this document were derived for firm rock sites and would be appropriate for sites characterized as A-Hard, B-Hard, C-Hard and D-Hard in Appendix A. Sites with lower shear wave velocities may also be able to use these factors but should justify their use.

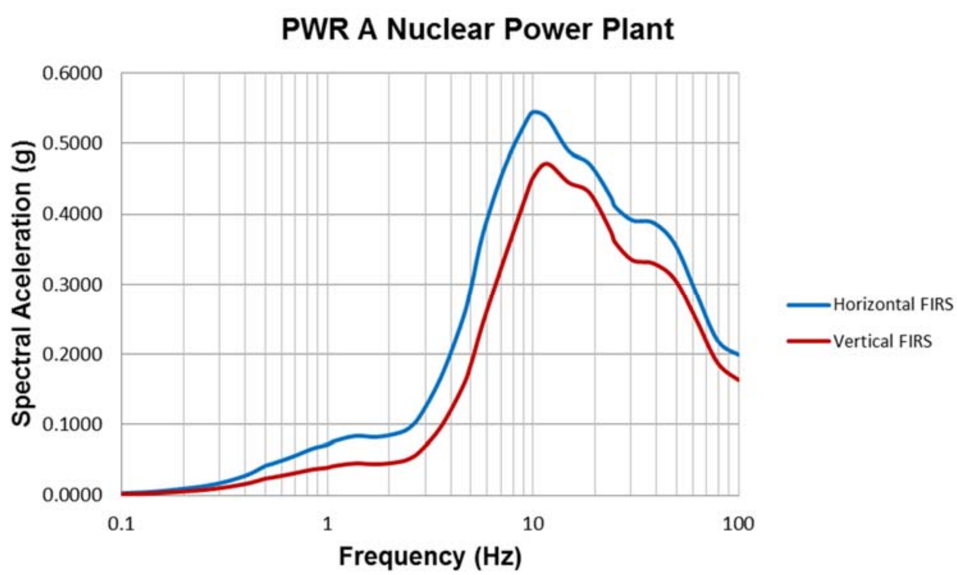

Figure 4-2
Horizontal and Vertical GMRS for PWR Plant A

The structures considered in these analyses were reinforced concrete shear wall structures which are judged representative of the structures where the components are expected to exist (e.g., auxiliary buildings, control buildings and the overall nuclear island structures for the new plant designs). As such, these structure responses to high frequency input represent a reasonable set of data from which to determine the HCLPF level amplification factors for use in the high frequency confirmation reviews. Appendix B contains further characterization of these structures and their applicability to use for nuclear plant structures which typically will house relays.

4.3.2 Development of HCLPF Amplification Scale Factors

As stated previously, the high frequency confirmation process being proposed to support the resolution of that portion of the NTTF 2.1 seismic process consists of demonstrating that the device HCLPF exceeds the GMRS demand in the high-frequency part of the spectrum for each device being reviewed. As such, the in-structure response due to the high-frequency input must be consistent with the requirements associated with the seismic response development for the HCLPF calculation (EPRI NP-6041 [21] contains the description of the specific seismic response criteria). Adjustments to some of the ISRS data from the five structures were made to develop HCLPF responses for use in this study.

- Structural damping levels aligned with the specific response levels expected for HCLPF calculations. In cases where alternate damping levels were used in the analyses, responses were adjusted to align with the appropriate HCLPF damping.
- The ISRS are clipped to obtain damage-equivalent broad-banded spectra. CDFM clipping factors are computed using the clipping procedure detailed in Appendix Q to EPRI NP-6041 [21].
- The ISRS data from two of the sites did not incorporate ground motion incoherency (GMI) effects into the seismic response. GMI has proven to change the response, particularly in the high-frequency portion of the spectrum. A study of representative GMI effects in the vertical direction (vertical was determined to be the critical direction for this high frequency confirmation) was conducted, and a conservative factor of 0.8 was used to adjust for GMI effects in the greater than 15 Hz part of the vertical response spectrum.

The assessment of the data from these three sites is contained in Appendix B.

The high frequency amplification factor was developed for each response data point (nodes in the finite element model where seismic responses were reviewed) from the five structures subjected to the high-frequency input motions. A high frequency seismic amplification function was developed for each of these data points based on the following:

- The numerator was defined as the peak (clipped) 5% damped response in the ≥ 15 Hz part of the ISRS.
- The denominator was defined as the peak 5% damped response in the ≥ 15 Hz part of the GMRS (the GMRS was used as input for each of the five structures reviewed) used in the seismic response analysis.

The resulting horizontal and vertical response data were plotted as a function of the height above the foundation in order to assess the change with building elevation. A regression analysis of the data was then performed to calculate the 84% non-exceedance probability (NEP) in conformance with the criteria for generating a HCLFP response. The resulting 84% NEP high frequency amplification factors are:

- Horizontal Response Structural Amplification Factor, AF_{SH} (Figure 4.3) – Bilinear curve that ranges from an amplification factor of 1.2 at the building foundation level to 2.1 at 40 ft above the foundation. The response data did not support a clear change in that amplification beyond the 40 ft level, and the 2.1 amplification factor represents an approximate 84% NEP for all of the data ≥ 40 ft above the foundation.
- Vertical Response Amplification Factor, AF_{SV} (Figure 4.4) – Linear amplification function that ranges from 1.0 at the foundation up to an amplification of 2.7 at 100 ft above grade.

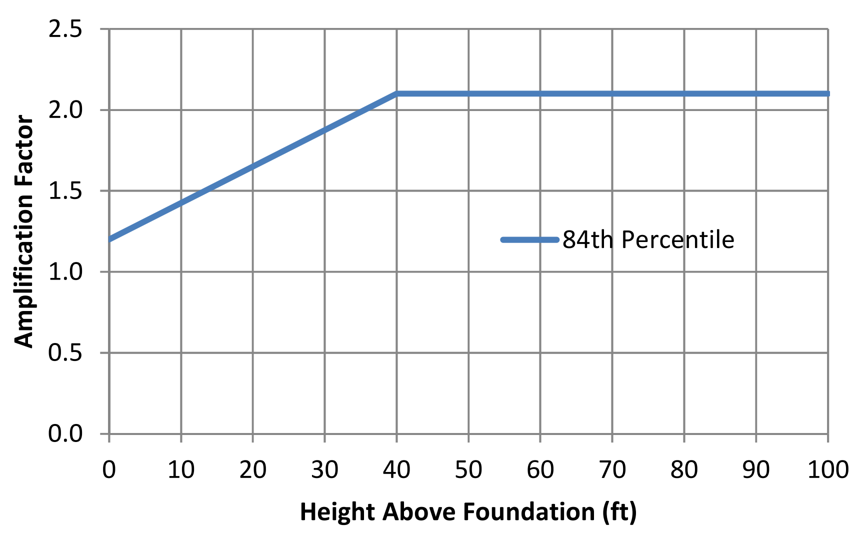

Figure 4-3
84% NEP Horizontal Amplification (AF_{SH}) for Nuclear Structures in High-Frequency Part of Response Spectrum: Bilinear Recommendation for Use in High Frequency Confirmation

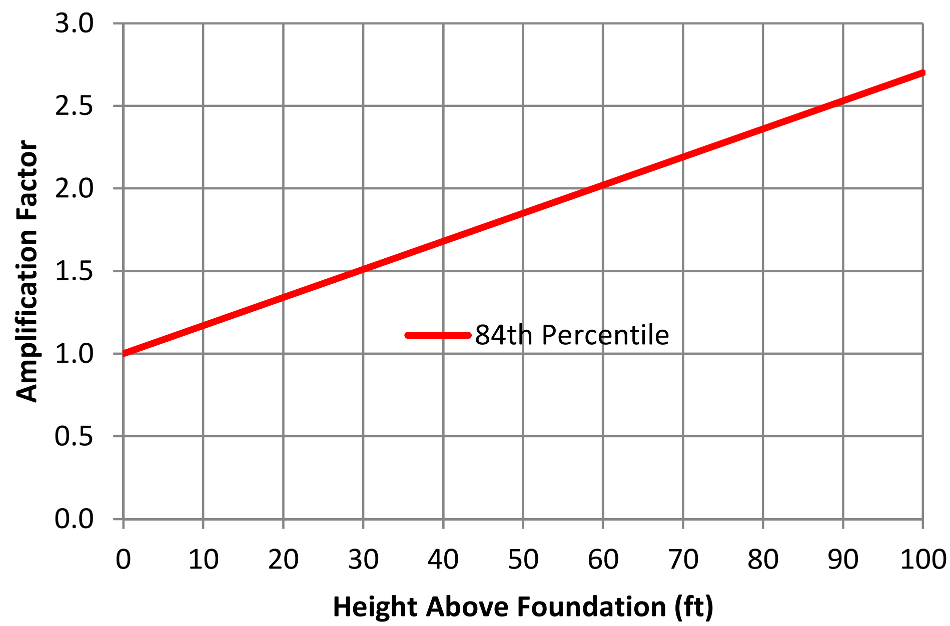

Figure 4-4
84% NEP Vertical Amplification (AF_{sv}) for Nuclear Structures in High-Frequency Part of the Response Spectrum

The clipped ISRS values at the location (elevation) of the cabinet housing a control component identified for high-frequency evaluation would then be estimated by factoring the peak spectral acceleration (>15 Hz) of the GMRS, SA_{GMRS}, by the respective building amplification factor AF_S, or

$$SA_{cH} = AF_{SH} (SA_{GMRS}) \quad \textit{Eq. 4-1a}$$

and

$$SA_{cV} = AF_{SV} (SA_{VGMRS}) \quad \textit{Eq. 4-1b}$$

where $SA_{VGMRS} = (SA_{GMRS})$(V/H from table 3-2).

4.4 Estimating High Frequency In-Cabinet Response Spectra

For the high frequency confirmation process, the CDFM procedures developed in EPRI NP-6041 [21] are the recommended approaches. In general, a component mounted within a floor or wall anchored cabinet is subjected to the amplified cabinet filtered motion caused by the motion of the structure at the cabinet anchor points. The in-structure floor motion is, in turn, the structure-filtered motion caused by the wide-band ground motion. At elevations within the structure, the motion has the appearance of a sinusoid with random amplitude centered at a building frequency. The resulting response spectrum of this in-structure motion is a narrow-band frequency function. Appendix Q to EPRI NP-6041 [21] outlines the development of a procedure, denoted as "clipping," for converting narrow-band structure motion to an effective wide-

band motion. The previous section considered the development of effective building clipped motion levels that are the result of a clipping factor multiplied times the peak value of the ISRS. The clipping procedure is further discussed in Appendix C to this report since it is also the basis for the development of cabinet amplification factors.

The determination of a component mounting point demand is, in general, a two-stage process. First, the clipped floor response is as described in the previous section. Then the effective cabinet motion is determined by a CDFM cabinet amplification factor, AF_c, which is associated with a given type of cabinet construction. These effective cabinet amplification factors were developed assuming that the in-structure motion was wide band; thus, they are meant to be factored times the clipped narrow-band in-structure spectra to obtain an overall effective wide-band input level for the cabinet mounted component. These amplification factors are effectively clipped values of maximum cabinet transmissibility functions. The following recommended CDFM AF_c values are provided in Appendix Q to EPRI NP-6041 [21] for three general cabinet types identified in EPRI NP-7148 [7] assuming 5% in-cabinet response spectrum damping:

Motor Control Centers	AF_c = 3.6, horizontal motion only	*Eq. 4-2a*
Switchgear (flexible panels)	AF_c = 7.2, horizontal motion only	*Eq. 4-2b*
Control Cabinets (e.g. Control Room electrical panels and benchboards)	AF_c = 4.5, horizontal motion only	*Eq. 4-2c*

EPRI NP-7148 [7] classified the cabinet types as 1) high amplification structures such as switchgear panels and other similar large flexible panels, 2) medium amplification structures such as control panels and control room benchboard panels, and 3) low amplification structures such as motor control centers. The high- and the low-amplification enclosures have easily recognizable configurations while the medium amplification enclosures represent a broad range of control cabinet configurations. EPRI NP-7148, Appendix I [7], identifies the recognizable characteristics of medium amplification cabinets and indicates certain configurations for which the amplification factors are not applicable.

Vertical cabinet amplification factors were not considered in EPRI NP-6041 [21]. A vertical amplification factor for cabinets is developed in Appendix C, as a generic CDFM value applicable to all cabinets. The recommended CDFM value is:

All Cabinets $AF_c = 4.7$, vertical motion only *Eq. 4-3*

These AF_c values are valid for both low- and high-frequency ranges since they are fundamentally associated with the statistics of the peak cabinet transmissibility values and with the application of clipping to cabinet transmissibility functions. The above factors were developed for base-anchored, free-standing electrical enclosures. Amplification factors for wall-mounted electrical enclosures or cabinets with both base and top anchorage will, in general, have lower amplification factors. In these cases, the analyst will need to separately justify the use of lower factors.

For the functional confirmation case, ISRS for the GMRS input motion are not available. Based on the review of new GMRS response analyses of nuclear-type structures performed for plants conducting SPRAs, an estimation procedure for clipped floor response spectra was developed in Appendix B to this report (summarized in Section 4.3). This procedure focused on the high-frequency response of structures in the greater than 15 Hz range. The clipped spectral levels were correlated with building height for both the horizontal and vertical response directions. Thus, given the location of a cabinet within a structure, an estimate of the clipped horizontal floor demand, SA_{cH} (maximum of each principal horizontal direction), and the clipped vertical floor demand, SA_{cV}, can be obtained for the building location of the cabinet for response spectrum frequencies greater than 15 Hz. In the horizontal direction, cabinets can have natural frequencies in either the low- or high-frequency range, depending on the support configurations (base-mounted cantilever, base- and top-anchored, and wall-mounted) and thus can have mounting point response in either the low- or high-frequency range. In the vertical direction, cabinet natural frequencies are dominantly within the high-frequency range. For example, a base-mounted control cabinet will have horizontal frequencies in the range of 8 to 15 Hz (11 Hz is common) with a vertical frequency greater than 15 Hz. Base-mounted control cabinets with both base and top wall anchorage will likely have horizontal and vertical frequencies greater than 15 Hz. Wall-mounted control cabinets or wall-mounted components will likely have horizontal and vertical frequencies that exceed 20 Hz. For the high-frequency confirmation task, it will be assumed that the mounted components of all cabinets with frequencies less than 15 Hz have been previously evaluated (SSE or IHS) for peak spectral demand values in the less than 15 Hz range of floor motion.

Appendix Q to EPRI NP-6041 [21] denotes the effective wide-band component mounting point seismic demand as the product of the cabinet amplification factor and the clipped in-structure spectrum. The maximum product of the clipped in-structure demand and the applicable cabinet amplification factor within the 15 to 40 Hz frequency range is used as the cabinet demand in each direction. This may be represented by the pair of demand values:

$$AF_{cH}\ SA_{cH},\ AF_{cV}\ SA_{cV}$$

The product of the effective cabinet amplification factor and the clipped in-structure spectrum is not to be interpreted as reduced values of component mounting point demand, but instead is to be considered as a conversion of narrow-band response to effective wide-band response for cabinet-mounted components placed at the location with the highest amplification. The clipping procedure was developed to reflect the level of conservatism embedded in the CDFM philosophy. The factors are meant to reflect the worst-case amplification for a cabinet mounted component.

4.5 High Frequency Confirmation Capacity Evaluation

The high frequency confirmation capacity evaluation consists of comparing the CDFM mounting point demand with the deterministic HCLPF component capacity over the frequency range of interest. As described in the SPID [3], for the High Frequency Confirmation process, the frequency range of interest is 20 to 40 Hz. This reflects the frequency range beyond which typical component qualification is performed using IEEE C37.98 [13] (4 to 16 Hz) and it corresponds to the frequency range established during the Phase 1 testing to best determine high frequency component sensitivity (Section 2.1.4).

The evaluation process is described below.

4.5.1 CDFM Mounting Point Demand

The effective wide-band component mounting point seismic demand is the maximum of the pair of the demand values computed as the product of the cabinet amplification factor and the clipped in-structure spectrum in each respective direction:

$$ICRS_c = \max\{AF_{cH}\ SA_{cH},\ AF_{cV}\ SA_{cV}\} \qquad \textit{Eq. 4-4}$$

The maximum of the horizontal and vertical mounting point demand accelerations are used as the component demand since the high frequency component capacities described in Section 2 were established using approximately equal test motion levels in all three directions. A geometric average of the three orthogonal test spectral acceleration levels was used to characterize the effective spectral test capacity. The maximum mounting point demand component is then compared to the effective spectral test capacity.

4.5.2 HCLPF Component Capacity

From EPRI NP-6041 [21], the effective wide-band component capacity is given by the effective spectral test capacity, SA_T, divided by the CDFM knockdown factor, F_K, and multiplied by single-axis correction factor, F_{MS}, if appropriate:

$$TRS = (SA_T/F_K)\,F_{MS} \qquad \textit{Eq. 4-5}$$

In the High Frequency Test Program, tests were generally conducted using increasing steps of spectral acceleration of 1.25g until chatter occurred. The component capacity SA* was defined as the highest test level without chatter or malfunction. The best estimate of the actual threshold of component malfunction SA_T is then determined by the defined capacity SA* plus ½ of the test level increment ($SA_T = SA^* + 1.25g/2$).

If a particular component was not tested in the High Frequency Test Program, a high frequency capacity can be estimated from other broad banded low frequency capacity data such as SQURTS testing [15] or GERS [14]. Since the High Frequency Program showed that the high-frequency test capacity was greater than the low-frequency test capacity, a conservative estimate of the 20 to 40 Hz capacity can be made by extending the low frequency capacity into the high-frequency range to a roll off frequency of about 40 Hz. Figure 4-5 shows the test capacity spectra of a tested component for both low- and high-frequency ranges overlaid on the same plot. The extension of the low-frequency capacity into the high-frequency range is also shown. If the HF Capacity was not available for this component, a SA_T value equal to the GERS spectral acceleration from 4 to 16 Hz could be used.

In general, the CDFM knockdown factor (F_k) depends on the source of the test value chosen to represent the test capacity. There are two possible results from a component test: (1) contact chatter or malfunction occurs at a given test motion level, or (2) the component sustains the maximum test motion level or capacity of the test table. EPRI NP-6041 [21] provides F_k factors for these two situations. For the estimate of chatter threshold used for the High Frequency Test Program results, an additional case is added to the cases identified in EPRI NP-6041 [21]. For the estimate of $SA_T = (SA^* + 0.625g)$, the CDFM F_k factor is set equal to 1.56; for the function confirmed case (table capacity without malfunction), the HCLPF or CDFM value is $F_k = 1/0.9 = 1.11$. The various conditions affecting the selection of this factor are given in Table 4-2.

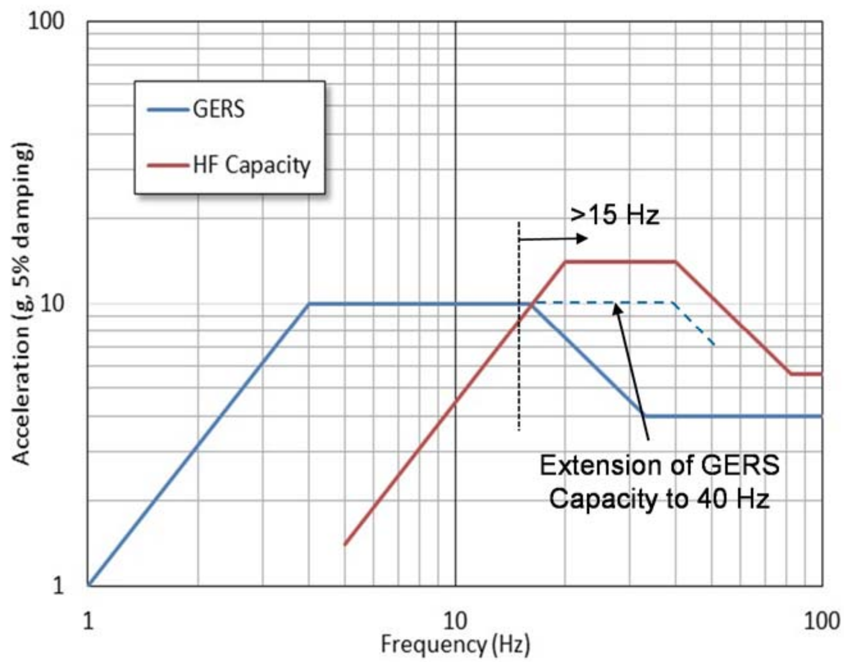

Figure 4-5
Example Extended Low-Frequency Test Capacity Profiles

Table 4-2
CDFM Knockdown Factor for Test Capacity Values

Test Source		F_k
Relay GERS [14] (SQURTS Test [15])	Lowest level without chatter	1.5
	No chatter, Test table capacity	1.2
High Frequency Test Program [12]	Fragility threshold $SA_T = (SA^* + 0.625g)$	1.56
	Function Confirmed, Test table capacity	1.11
Qualification Test (IEEE 344 [25])	No chatter	1.2

The F_{MS} factor from EPRI NP-6041 [21] is often misunderstood and is meant to be used at the discretion of the analyst, to handle situations where the cabinet configuration is such that the cabinet response has a dominant single-axis response motion. As an example, a long lineup of cabinets will often have dominant front-to-back response since the side-to-side motion is suppressed. In the past, the vertical motion was also considered to be negligible. For the case of both base- and top-anchored cabinets or wall-mounted cabinets/components in the high-frequency range, vertical and horizontal high frequency motion will always be present; thus, it is recommended that the F_{MS} factor be taken as

F_{MS} = 1.0 in these cases. For base-mounted cantilever cabinets (without top bracing), the horizontal low-frequency motion is well separated from the vertical high-frequency motion, and the two motions may be considered as independent from each other. If the analyst judges that the horizontal and vertical in-cabinet motions are well separated, then an F_{MS} value of 1.2 is recommended.

The seismic margin is provided by the capacity/demand ratio:

$$C/D = TRS/ICRS_c \quad \textit{Eq. 4-6}$$

4.5.3 Example HF Confirmation Evaluation

This section presents an example high frequency confirmation evaluation. The results of the horizontal and vertical evaluations are shown graphically in Figures 4-6 and 4-7.

This example considers a Square D 8501 industrial control relay in a floor mounted Control Room benchboard mounted 60 ft up from the foundation in a control building.

The horizontal GMRS is shown in Figure 4-6 and the Vs30 and PGA values from the Seismic Hazard and GMRS report are 3200 ft/sec (975 m/sec) and 0.27g. The maximum horizontal spectral acceleration in the 15-40 Hz range is 0.51g. From Table 3-1, the site is close to the B-Hard and C-Hard classes so the C-Hard V/H ratios are used from Table 3-2. The maximum product of horizontal spectral acceleration and V/H ratio (maximum vertical spectral acceleration) in the 15-40 Hz range is 0.41g. From Figures 4-3 and 4-4 the horizontal in-structure amplification factor AF_{SH} is 2.1 and the vertical in-structure amplification factor AF_{SV} is 2.0.

The Control Room benchboard amplification factors AF_c are 4.5 in the horizontal direction (Equation 4-2c) and 4.7 vertical (Equation 4-3). Control Room benchboards typically have horizontal natural frequencies in the lower frequency range so the horizontal and vertical responses are considered to be reasonably well separated (F_{MS} = 1.2).

The Square D 8501 industrial control relay was included in the High Frequency Test Program and it achieved a high frequency test capacity of 11.9g (test capacity from Figure 2-14 and Reference [10]). Since the component test capacity is from the High Frequency Program and the component capacity is defined as a fragility threshold, SA_T = 11.9g + 0.625g = 12.525g and F_k = 1.56.

The horizontal and vertical High Frequency Confirmation values are shown in Tables 4-3 and 4-4.

Table 4-3
Horizontal HF Confirmation Example

Variable	Value	Reference
SA_{GMRS} (peak 15-40 Hz)	0.51g	Site GMRS report
AF_{SH}	2.1	Figure 4-3
SA_{cH}	1.08g	AF_{SH} (SA_{GMRS})
AF_C	4.5	Equation 4-2c
$ICRS_c$	4.86	SA_{cH} (AF_C)
SA*	11.9g	Figure 2-14 and Reference [10]
SA_T	12.53g	Section 4.5.3
F_k	1.56	Table 4-2
F_{MS}	1.2	Section 4.5.3
TRS	9.63g	$(SA_T/F_k)(F_{MS})$
$TRS/ICRS_c$	1.9	

Table 4-4
Vertical HF Confirmation Example

Variable	Value	Reference
SA_{GMRS} (peak 15-40 Hz)	0.51g	Site GMRS report
Horizontal PGA	0.27g	Site GMRS report
Vs30	975 mps	Site GMRS report
Site Class	C-Hard	Table 3-1
V/H (15 – 40 Hz)	0.7 – 0.91	Table 3.2
SA_{VGMRS} (15 – 40 Hz)	0.41	$\max[(SA_{GMRS})(V/H)]$
AF_{SV}	2.0	Figure 4-4
SA_{cV}	0.82	AF_{SV} (SA_{VGMRS})
AF_C	4.7	Equation 4-3
$ICRS_c$	3.83	SA_{cV} (AF_C)
SA*	11.9g	Figure 2-14 and Reference [10]
SA_T	12.53g	Section 4.5.3
F_k	1.56	Table 4-2
F_{MS}	1.2	Section 4.5.3
TRS	9.63g	$(SA_T/F_k)(F_{MS})$
$TRS/ICRS_c$	2.5	

The two examples are shown graphically in Figures 4.6 and 4.7. Note that, in this example, the horizontal direction has the greater demand and thus governs with the lower margin.

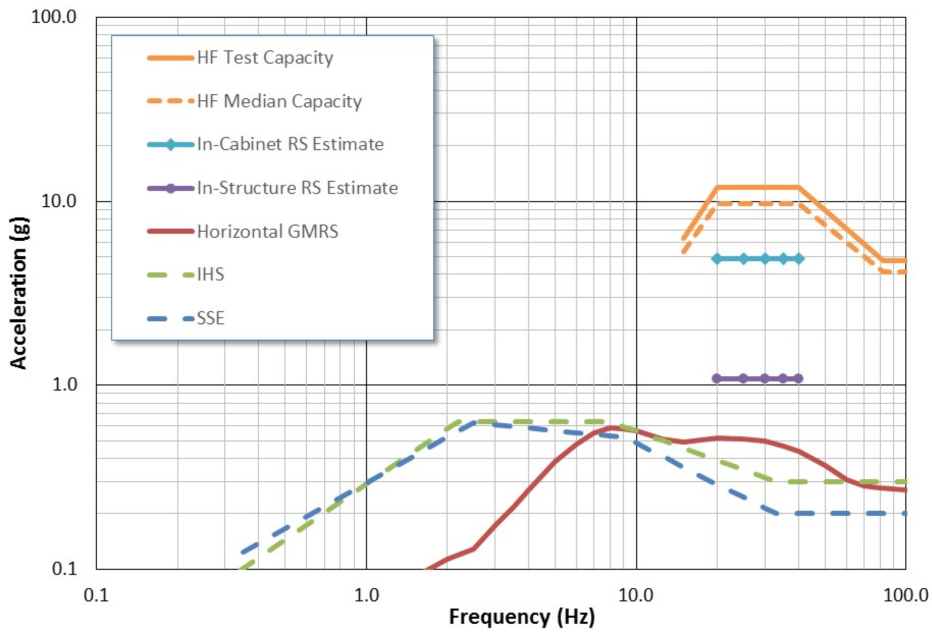

Figure 4-6
Horizontal High Frequency Confirmation Example

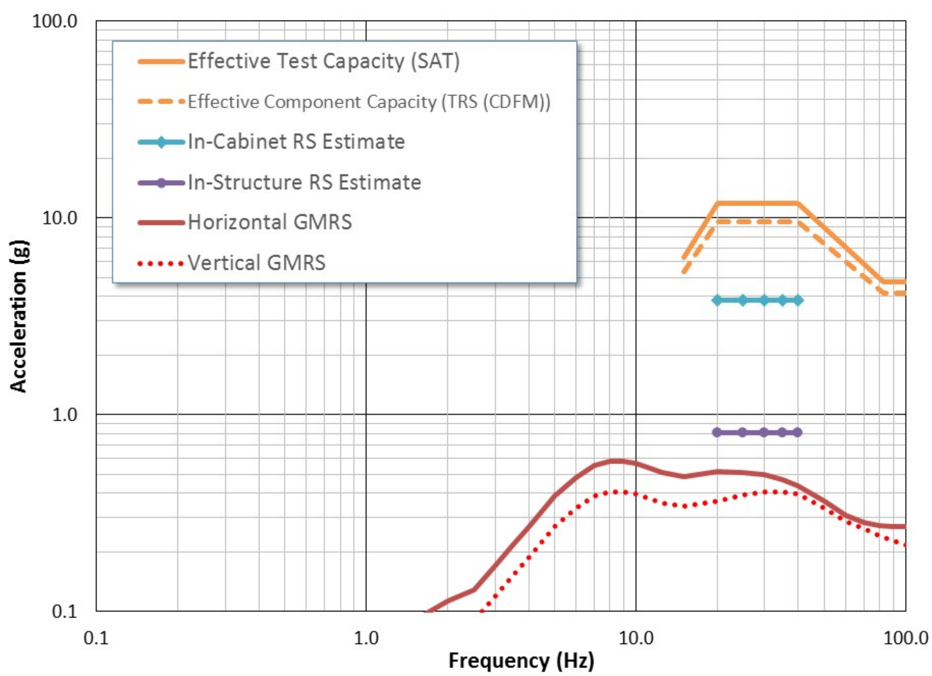

Figure 4-7
Vertical High Frequency Confirmation Example

4.6 High Frequency Confirmation Resolution Options

A number of options are available to resolve cases where the component HCLPF capacity is not greater than the CDFM mounting point demand or if a HCLPF value cannot be estimated. Those options generally fall into four options; additional component testing, refined mounting point seismic demand estimates, operator actions, and plant modifications. Additional considerations for the options are provided below. Other resolution methods may be used where technically justified.

4.6.1 Additional Component Testing

Component shake table testing can be a valuable tool in resolving specific cases where the HCLPF capacity is not greater than the CDFM mounting point demand. If component specific high frequency capacity data is not available, and if extending the 4-to-16 Hz capacity data as shown in Figure 4-5 is not adequate, then additional component specific high frequency testing would be necessary to provide the component capacity.

In some cases, there may be a significant difference between the mounting point demands in the three orthogonal directions. In these cases, it may be helpful to retest a component to account for those directional demand differences and show that the component can properly function with the location specific seismic demands.

In other cases, it may be possible to show that the downstream component requires more than 2 ms of contact chatter to malfunction. One way to treat this in a seismic test is to wire the downstream component to the primary component during the seismic test to demonstrate that chatter in the primary component does not cause the downstream component to malfunction.

4.6.2 Refined Mounting Point Seismic Demand Estimates

The criteria specified in Sections 4.3 and 4.4 provide generic estimates of in-structure and in-cabinet amplification factors. More detailed site specific and component location specific seismic demand estimates may provide more realistic mounting point seismic demands. These more detailed estimates may use previous analyses or test data to support the more refined seismic demands.

4.6.3 Operator Actions

Other relay chatter effects may be resolved with Operator Actions. Examples of this resolution strategy include resetting lockout or seal-in relays that lead to undesired plant conditions. Credited operator actions should be addressed in plant procedures. Care should be exercised to avoid overloading the Operators by crediting too many Operator Actions.

4.6.4 Plant Modifications

There are a number of plant modification options that can be used to resolve cases where the component capacity is less than the mounting point demand. For example, sensitive components with moderate or low seismic capacities can be replaced with comparable components with higher seismic capacities. Alternatively, components can be moved to a location where the mounting point seismic demand is less than the component capacity.

Another acceptable option would be to implement modifications to the circuit such that the seal-in or lockout chatter does not cause misoperation. For example, a time delay relay could be added down-stream of the chatter sensitive relay to filter out the contact chatter.

4.7 High Frequency Confirmation Report Content

Each plant screening in to perform High Frequency Confirmation using the criteria in the SPID [3] should submit a report to the NRC describing their evaluation and results.

For plants using the Low Spectral Acceleration screening in Section 3.1.1, the High Frequency Confirmation submittal should include the SSE and GMRS information in graphical and tabular form along with text noting that the GMRS accelerations are within the limits identified in Section 3.1.1, therefore, no additional evaluation is necessary.

For plants using the Limited High Frequency Exceedance screening in Section 3.1.2, the High Frequency Confirmation submittal to the NRC should include the following:

- SSE and GMRS information in graphical and tabular form
- The calculated exceedance area percentage consistent with the criteria in Section 3.1.2
- Text noting that the GMRS exceedances are consistent with the criteria identified in Section 3.1.2, therefore, no additional evaluation is necessary

For plants performing a site-specific High Frequency Confirmation evaluation, a report should be prepared summarizing the evaluations and results and submitted to the NRC for review following completion of the evaluations. The level of detail provided in the report should be sufficient to enable NRC to understand the inputs used, the evaluations performed, and the decisions made as a result of the high-frequency evaluations. It is not necessary to submit HCLPF calculations although relevant documentation should be cited in the submittal, and be available for NRC review on-site in an easily retrievable form.

The report should include the following information.

- A description of the equipment scope selection process and the seal-in and lock out circuits associated with the applicable functions and components identified in Table 4-1.
- A list of the specific components identified for high frequency confirmation including the plant specific component ID, component type (relay, contactor, etc.) model number, location in the plant (floor elevation, enclosure type), system, and function to which it belongs.
- A plot of the GMRS submitted by the licensee and accepted by the NRC in accordance with the 50.54(f) letter and EPRI 1025287 [3]. A table of values should also be included.
- A description of the estimated vertical GMRS including the information used to select the applicable site Class in Table 3-1 (horizontal PGA and V_S30 values) and a plot of the vertical GMRS along with tabulated values.
- A description of ISRS used in accordance with Section 4.3.
- A table listing the results of the component evaluations for the components listed above (i.e. basis for capacity (e.g. GERS, test data), and the evaluation result (e.g. capacity > demand, Operator action to reset, resolution required).
- A table listing any components where the component capacity is not shown to be greater than the estimated demand and a planned resolution schedule. Alternately, the resolution schedule may be contained in the utility transmittal letter to the NRC for the High Frequency Confirmation report.
- An appendix showing two representative sample component evaluations of different scenarios including the following information for each example.
    - A description of the component being evaluated (component type, manufacturer, model number, other relevant component specific information).
    - A description of the location of the component including building, floor elevation, enclosure type.
    - A description of the mounting point demand estimate including the in-structure and in-cabinet amplification factors used.
    - A description of the component capacity and the basis for that capacity (e.g. reference to the test information).
    - The values for the parameters used in the horizontal and vertical capacity to demand high frequency component evaluations and the resulting $TRS/ISRS_c$ ratio.

Section 5: High Frequency Fragility Guidance

For those sites conducting an SPRA, components are either screened by a control circuit evaluation which demonstrates that the consequences of assumed device malfunction does not lead to an unacceptable system state, or probabilistic measures of device mounting point capacity and demand are required to be determined. This section provides additional fragility methodology guidance for the estimation of in-cabinet median demand and median component capacity, based on the test capacities determined for components. For SPRAs, the fragility methodology in EPRI TR-103959 [11] for cabinet-mounted components is directly applicable for both the low- and high-frequency input motion cases, given the median ISRS for the cabinet location. It is assumed that the control contact configuration (NO, NC, energized (E) or de-energized (DE)) of concern has been identified by circuit evaluation. Often, an analyst is forced to assume the worst contact configuration (NC, DE) simply due to lack of information concerning the control circuit.

The median horizontal cabinet amplification factors presented in EPRI TR-103959 [11] are directly applicable in the high-frequency case. A median vertical in-cabinet amplification factor is developed in Appendix C. Additional fragility methodology guidance for the estimation of median component capacity, based on the test program results, is also provided using an envelope of low-frequency and high-frequency test capacities and recommended values of Broad Frequency Input Device Capacity Factors to cover both the low- and high-frequency regions.

5.1 Estimating Component Mounting Point Seismic Demand

For an SPRA, the reference median ISRS for the cabinet location is assumed to be available. The effective wide-band seismic demand is defined in EPRI TR-103959 [11] as

$$\breve{ICRS}_c = \breve{AF}_c \ \breve{C}_c \times max\{SA_{pi}\} \times (1/\breve{F}_{MS}) \times \breve{D}_R \qquad \text{Eq. 5-1}$$

Recommended median values of $\breve{C}_c$ and horizontal $\breve{AF}_c$ along with the associated variability in terms of both randomness and uncertainty are provided in EPRI TR-103959 [11] for the same general cabinet types considered previously:

Motor Control Centers	$\breve{AF}_c$ = 2.8, horizontal motion only β_r = 0.10, β_u =0.23	*Eq. 5-2a*
Switchgear (flexible panels)	$\breve{AF}_c$ = 4.4, horizontal motion only β_r= 0.13, β_u=0.37	*Eq. 5-2b*
Control Cabinets	$\breve{AF}_c$ = 3.3, horizontal motion only β_r= 0.11, β_u=0.27	*Eq. 5-2c*

In Equation 5-1, the term SA_{pi} represents the peak spectral acceleration of the reference in-structure response spectrum. For the horizontal direction, there may be more than one spectral peak due to increased second mode structure response caused by the high-frequency GMRS or FIRS input motion, but the peak associated with the fundamental structure mode usually governs for the horizontal direction. Vertical amplification factors were not considered in EPRI TR-103959 [11]. A vertical amplification factor for cabinets is considered in the following subsection, as a general median value for all cabinets. It should also be noted that the factor $\breve{F}_{MS}$ = 1.25 (β_u =0.09) is included in the demand equation and an additional demand reduction factor $\breve{D}_R$ = 0.92 (β_u =0.04) is also included.

These values are valid for both low- and high-frequency ranges since they are fundamentally associated with the statistics of the peak transmissibility values and with the application of clipping procedure to the effective cabinet transmissibility functions. In the horizontal direction, cabinets can have natural frequencies in either the low- or high-frequency range, depending on the support configurations (base-mounted cantilever, base- and top-anchored, and wall-mounted) and thus can have mounting point response in either the low- or high-frequency range.

5.2 Estimating Median Vertical In-Cabinet Amplification Factors

The development of a median vertical cabinet amplification factor is considered in Appendix C to this report as a generic factor applicable to all cabinets. The resulting median value is:

All Cabinets	$\breve{AF}_c$ = 3.0, vertical motion only β_r = 0.11, β_u =0.36	*Eq. 5-3*

This value is valid for both the low- and high-frequency ranges; however, it should be noted that the vertical control cabinet natural frequencies are in the 20 to 30 Hz range, and thus have mounting point response in the high-frequency range.

5.3 Estimation of Component Seismic Capacity and Determination of Component Fragility

The effective wide-band component capacity is given by the effective spectral test capacity, SA_T, times the product of the capacity increase factor, $\breve{C}_{I,}$ and $\breve{F}_D$ is the broad frequency input spectrum device capacity factor:

$$\breve{TRS} = SA_T \breve{C}_I \breve{F}_D \qquad \text{Eq. 5-4}$$

In the 20 to 40 Hz frequency range, the value of $SA_T = (SA^* + \Delta SA)$ determined using the test capacity from the High Frequency Program applies, where $\Delta SA = 0.625g$. In general, the high frequency tests were conducted using incremental steps of spectral acceleration of 1.25g until chatter occurred, and then test capacity SA* was determined for the next lowest increment of test motion. The increment of $\Delta SA = 0.625g$, when added to the test capacity, is the best estimate of the actual threshold of component malfunction. For the 4 to 16 Hz range, the $SA_T = SA_{GERS}$ [14] for the mounted device usually applies. Low-frequency (4.5 to 16 Hz) test capacity values from the SQURTS program [15] may also be used. In general, an envelope of the two spectra may be used to determine the capacity over the 4 to 40 Hz frequency range, or the two spectra may be used independently for separate evaluations. Figure 5-1 shows the test capacity spectra of a tested component for both low- and high-frequency ranges overlaid on the same plot. The extension of the low-frequency capacity into the high-frequency range is also shown. Since the High Frequency Program showed that the high-frequency test capacity was greater than the low-frequency test capacity, at a minimum the low-frequency spectral acceleration may be extended into the high-frequency range (spectral plateau roll off at 40 Hz) and serve as a surrogate capacity for a component when the high-frequency test capacity is not available for a given component.

As an example, consider a base-anchored cabinet with an estimated horizontal natural frequency of 10 Hz and an estimated vertical natural frequency of 20 Hz. The cabinet is located at a higher elevation within a building with a horizontal first mode frequency of 10 Hz and a vertical first mode of 20 Hz. The clipped horizontal ISRS will govern the horizontal demand, and the clipped vertical ISRS will govern the vertical demand. Depending on the actual demand levels, either the low- or high-frequency capacity will govern the fragility determination for the mounted component. Typically, the fragility analyst needs to make a judgment regarding the approximate cabinet frequency. Guidance for estimating cabinet frequencies is given in EPRI TR-102180 [45]. In general, base-mounted control cabinets will have horizontal frequencies in the range of 8 to 15 Hz (11 Hz is common) with a vertical frequency greater than 15 Hz. Base-mounted control cabinets with both base and top wall anchorage will likely have horizontal and vertical frequencies greater than 15 Hz. Wall-mounted control cabinets or wall-mounted components will likely have horizontal and vertical frequencies that exceed 20 Hz.

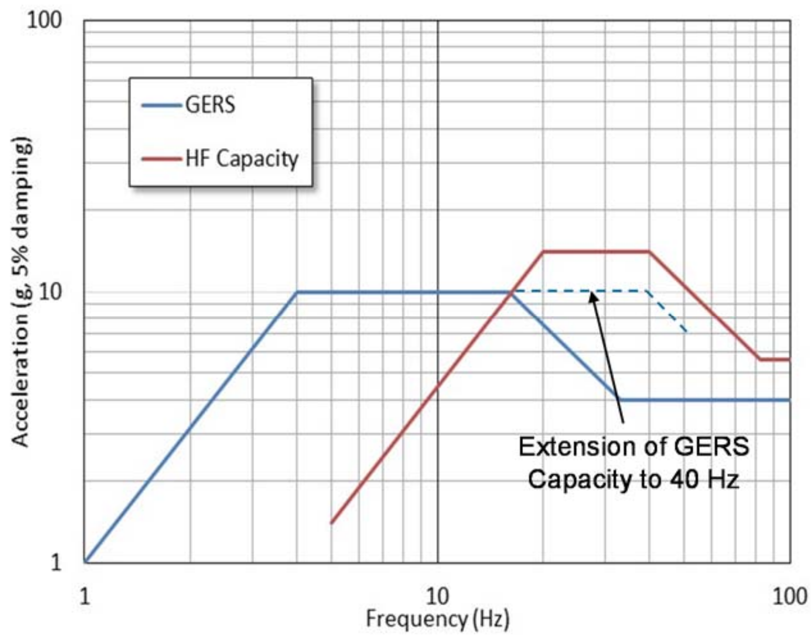

Figure 5-1
Test Capacity Profiles

The $\breve{C}_I$ factor is normally taken as $\breve{C}_I$ =1.1 (β_u =0.05). The $\breve{F}_D$ factor is a bit more involved and generally depends on the source of the test value chosen to represent the test capacity. There are two possible results from a component test:
(1) contact chatter or malfunction occurs at a given test motion level, or (2) the component sustains the maximum test motion level or capacity of the test table. EPRI TR-103959 [11] provides $\breve{F}_D$ factors for these two situations. For the estimate of chatter threshold used for the High Frequency Program results, an additional case is added to the cases identified in EPRI TR-103959 [11]. For the estimate of SA_T = (SA^* + ΔSA), the $\breve{F}_D$ factor is set equal to unity. For the function confirmed case (table capacity without malfunction), the HCLPF or CDFM F_ke is set to a value of 0.9 which yields a value of $\breve{F}_D$ = 1.5 using the guidance for the variability given in EPRI TR-103959 [11]. The various conditions affecting the selection of this factor are given in Table 5-1. Also included in Table 5-1 is the corresponding F_{DCDFM} factor (HCLPF), which is also the approximate reciprocal of the F_k factor used in Section 4 of this report.

Table 5-1
Broad Frequency Input Spectrum Device Capacity Factor and Associated Variability

Test Source		$\breve{F}_D$	$\breve{\beta}_r$	$\breve{\beta}_u$	$F_{DCDFM} = 1/F_k$
Relay GERS [14] (SQURTS Test [15])	Lowest level without chatter	1.07	0.09	0.18	0.67
	No chatter, Test table capacity	1.4	0.09	0.22	0.83
High Frequency Test Program [12]	Fragility threshold $SA_T = (SA^* + \Delta SA)$, $\Delta SA = 0.625g$	1.0	0.09	0.18	0.64
	Function Confirmed, Test table capacity	1.5	0.09	0.22	0.9
Qualification Test (IEEE 344 [25])	No chatter	1.4	0.09	0.22	0.83

The median acceleration capacity of the mounted components, in terms of the PGA anchor acceleration of the GMRS shape, is given by:

$$A = (\breve{TRS}/\breve{ICRS}) \times \breve{F}_{RS} \times PGA \qquad \text{Eq. 5-5}$$

This value of A when associated with the square-root-sum-of-squares of the respective β_r and β_u values defines the fragility function of the component. Where $\breve{F}_{RS}$ is the Response Factor for the building and PGA is the PGA of the GMRS. The F_{RS} factor is determined by the building response characteristics. For median in-structure spectra, this factor will normally be taken as unity, $F_{RS} = 1.0$, with the variability and uncertainty, $\beta_{r,RS}$ and $\beta_{u,RS}$, assigned using the guidelines given in EPRI TR-103959 [11] for structural response.

5.4 Ongoing Research into High Frequency Fragilities

There is limited experience in the high frequency seismic response analysis of buildings and electrical cabinets. As additional SPRAs are performed for sites with significant high frequency ground motions, the above-stated criteria could evolve to account for the new insights gained from those studies addressing elements of the fragility process and the risk significance of these high frequency efforts.

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Appendix A: Guidance for Estimating High Frequency Vertical GMRS

A.1 Introduction

This study develops generic vertical-to-horizontal (V/H) ratios that can be used at nuclear power plants in the CEUS to calculate approximate, appropriate vertical motions that are consistent with horizontal GMRS for a range of plant conditions (surficial rock and soil conditions, and level of ground motion associated with the GMRS). These V/H ratios are generic in that they do not consider plant-specific site conditions or specific horizontal GMRS; they are appropriate for general investigations and screenings of nuclear power plants to evaluate seismic safety.

A.2 Range Of Conditions

Based on conditions at twenty nuclear power plants where generic V/H ratios might be useful, several classes of sites were identified, as indicated in Table A-1.

Table A-1
Classes of Sites Identified for Characterization

Class	Horizontal PGA	Vs30, mps (ft/sec)	No. of Plants
A-Hard	≤ 0.20g	≥ 700 (2300)	5
B-Hard	~ 0.25g	≥ 1000 (3280)	4
C-Hard	~ 0.30g	≥ 1000 (3280)	5
D-Hard	~ 0.45g	≥ 1000 (3280)	2
A-Intermediate	≤ 0.20g	~ 400 (1310)	1
A-Soft	≤ 0.20g	~250 (820)	1
C-Soft	≤ 0.30g	~250 (820)	2

"Horizontal PGA" in Table A-1 is the PGA associated with the horizontal GMRS. "Vs30" in Table A-1 is the site classification measure which is defined [44] by the time required for a shear wave to travel from a depth of 30 meters (98.4 ft.) within the site geologic profile to the ground surface. This results in a measure that is not the arithmetic average of the shear velocity (Vs) for all layers to a depth of 30 m. The time-averaged Vs30 is calculated as 30 m divided by the sum of the travel times for shear waves to travel through each layer. The travel time for each layer is calculated as the layer thickness (d_i) divided by Vs_i for the respective layer.

$$Vs30 = (30\ m)/\sum_i[(d_i/Vs_i)] \qquad \textit{Eq. A-1}$$

For example, the Vs30 for a soil profile containing 18 m of soft clay (Vs = 90 m/sec) over 12 m of stiff clay (Vs = 260 m/sec) would be calculated: 30/(18/90 + 12/260) = 122 m/sec.

A.3 Methods of Analysis

Three methods were used to estimate V/H ratios for the range of site conditions listed above. These were as follows.

Gulerce and Abrahamson (2011). This paper [26] developed V/H ratios for a range of PGA values and Vs30 values, based on empirical data from recorded ground motions. The V/H ratios also depended on the dominant magnitude M and distance R from the earthquake to the site of interest. For this study, general values of M=6 and R=20 km were assumed; these are reasonable values for the M and R that control high-frequency ground motion (which is where V/H ratios are high), and the resulting V/H ratios are not highly dependent on the exact M and R values used in the estimates.

A range of Vs30 values were used to represent the Vs30 values used to define the range of conditions. Generally, the lower Vs30 values gave higher V/H ratios at high frequencies.

The Gulerce and Abrahamson [26] V/H ratios were developed from recorded ground motions. CEUS earthquake motions are known to have more high-frequency energy than, for example, California ground motion. In order to translate the Gulerce and Abrahamson [26] V/H ratios to represent CEUS conditions, the frequency for each calculated V/H ratio was multiplied by a factor of 3.33. This scaling of frequencies was used in other applications in the CEUS [39, 40, 41, 42, 43] and indicates a good agreement with independent estimates of V/H ratios, in terms of the dominant frequencies, as discussed below.

The Gulerce and Abrahamson [26] equations calculate median V/H ratios and logarithmic standard deviations ($\sigma_{\ln V/H}$). The mean V/H ratio was estimated as

$$\text{mean V/H} = \text{median V/H} \times \exp(\sigma^2_{\ln V/H}/2)$$

which is a standard assumption for lognormally distributed variables.

Campbell and Bozorgnia (2003). This paper [27] developed V/H ratios for site categories comprised of the following (with associated Vs30 values):

firm soil, Vs30 = 210 to 390 mps

very firm soil, Vs30 = 290 to 490 mps

soft rock, Vs30 = 310 to 530 mps, and

firm rock, Vs30 = 490 to 1170 mps.

These V/H ratios were based on empirical data from recorded ground motions. The V/H ratios also depended on the dominant magnitude M and distance R from the earthquake to the site of interest. For this study, general values of M=6 and R=20 km were assumed, as they were for the Gulerce and Abrahamson [26] estimates. To apply the Campbell and Bozorgnia [27] procedure, the Vs30 value for each site condition was translated into a site category, consistent with the above list.

The Campbell and Bozorgnia [27] V/H ratios were developed from recorded ground motions. To represent CEUS V/H ratios, the frequency for each calculated V/H ratio was multiplied by a factor of 3.33. This scaling of the frequencies has been used in other applications in the CEUS [39, 40, 41, 42, and 43] and indicates a good agreement with independent estimates of V/H ratios, in terms of the dominant frequencies, as discussed below.

The Campbell and Bozorgnia [27] equations calculate median V/H ratios and logarithmic standard deviations ($\sigma_{\ln V/H}$). The mean V/H ratio was estimated in the same way as explained above for the Gulerce and Abrahamson (2011) equations.

NUREG/CR-6728 (2001). This document [28] developed recommended V/H ratios for rock sites in the CEUS, for three ranges of PGA: < 0.2g, 0.2g to 0.5g, and >0.5g. These V/H ratios were implemented for comparison purposes with the following assumptions:

> PGA < 0.2g: The V/H ratios for this range of PGA values were calculated as recommended in NUREG/CR-6728 [28].
>
> PGA between 0.2g and 0.5g: The V/H ratios from NUREG/CR-6728 [28] for this range were assumed to apply to PGA = 0.5g because these ratios were developed to be conservative and applicable to PGA as high as 0.5g. For PGA values between 0.2g and 0.5g, a linear interpolation at each frequency was used based on PGA, starting with the V/H ratio at 0.2g, so that continuous V/H ratios from 0.2g to 0.5g were obtained.

As recommended in Ref. 3, the V/H ratio had a discontinuous jump from PGA = 0.2g to PGA = 0.201g, which was neither realistic nor physical. The interpolation method used here achieves a smooth, continuous V/H ratio as a function of PGA.

PGA > 0.5g: V/H ratios for PGA in this range were not needed.

The NUREG/CR-6728 [28] V/H ratios were applicable to hard-rock sites; these ratios were calculated for intermediate- and soft-soil sites for comparison purposes in results presented below, but the NUREG/CR-6728 V/H ratios were not used to calculate recommended V/H ratios for the intermediate- and soft-soil conditions.

A.4 Results

V/H ratios are presented in Figures A-1 through A-4 for the first four site classes listed in Table A-1. The "Mean" in each figure is the mean V/H ratio among the three methods identified in the previous section. Note the following characteristics of these figures:

The shape of V/H ratios vs. frequency for the Gulerce and Abrahamson (2011) method and the Campbell and Bozorgnia (2003) method, is consistent with the shape of the V/H ratios vs. frequency for the NUREG/CR-6728 method. This confirms the frequency scaling used for the Gulerce and Abrahamson (2011) method and the Campbell and Bozorgnia (2003) method.

The mean of V/H ratios was calculated as the mean of the three methods down to a frequency of about 15 Hz. Below that frequency, the empirical methods gave unrealistically high V/H ratios at some spectral frequencies, that are inconsistent with the understanding that high V/H ratios are a high-frequency phenomenon caused by nearby earthquakes. High V/H ratios at low frequencies are attributed to poorly constrained equations at those frequencies.

V/H ratios labeled "GA2011-1," "GA2011-2," and "GA2011-3" are three applications of the Gulerce and Abrahamson (2011) method with three Vs30 values representing the range of values indicated in Table A-1. GA2011-1 indicates the lower limit of Vs30 in Table A-1, and GA2011-2 and GA2011-3 used Vs30 values of 1,100 mps and 2,000 mps, respectively. The lowest Vs30 value generally gives the highest V/H ratios, at high frequencies. To calculate the mean V/H ratio, the GA2011 application giving the highest V/H ratio among the three Vs30 values was used at each frequency, to estimate a mean (or slightly conservative) value for any individual site Vs30 within the range.

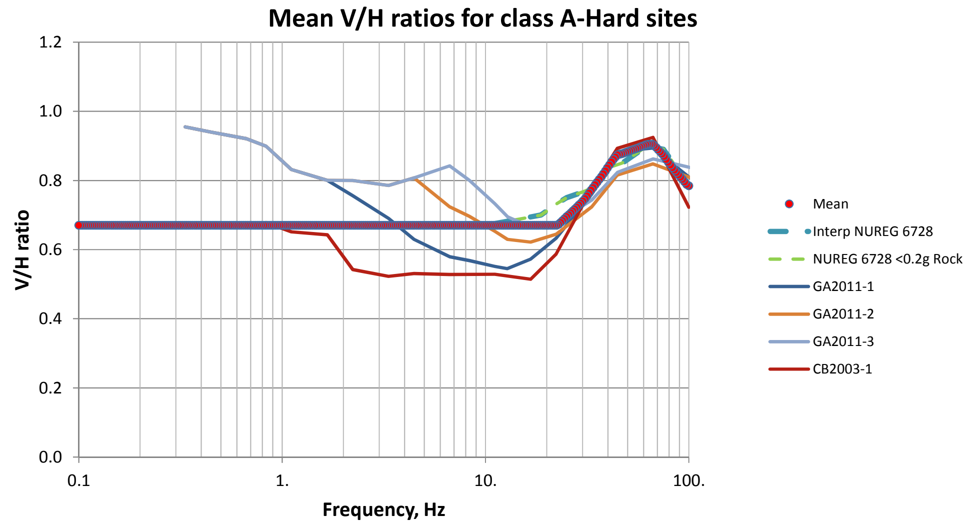


Figure A-1
Mean V/H Ratios for Class A-Hard Sites

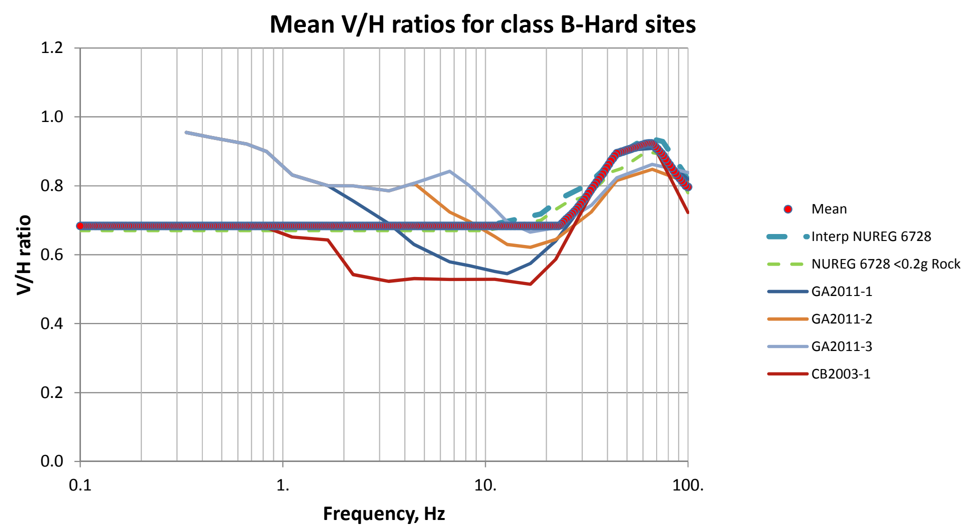


Figure A-2
Mean V/H Ratios for Class B-Hard Sites

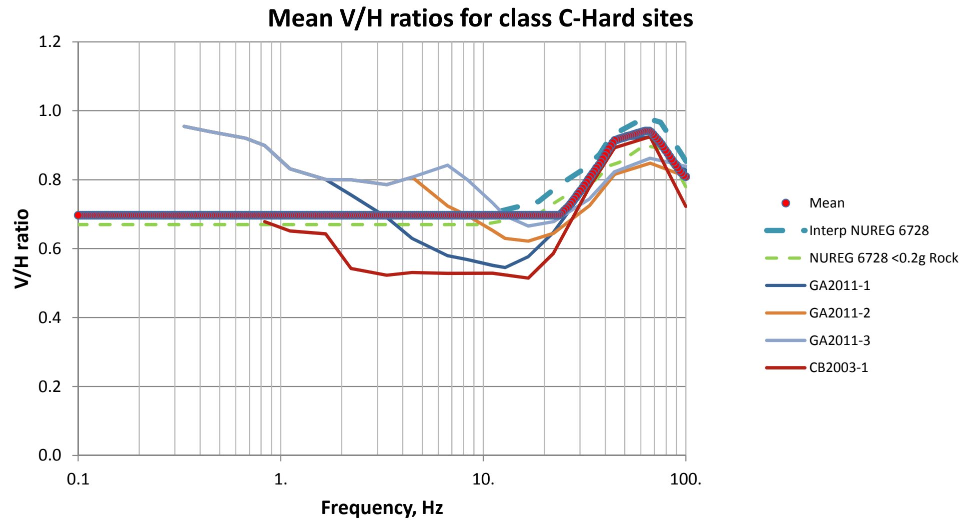


Figure A-3
Mean V/H Ratios for Class C-Hard Sites

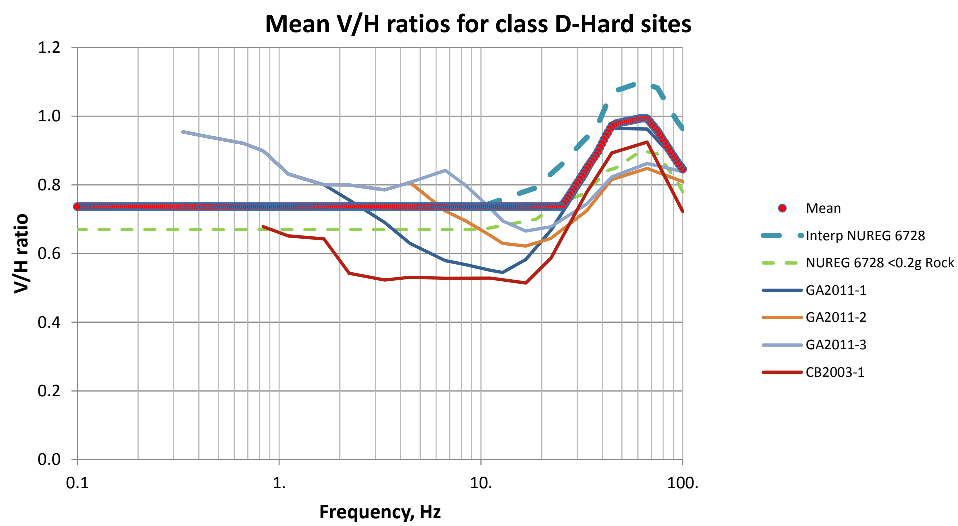


Figure A-4
Mean V/H ratios for Class D-Hard sites

Figure A-5 shows mean V/H ratios for class A-Intermediate sites, where Vs30 is ~400 mps. For this class, the GA2011-1 estimate (using Vs30 = 400 mps) gives the highest V/H ratios at high frequencies. The mean was calculated using this equation and the CB2003-1 V/H ratios (the NUREG/CR-6728 V/H ratios do not apply to soil sites). For this class, the Campbell and Bozorgnia (2003) estimates were made assuming "soft rock" site conditions, which represents the range Vs30 310 to 530 mps.

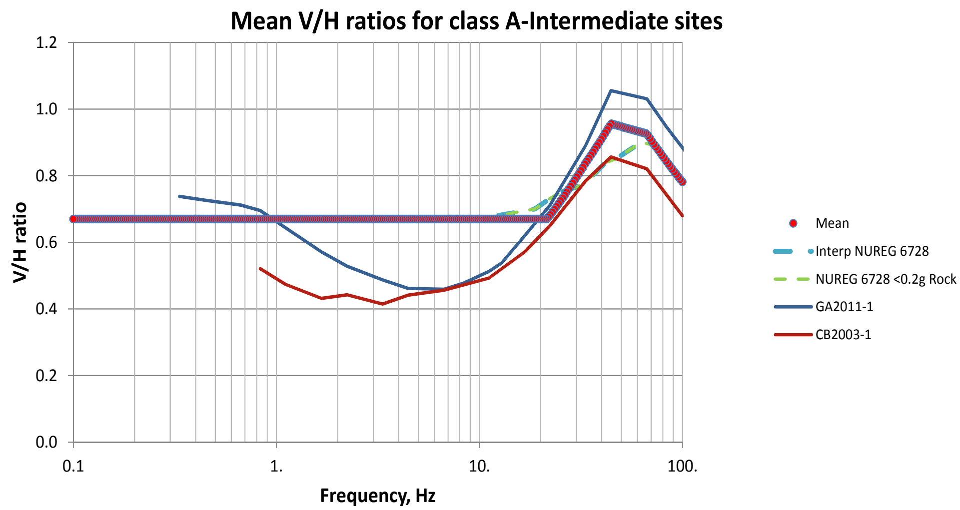


Figure A-5
Mean V/H Ratios for Class A-Intermediate Sites

Figure A-6 shows mean V/H ratios for class A-Soft sites, where Vs30 is ~250 mps. For this class, the GA2011-1 estimate (using Vs30 = 250 mps) gives the highest V/H ratios at high frequencies. The mean was calculated using this equation and the CB2003-1 V/H ratios (the NUREG/CR-6728 V/H ratios do not apply to soil sites). The Campbell and Bozorgnia (2003) estimates were made assuming "firm soil" site conditions, which represents the range Vs30 210 to 390 mps.

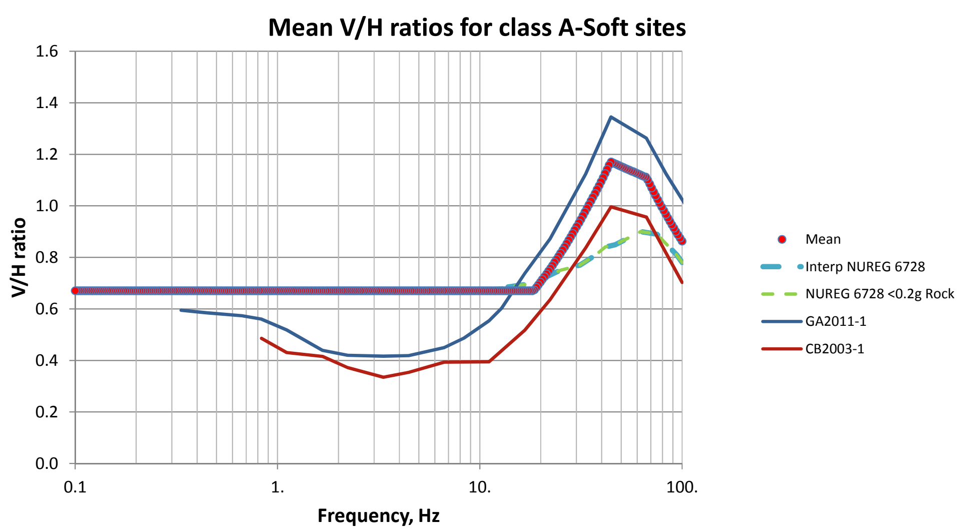


Figure A-6
Mean V/H Ratios for Class A-Soft Sites

Figure A-7 shows mean V/H ratios for class C-Soft sites, where Vs30 is ~250 mps. For this class, the GA2011-1 estimate (using Vs30 = 250 mps) gives the highest V/H ratios at high frequencies. The mean was calculated using the GA2011-1 equation and the CB2003-1 equation (the NUREG/CR-6728 V/H ratios do not apply to soil sites). For this class, the Campbell and Bozorgnia (2003) estimates were made assuming "firm soil" site conditions, which represents the range Vs30 210 to 390 mps.

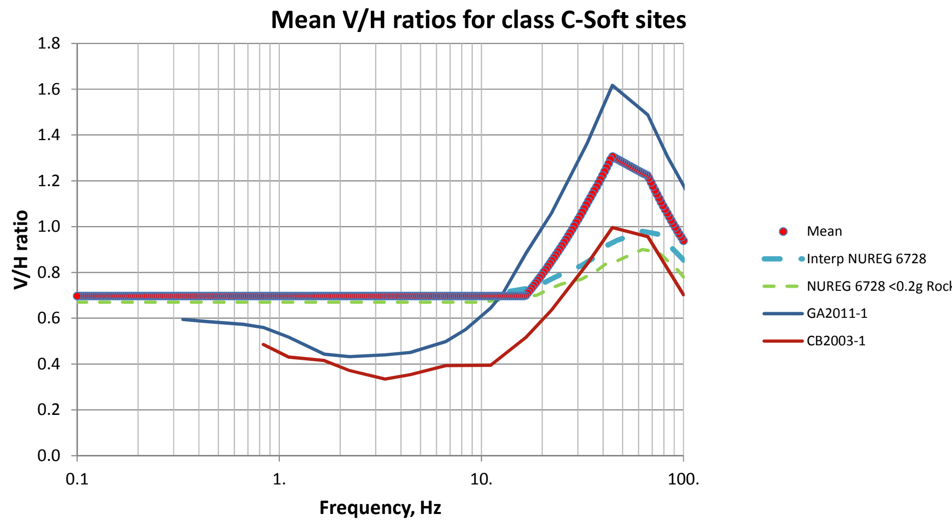


Figure A-7
Mean V/H ratios for Class C-Soft sites

Table A-2 documents the mean V/H ratios shown in Figures A-1 to A-7 for the seven site classes as a function of spectral frequency.

A.5 Conclusions

Figures A-1 to A-7 and Table A-2 give mean V/H ratios that can be used for a range of plant conditions (surficial rock and soil conditions, and level of ground motion associated with the horizontal GMRS). These V/H ratios are generic in that they do not consider plant-specific site conditions or specific horizontal GMRS, but they are appropriate for general investigations and screenings of nuclear power plants to evaluate seismic safety.

Table A-2
Mean V/H Ratios by Frequency for Different Site Classes

Freq.	A-Hard	B-Hard	C-Hard	D-Hard	A-Intermediate	A-Soft	C-Soft
100	0.78	0.80	0.81	0.85	0.78	0.86	0.94
90	0.81	0.82	0.84	0.88	0.82	0.92	1.01
80	0.85	0.87	0.88	0.93	0.86	0.99	1.09
70	0.89	0.91	0.93	0.98	0.91	1.08	1.18
60	0.90	0.92	0.94	0.99	0.93	1.13	1.24
50	0.88	0.90	0.92	0.98	0.95	1.15	1.28
45	0.87	0.89	0.91	0.97	0.96	1.17	1.30
40	0.84	0.86	0.87	0.92	0.91	1.10	1.23
35	0.79	0.81	0.82	0.87	0.86	1.01	1.13
30	0.74	0.75	0.77	0.80	0.79	0.92	1.03
25	0.69	0.70	0.71	0.74	0.72	0.81	0.91
20	0.67	0.68	0.70	0.74	0.67	0.70	0.79
15	0.67	0.68	0.70	0.74	0.67	0.67	0.70
10	0.67	0.68	0.70	0.74	0.67	0.67	0.70
0.1	0.67	0.68	0.70	0.74	0.67	0.67	0.70

Note: V/H ratios are constant between 10 Hz and 0.1 Hz.

Appendix B: Estimating High Frequency In-Structure Response Spectra

B.1 High Frequency Structural Amplification Factors for NTTF 2.1 Seismic Confirmation

B.1.1 Background

Section 4.3.1 summarizes the results from a study of existing high frequency seismic response data used to develop a generic high frequency structural amplification factor to be applied as part of the high frequency confirmation task associated with the NTTF 2.1 seismic program. The high frequency confirmation process consists of developing deterministic HCLPF[3] capacity and demand for the selected set of equipment that ultimately needs to be evaluated for functional confirmation (per section 4.2). The GMRS are recommended as the appropriate RLGM for purposes of this HCLPF demand characterization. However, the plants that screened-out of the SPRA and require high frequency confirmation do not, in general, have ISRS consistent with the GMRS. Development of new seismic response consistent with the new GMRS can be a very large effort, and this effort is not judged to be cost beneficial given the relatively high capacities shown for the devices tested to the high frequency motions (Section 2). As such, guidance is provided for the generic estimation of the horizontal and vertical high frequency ISRS using the GMRS (or FIRS) input motion. These generic high frequency amplification factors have been empirically developed from the available set of recent analyses that could be collected where nuclear structures have been subjected to high frequency input motions.

[3] HCLPF and CDFM are used somewhat interchangeably in the literature. For purpose of this paper, the term HCLPF will be used to incorporate the use of CDFM methods.

B.1.2 Description of Data Sources

Seismic amplification data in the high frequency part of the spectrum were reviewed from available data sources with the following characteristics:

- Nuclear power plant structures that are similar to those that typically house contact devices
  - Auxiliary buildings, control buildings and nuclear island structures for new plant designs
- Analyses that were conducted for high frequency seismic input
  - Sites with relatively high shear wave velocity (referred to as relatively firm rock sites; see Appendix A characterizations) typically have UHS with peak responses in the 12 to 40 Hz range

The seismic response analyses reviewed as part of this effort to define the high frequency structural response of nuclear structures included:

- Westinghouse AP 1000 analyses to support the Lee Site new plant licensing application
  - Nuclear Island Structure
- PWR A seismic response analyses to support a recent SPRA
  - Auxiliary Building 1
  - Auxiliary Building 2
- BWR B seismic response analyses to support a recent SPRA
  - Auxiliary Building
  - Control Building

The two studies labeled as PWR A (example pressurized water reactor) and BWR B (example boiling water reactor) have not yet been publically documented, but were made available to EPRI for purposes of this study to define high frequency amplification factors.

Each of these three sites consist of firm rock (Vs30 greater than 490 mps from [27]). As such, their corresponding seismic hazards (GMRS or FIRS) are appropriately rich in the desired high frequency part of the response spectra. The three sites with the five structures reviewed for this study along with the site shear wave velocities are listed in Table B-1.

As mentioned, these firm rock sites result in the high frequency input that allow us to identify the high frequency response that exists in nuclear structures from a high frequency input. The GMRS (5% damping) used as the input to the seismic response analyses for these structures are shown in Figures B-1 through B-3.

Table B-1
Shear Wave Velocity Characteristics of Sites Reviewed

Site	Building	Vs (fps)
PWR Plant A	Auxiliary 1	5200
	Auxiliary 2	5200
BWR Plant B	Auxiliary	5100
	Control	5100
Lee (AP1000)	Nuclear Island Structure	8000

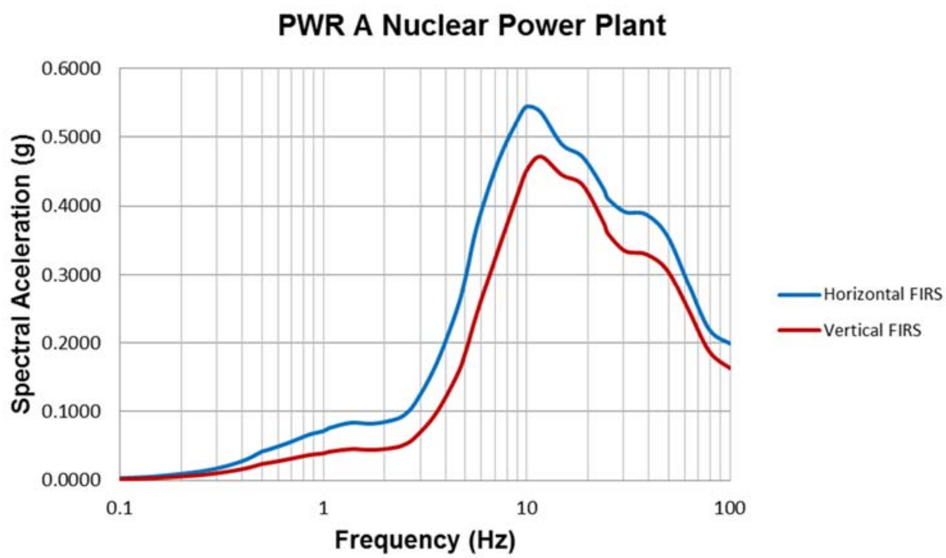


Figure B-1
Horizontal and Vertical FIRS Auxiliary Buildings 1&2 Foundations PWR A Site

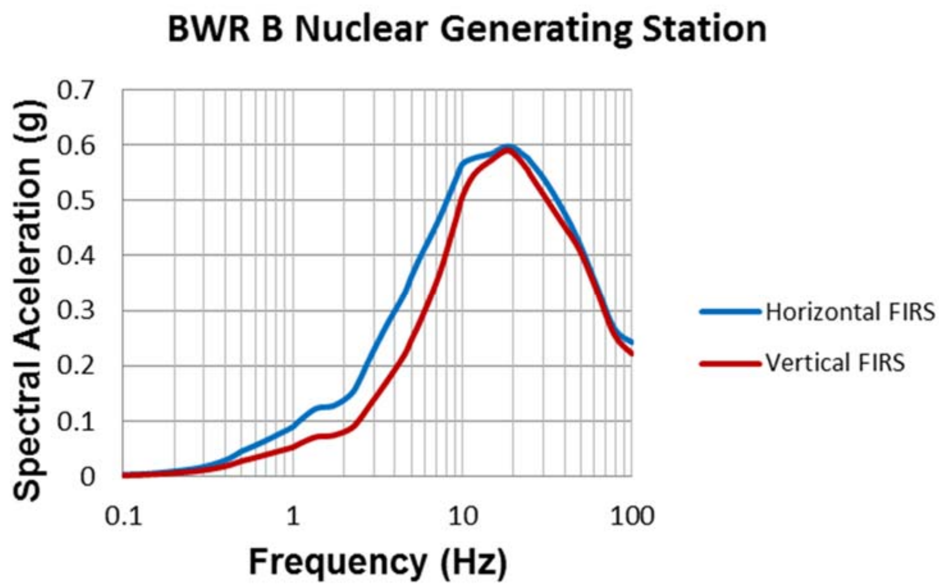


Figure B-2
Horizontal and Vertical FIRS Control & Auxiliary Foundations BWR B Site

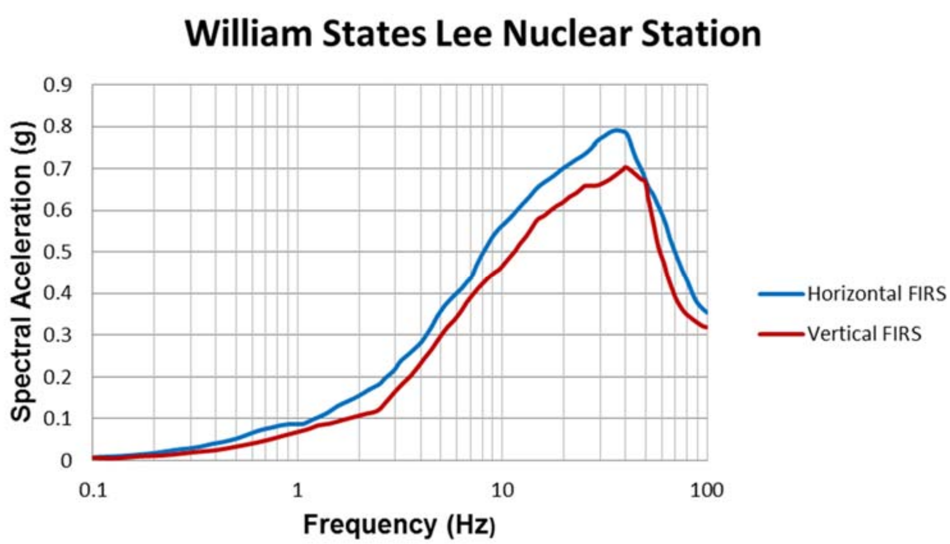


Figure B-3
Horizontal and Vertical FIRS at the Nuclear Island Foundation, William States Lee Nuclear Station

B.1.3 Data Reviewed and HCLPF Response Conversion

Table B-2 lists the locations within the five structures where seismic response data were used for this high frequency amplification study.

The Lee AP1000 plant analyses and resulting ISRS (Document No. WLG-GW-GLR-815 [29]) were used for this study because the evaluation report stipulates that the Lee NI20u model is more realistic/accurate than previous analyses. The NI20u model is stated to produce responses that more closely match the more refined NI10 model, which has 10 ft elements instead of 20 ft elements.

ISRS are provided in the PWR A and BWR B reports for three nodes at each main floor in each structure. The node locations are chosen to be close to important equipment. The Lee AP1000 analysis report provides broadened envelope ISRS at several floors. Two elevations are considered for this study: the control room elevation (Elevation 116 ft) and the top (Elevation 160 ft) of the Auxiliary Building portion of the AP-1000 Auxiliary and Shield Building (ASB).

As stated previously, the high frequency confirmation process being proposed to support the resolution of that portion of the NTTF 2.1 seismic process consists of demonstrating that the relay HCLPF exceeds the GMRS (or associated FIRS) in the high frequency part of the spectrum for each relay being reviewed. As such, the in-structure response due to the high frequency input is required to be consistent with the requirements associated with the seismic response development for the HCLPF calculation (EPRI NP-6041 [21] contains the description of the specific seismic response criteria). Damping and clipping adjustments were made to some of the ISRS data in order to appropriately reflect the HCLPF response requirements:

The structural damping levels that are aligned with the response levels documented in ASCE 4 [24] are appropriate for HCLPF calculations. In cases where alternate damping levels were used in the analyses included in this study, the seismic responses were adjusted to align with the appropriate HCLPF damping. The seismic response analyses performed for the PWR A and BWR B SPRAs used 7% structural damping and were developed to represent the median response at a higher ground motion corresponding to a much higher level than the GMRS for these sites. EPRI TR-103959 [11] defines the damping level for reinforced concrete at about half yield to be 5%. For the high frequency confirmation, 5% damping is considered to be more appropriate at the GMRS level of input. It should be noted that the ASCE 4 [24] damping value for Response Level 1 reinforced concrete is 4%, but that is judged to be too conservative since some walls are expected to reach Response Level 2 at the GMRS input level. The PWR A and BWR B ISRS were scaled following NUREG/CR-6728 [28] Section 4.9.1 to obtain an approximation to ISRS from a 5% damped structure response analysis. The scaling results in an approximate 10% increase in the GMRS from about 0.5 Hz to about 40 Hz. This range is

expected to capture all significant modes in the four PWR A and BWR B structures. To account for this increase in input motion, the ISRS for PWR A and BWR B were scaled up by 10% across all frequencies.

- The ISRS included in this study are clipped to obtain damage-equivalent broad-banded spectra. HCLPF clipping factors are computed using equation Q-6 from Appendix Q to EPRI NP 6041 [21]. When multiple peaks are present, each peak is treated independently since the spectra provided are envelopes and it is likely that the constituent spectra did not have the same multi-peak character. (It should be noted that both the Lee AP1000 ISRS are smoothed and broadened, and are enveloped for each floor elevation. As such, these ISRS were manually unbroadened before the appropriate clipping was performed. Representative data points were selected from both the AP1000 analysis results to verify that these structural response results confirmed the range of high frequency structure amplification results observed from the broader range of data available from the PWR A and BWR B results.)

Table B-2
Building Floor Locations where HF Response Data Included in Study

Site	Structure	Elevation (ft)	Distance Above Foundation (ft)
PWR A	Auxiliary Building 1	545	0
		565	20
		585	40
		603	58
		623	78
		643	98
		660	115
	Auxiliary Building 2	545	0
		565	20
		585	40
		603	58
		623	78
		643	98
		660	115

Table B-2 (Continued)
Building Floor Locations where HF Response Data Included in Study

Site	Structure	Elevation (ft)	Distance Above Foundation (ft)
PWR B	Auxiliary Building	575	10
		599	34
		620	55
	Control Building	574	9
		599	34
		620	55
		638	73
		654	89
		679	114
Lee Plant (AP1000)	Nuclear Island	116	52
		160	96

B.1.4 Ground Motion Incoherence Effects

The ISRS data from two of the sites (PWR A and PWR B) did not incorporate SSI or ground motion incoherence (GMI) effects into the seismic response. Studies were reported to have been conducted at both of these sites to demonstrate that the SSI effects at these sites resulted in negligible differences. As such, no adjustments for SSI were required for the HCLPF response characterization. GMI was not included in those SSI sensitivity studies and has proven in past studies to change the response, particularly in the high frequency portion of the spectrum. As such, incoherency effects should be incorporated into the HCLPF response calculation. As opposed to having to perform new SSI analyses to quantify the correct response incorporating incoherency effects, a generic study of representative GMI effects for hard rock was conducted. The study conducted by EPRI on seismic wave incoherence in SSI analysis for nuclear plant structures (EPRI 1015111 [30]) contains comparisons of the responses with and without coherency corrections for a variety of nuclear structures. The ratios between coherent to incoherent responses were tabulated at key locations (the common basemat and the tops of all three different structures documented in that study). Incoherence factors were developed for these four locations, which defined the ratios between the incoherent and coherent response. The ratios for the vertical direction were fairly uniform across the ≥ 15 Hz high frequency part of the spectrum being evaluated for this study. However, the incoherent response ratios for the horizontal direction had larger uncertainties that made it difficult to generate a simple/conservative characterization of the incoherence factor for this study. Since the governing case for the high frequency confirmation is likely the vertical direction (see Section 3), only the vertical direction responses are corrected to conservatively account for incoherency effects. Figure B-5 documents the results of the vertical incoherency factors for the range of

structures and locations from EPRI 1015111 [30]. As can be seen, in the ≥ 15 Hz high frequency part of the spectrum, a factor of 0.8 represents a conservative value that could be used to adjust the PWR A and BWR B vertical ISRS in the high frequency range to account for incoherency effects.

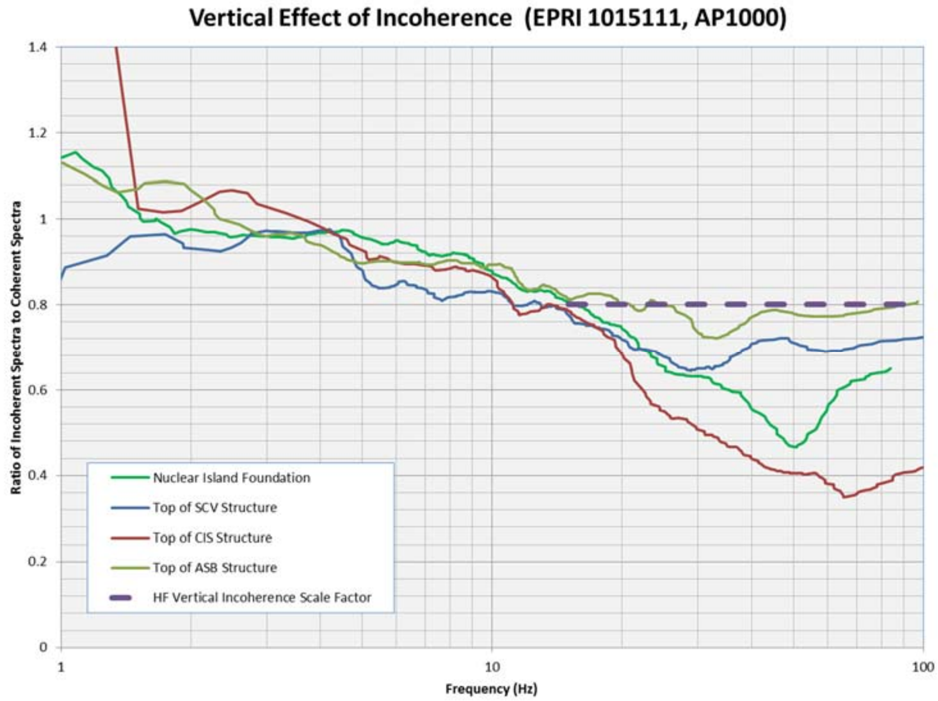


Figure B-4
Ratio of Vertical Incoherent / Coherent Responses for the AP1000 Structures Studied in EPRI 1015111

B.2 High Frequency Amplification Factors Recommendations

The high frequency amplification factor was developed for each data point (nodes in the finite element model where seismic responses were reviewed) reviewed from the five structures subjected to the high frequency input motions. A high frequency seismic amplification factor was developed for each of these data points based on:

- The numerator defined as the peak (clipped) 5% damped response in the ≥15 Hz part of the ISRS
- The denominator defined as the peak 5% damped response in the ≥15 Hz part of the GMRS (the GMRS was used as input for each of the five structures reviewed) used in the seismic response analysis

The resulting horizontal and vertical data were plotted as a function of the height above the foundation in order to assess the change with building elevation. A regression analysis of the data was then performed to calculate the 84% NEP in conformance with the criteria for generating a HCLFP response. These data from this study as well as the resulting 84% NEP high frequency amplification factors are:

- Horizontal Response (Figure B-5) – Bilinear curve that ranges from an amplification factor of 1.2 at the building foundation level to 2.1 at 40 ft above the foundation. The data did not support a clear change in that amplification beyond the 40 ft level, and the 2.1 amplification factor represents an 84% NEP for all of the data ≥ 40 ft above the foundation.
- Vertical Response (Figure B-6) – Linear amplification function that ranges from 1.0 at the foundation up to an amplification of 2.7 at 100 ft above grade.

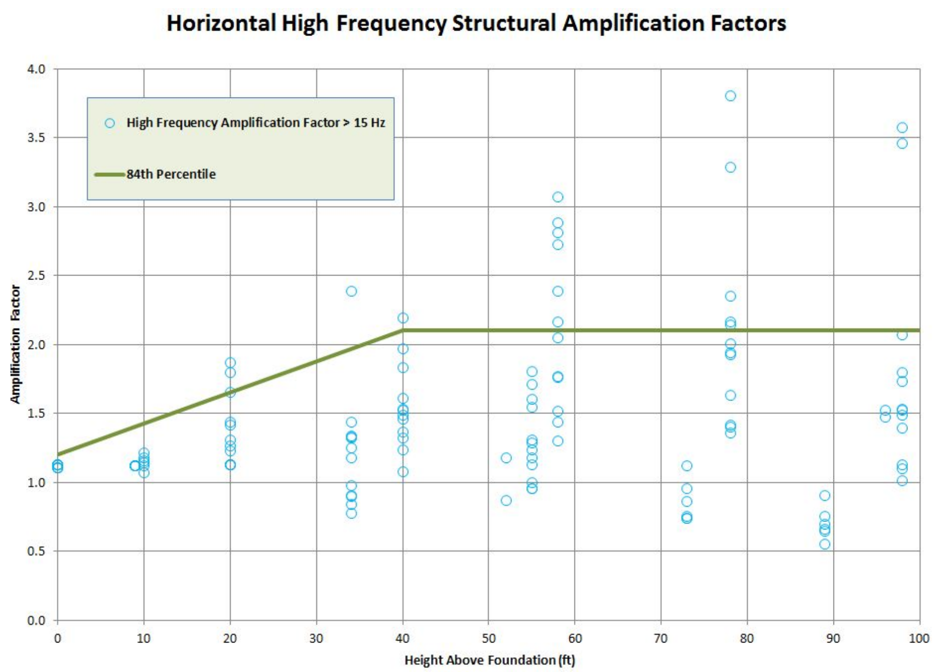


Figure B-5
Horizontal 84% NEP Characterization of Structural Response in the High Frequency (15 Hz) Part of the Spectrum

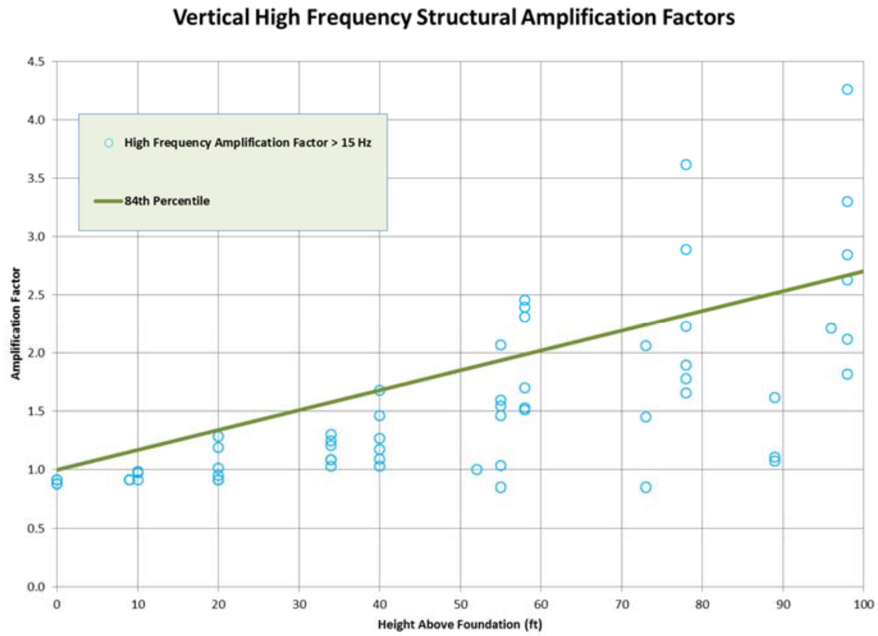


Figure B-6
Vertical 84% NEP Characterization of Structural Response in the High Frequency (15 Hz) Part of the Spectrum

These horizontal and vertical high frequency amplification factors defined in Figures B-5 and B-6 are judged to be appropriate for the subject nuclear plant in-structure locations where critical relays would typically exist. Complex structures were selected (auxiliary buildings, control buildings and nuclear island structures for the AP1000) where experience has shown that the amplification factors are highest. These more complex nuclear structures are also where the vast majority of the important relays are located and include the control room and electrical equipment rooms for the existing fleet of nuclear plants. The five structures where the seismic responses were reviewed are a reasonable representation of seismic responses for purposes of generating these HCLPF amplification factors for this high frequency confirmation review. Responses were included from a wide variety of locations within these structures such as locations at the walls, floor centers, locations with torsional response, etc. In addition, two PWR structures, two BWR structures and the global nuclear island structure from the AP1000 design were included. All of this data from the five structures were reasonably consistent and did not indicate a significant variance in the response based on the individual structures. As such, the data supports the conclusion that these are appropriate high frequency structure response factors.

Appendix C: Estimating High Frequency In-Cabinet Response Spectra

C.1 Mounting Point Seismic Demand

Component test capacities are provided in the form of response spectra that provide a measure of the input motion that causes the threshold of malfunction (or test machine limits). The test input motions are best described as multi-axial and wide-band random in terms of frequency content. An individual test capacity spectrum documents the input motion at the component mounting point in terms of equal wide-band random motion levels in each orthogonal direction. In actual use, the components are mounted in cabinets (also racks, support brackets, or other mounting fixtures), which are housed at different elevations within a structure. Thus, the actual mounting point motions resulting from earthquake ground motion are filtered by the response of both the building and cabinet, resulting in amplified narrow-band random motion, which can be unidirectional. In general, these narrow-band motions (which can be denoted as the seismic demand) are not directly comparable to the wide-band random test motion (which can be denoted as the seismic capacity) applied to the component. In order to compare the demand motion to the component test capacity spectra on an equal basis, the actual narrow-band mounting point motion must be converted to an equivalent wide-band motion. Appendix Q to EPRI NP-6041 [21] outlines the development of a procedure, consistent with the CDFM philosophy, for converting narrow-band structure and cabinet filtered motion for use in seismic margin evaluations. EPRI TR-103959 [11] outlines another procedure used to obtain median estimates of narrow-to wide-band conversion for use in fragility evaluations. These processes, denoted as "clipping," can be applied for converting both the narrow-band structure and cabinet filtered motion. While not considered herein, narrow-band component test data, such as a sine sweep test capacity, can also be evaluated by the procedures.

C.2 Clipped In-Structure Demand

The determination of a component mounting point demand is, in general a two-stage process. First, the peak response regions of ISRS that result from the building response (effective filtering of motion in the vicinity of the structure modal frequencies) are evaluated. Raw or unbroadened in-structure spectra are preferred for the clipping process, which is a function of the bandwidth ratio of the modal response region. Broadened in-structure spectra may also be utilized;

however, the resulting values will reflect additional conservatism. The spectral demand for most building locations typically includes regions of very narrow-band input motion, as indicated for an example building location shown in Figure C-1. The CDFM approach was defined in EPRI NP-6041 [21] for determining HCLPF capacities for structures and structure mounted components. These capacities were then used to judge the seismic margin that exists when the plant is subjected to a deterministic RLE defined for the plant site. The clipping procedure was developed to reflect this CDFM philosophy. For NTTF evaluations requiring confirmation of high-frequency functionality of components, the CDFM clipping procedure should be used using structure response based on the GMRS (and associated FIRS) input motions developed for a given plant site.

For NTTF evaluations that require the performance of an SPRA, the clipping procedures of EPRI NP-6041 [21] are reformulated in EPRI TR-103959 [11] to achieve median values and the associated lognormal uncertainty by assigning probability constraints (i.e., quantifying the conservatism) to the CDFM relations developed in EPRI NP-6041.

C.2.1 CDFM Clipping Procedure

There are two considerations associated with the process of converting narrow-band motion to an equivalent wide-band motion: (1) a bandwidth correction and (2) a modal interaction correction. Both of these considerations are incorporated into a factor, C_c, which is developed in Appendix Q to EPRI NP-6041 [21] as a function of the bandwidth to central frequency ratio, B, which is defined as

$$B = \Delta f_{0.8} / f_c \quad \textit{Eq. C-1}$$

where $\Delta f_{0.8}$ is total frequency range over which the spectral amplitudes exceed 80% of the peak spectral amplitude and f_c is the central frequency for the frequencies which exceed 80% of the peak spectral amplitude. The peak "clipping" factor, C_c, which is a function of the bandwidth of the floor spectra, converts the narrow-band input to an effective wide-band input level. The recommended CDFM values of C_c (EPRI NP-6041 [21]) are as follows:

$$C_c = 0.55 \qquad B \leq 0.2 \quad \textit{Eq. C-2}$$

$$C_c = 0.4 + 0.75B \qquad 0.2 \leq B \leq 0.8 \quad \textit{Eq. C-3}$$

$$C_c = 1.0 \qquad B \geq 0.8 \quad \textit{Eq. C-4}$$

Typical values of C_c range from 0.55 to 0.70. The narrow-band regions of an in-structure spectrum defined by the set of values, SA_{pi}, are then "clipped" to obtain an effective wide-band input level:

$$SA_{ci} = C_c \text{ x } \max\{SA_{pi}\} \quad \textit{Eq. C-5}$$

An example of the clipping procedure applied to in-structure spectra at the anchorage point of an in-structure mounted item of equipment is shown in Figure C-1.

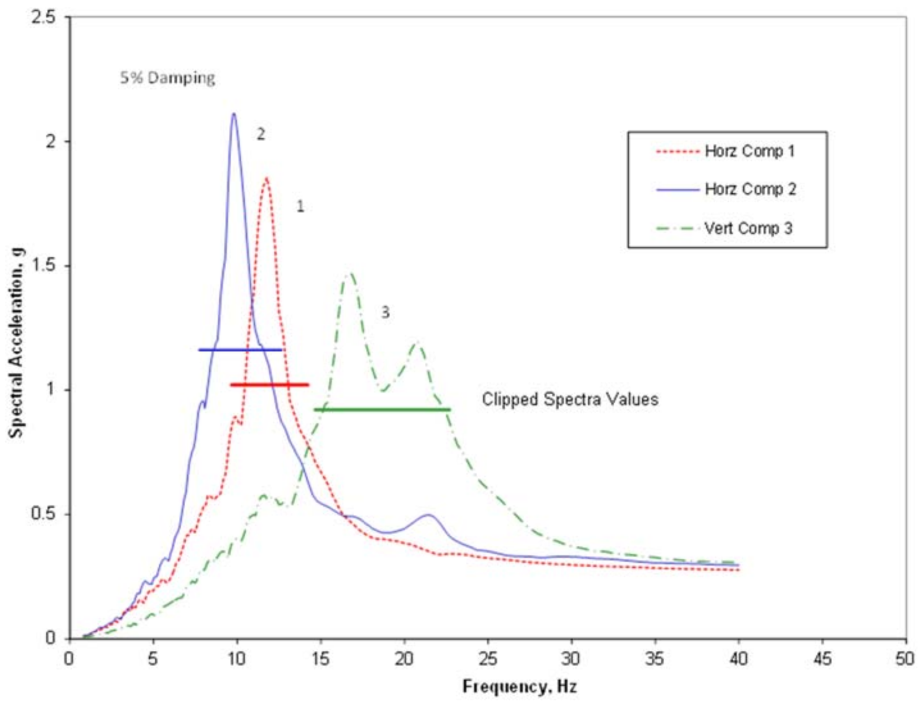


Figure C-1
Example In-Structure Spectra with Clipped Levels

This example reflects the expected floor spectra for a stiff nuclear plant structure when subjected to a ground motion with dominant frequency input in the greater than 10 Hz range. The spectra for the two horizontal response directions are very narrow band input motion with peak horizontal accelerations of 1.9g at 11.1 Hz and 2.1g at 9.7 Hz, which are the major horizontal structure modes. Both spectra have a bandwidth ratio less than 0.2, thus a clipping factor C_c = 0.55 applies and the spectra are clipped at 1.9 x 0.55 = 1.05g and 2.1 x 0.55 = 1.16g which are the effective wide band spectral levels. The vertical spectrum, however, appears to be associated with two coupled narrow band modes at 17 Hz and 21 Hz. In general, coupled modes will be: 1) well separated, for which the clipping procedure is applied to each peak; 2) closely coupled, for which the overall bandwidth ratio of both peaks governs; or 3) intermediate coupling, for which the maximum clipped spectral value determined for the set of peaks governs. In Figure C-1, the clipped value for the vertical spectrum based on the bandwidth ratio of the 17 Hz peak would be 0.81g; however, the overall bandwidth ratio of the two peaks governs with a clipped value of 0.92g.

C.2.2 Clipping Procedure for Fragility Evaluations

As noted above, the clipping factors for use in component fragility evaluations were developed in EPRI TR-103959 [11] by removing the conservatism associated with the CDFM philosophy.

The recommended median values of $\breve{C}_c$ (EPRI TR-103959) are as follows:

$\breve{C}_c = 0.30 + 0.86B \qquad B \leq 0.4$ *Eq. C-6a*

$\breve{C}_c = 0.50 + 0.36B \qquad B > 0.4$ *Eq. C-6b*

where B is again given by Equation (1) and the associated uncertainty, β_u, is given by:

$\beta_u = 0.37 - 0.50B \qquad B \leq 0.4$ *Eq. C-7a*

$\beta_u = 0.24 - 0.17B \qquad B > 0.4$ *Eq. C-7b*

This fragility clipping procedure was validated for the high frequency range greater than 20 Hz in the Phase 1 portion of the EPRI High Frequency Program by comparing the clipped spectral test capacity determined using narrow-band filtered input motion to the wide-band test capacity determined for the same component. Since the fragility procedure was developed from the CDFM procedure, the CDFM procedure is also validated for the high-frequency range.

C.3 Cabinet Amplification Factors

The second stage of the process for determining the component mounting point demand involves estimating the peak response regions of in-cabinet response spectra that result from the cabinet response (effective filtering of motion near the cabinet modal frequencies). A cabinet-mounted component is subjected to a narrow-band motion, which is the response of the cabinet enclosure to motion at the cabinet anchor points. It is assumed that this motion at the cabinet base is wide-band random structure motion. Effective amplification factors, denoted as AF_c, have been developed from actual cabinet tests (using wide-band input motion at the base) which provide the ratio of in-cabinet spectra to cabinet base motion, which may be interpreted as effective transmissibility functions. The amplification factor, AF_c, is meant to be applied to the clipped in-structure effective wide-band motion. Appendix I to EPRI NP-6041 [21] provides a review of the development of these amplification factors. These amplification factors are essentially clipped values of normalized in-cabinet response spectra. The median values and the associated variability were determined from cabinet tests focusing on the cabinet locations with the highest measured amplification. The HCLPF value for this subset of data for a given type of cabinet was then determined. It is recognized that the use of a HCLPF based factor introduces additional conservatism in the in-cabinet mounting point response above the desired target CDFM response level at the 84% percentile. These amplification factors were developed jointly by the USNRC and EPRI during the A-46

program resolution, and as such, represent a conservative bias. The focus of this prior development was on horizontal cabinet amplification with the assumption that amplified vertical response would be negligible due to high vertical cabinet frequencies and low vertical frequency content considered in design input motions. For input motions with high-frequency content, the vertical cabinet response will be amplified. The development of vertical cabinet amplification factors for high frequency input motion is presented in the following subsection of this Appendix.

An alternate approach is presented in EPRI NP-5223 [31], which uses the ratio of test measured horizontal in-cabinet response spectra and cabinet base response spectra as approximate transmissibility functions. The subset of these narrow-band transmissibility functions with the highest amplification is then clipped to obtain worst-case effective wide-band response amplification factors, which are independent of the component mounting point within the cabinet. The resulting factors were in the same range as those recommended in the A-46 Program and adopted, with a general procedure modification, in EPRI NP-6041 [21] for use in the IPEEE Program [6]. Similar to the previous study, vertical cabinet amplification was not considered.

These effective cabinet amplification factors were developed assuming that the in-structure motion was wide band; thus, they are meant to be factored times the clipped narrow-band in-structure spectra to obtain an overall effective wide band input level for the cabinet-mounted component. The maximum product of the clipped in-structure demand and the applicable cabinet amplification factor within the 4 to 40 Hz frequency range is used as the cabinet demand.

$$AF_c\ SA_{ci} = AF_c\ C_c \text{ x } \max\{SA_{pi}\} \qquad \textit{Eq. C-8}$$

It must be noted that the product of the effective cabinet amplification factor and the clipped in-structure spectra is not to be interpreted as reduced values of component mounting point demand, but instead is to be considered as a conversion of narrow-band response to effective wide-band response for cabinet-mounted components placed at the location with the highest amplification. Since these factors are not true amplification factors, they have also been denoted as "screening amplification factors" [31]. There is also a conservative bias in this approach since it assumes that the clipped region of the in-structure spectrum is effectively within the frequency bandwidth region of the clipped peak in-cabinet response spectrum.

C.3.1 CDFM Cabinet Amplification Factors (Horizontal Direction)

Recommended CDFM values of AF_c for the horizontal direction are provided in Appendix Q to EPRI NP-6041 [21] for three general cabinet types identified in EPRI NP-7148 [7] assuming 5% in-cabinet response spectrum damping:

Motor Control Centers	AFc = 3.6	*Eq. C-9a*
Switchgear (flexible panels)	AFc = 7.2	*Eq. C-9b*
Control Cabinets (e.g., Control Room electrical panels and benchboards)	AFc = 4.5	*Eq. C-9c*

EPRI NP-7148 [7] classified the cabinet types as 1) high amplification structures such as switchgear panels and other similar large flexible panels, 2) medium amplification structures such as control panels and control room benchboard panels, and 3) low amplification structures such as motor control centers. The high- and the low-amplification enclosures have easily recognizable configurations while the medium amplification enclosures represent a broad range of control cabinet configurations. EPRI NP-7148, Appendix I, identifies the recognizable characteristics of medium amplification cabinets and indicates certain configurations for which the amplification factors are not applicable.

These values are valid for both low- and high-frequency ranges since they are fundamentally associated with the application of clipping to effective cabinet transmissibility functions. It must be noted that these factors differ from the values developed for the A-46 Program [37] by inclusion of the multi-axis to single-axis correction factor, $F_{MS} = 1.2$, in the general evaluation procedure. The use of this factor, and other factors associated with HCLPF capacity determination, is explained in Section 4.5 of this report. It also should be noted that the horizontal amplification factor for control cabinets was developed in EPRI NP-7146 [32] using measured in-situ modal frequency and mode shapes from actual installed cabinets in plants and then adapted for the procedure of EPRI NP-6041.

Figure C-2 shows a plot of the clipped in-structure horizontal spectra of Figure C-1 factored by the cabinet horizontal amplification factor for a control cabinet ($AF_c = 4.5$). Plots, such as shown in Figure C-2, are not actual in-structure spectra but rather are a computational aid for choosing the frequency regions of the maximum mounting point demand to be used for comparison with relay capacity values which, in general, for the current evaluation procedure, are defined as an envelope of test capacity spectra within the 4 to 40 Hz frequency range. The clipped frequency band, or plateau region, defined by the spectral value $SA = [AF_c\ C_c \times \max\{SA_{pi}\}]$ is the converted region of effective wide-band motion that should be compared to the factored component wide-band test capacity. For example, in CDFM evaluations, the HCLPF capacity for relays in the low-frequency range is taken as the GERS capacity divided by the knockdown factor, $F_K = 1.5$.

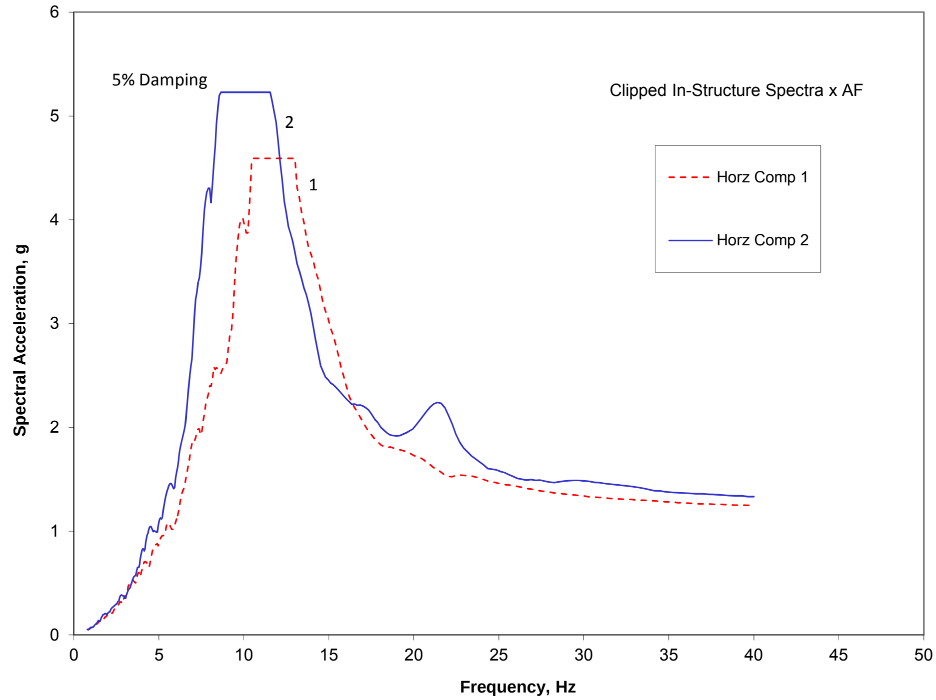


Figure C-2
Example In-Structure Clipped Horizontal Spectra Factored by AFc = 4.5

C.3.2 Cabinet Factors for Fragility Evaluations (Horizontal Direction)

Recommended median values of horizontal $\breve{AF}_c$ along with the associated variability in terms of both randomness and uncertainty are provided in EPRI TR-103959 [11] for the same general cabinet types assuming 5% spectral damping:

Motor Control Centers	$\breve{AF}_c = 2.8$, $\beta_r = 0.10$, $\beta_u = 0.23$	*Eq. C-10a*
Switchgear (flexible panels)	$\breve{AF}_c = 4.4$, $\beta_r = 0.13$, $\beta_u = 0.37$	*Eq. C-10b*
Control Cabinets	$\breve{AF}_c = 3.3$, $\beta_r = 0.11$, $\beta_u = 0.27$	*Eq. C-10c*

These values are valid for both low- and high-frequency ranges since they are fundamentally associated with the statistics of the peak transmissibility values and with the application of clipping to cabinet transmissibility functions. As noted above for the CDFM factors, there are other factors that are included in the evaluation procedure, such as the multi-axis to single-axis conservatism factor, $\breve{F}_{MS}$ = 1.25. The use of this factor, and other factors associated with median capacity and demand determination, is explained in Section 5.3 of this report.

C.4 Development of Vertical Cabinet Amplification Factors

As noted above, the prior development of cabinet amplification factors focused on the horizontal direction only. Cabinets and structures were considered as having high vertical frequencies (> 20 Hz) and thus were not in the range of the primary frequency content of ground input motion (2 to 10 Hz) considered for design or IPEEE evaluations. The vertical response level of equipment was assumed to be very small compared to the response level of equipment in the horizontal direction. The new hazard studies have resulted in vertical GMRS that are often equal or greater than the horizontal GMRS with peak values occurring in the 25 to 35 Hz range for firm rock sites. For these ground input motions, the vertical acceleration response of both structures and mounted equipment can no longer be ignored. While the induced stress levels due to high frequency vertical response of components are expected to be small, the acceleration response can no longer be dismissed as negligible. To determine the demand on cabinet mounted components, it is now necessary to develop vertical cabinet amplification factors.

C.4.1 Determination of Cabinet Response Characteristics

Electrical cabinets and enclosures are usually not designed for resisting dynamic loads. They are designed for manufacturing convenience, electrical code requirement (e.g., minimum 14 ga. steel sheet construction), and loads encountered in shipping. For earthquake loading, the usual practice is to test a typical cabinet on a shake table for the specified dynamic environment and provide reinforcement in critical locations as required. However, since the vertical design input motion was a secondary consideration, cabinets usually had limited test instrumentation to determine the vertical response characteristics. Thus, the cabinet vertical response will be idealized by using a simplified dynamic model. In the vertical direction, most cabinets are simple structures. The corners are formed heavy gage formed steel sheet shapes with attached steel sheet metal sides. There may be internal vertical back panels for the attachment of components. In general, the vertical load path is direct axial loading of the vertical structure members without significant flexure or shear of the member connections. In general, a cabinet may be idealized as an equivalent uniform axial bar in the vertical direction with mass distributed uniformly along the height. The axial stiffness of the cabinet can be represented by (EA)/H, where (EA) is an effective area times the elastic modulus and H is the cabinet height. The

quantity (EA) can be considered as an equivalent property of the cabinet structure in the vertical direction. If the effective vertical bar is considered fixed at the base (an unrealistic assumption), the fixed-base frequency of the axial bar is given by Blevins [36]:

$$f_\infty = \omega_\infty/(2\pi) = (\beta H)/(2\pi)\sqrt{EA/(mH^2)} \qquad \textit{Eq. C-11}$$

where $(\beta H) = \pi/2$, ω is the circular frequency, and m is the mass per unit height. The normalized mode shape is given by:

$$\bar{\emptyset} = \sqrt{2}\, Sin\left[\beta H \left(\frac{x}{H}\right)\right] \qquad \textit{Eq. C-12}$$

The participation factor for base input is:

$$\Gamma = \frac{\sqrt{2}}{\beta H} = 0.9 \text{ , thus } \Gamma\bar{\emptyset}[@\frac{x}{H} = 1.0] \text{ is 1.27.}$$

Since the theoretical ideal of a fixed boundary cannot be achieved in practice (particularly for a base anchored cabinet), a base spring is introduced to represent the local compliance of the cabinet base and anchorage as shown in Figure C-3.

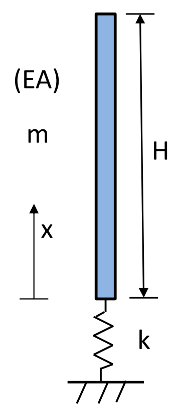


Figure C-3
Idealization of Cabinet as Vertical Bar with Base Compliance

For the case with base compliance present, the frequency is given by Blevins [36]:

$$f = \omega/(2\pi) = \lambda_k/(2\pi)\sqrt{EA/(mH^2)} \qquad \textit{Eq. C-13}$$

where λ_k is given by the frequency equation, $Tan(\lambda_k) = \gamma/\lambda_k$, and where $\gamma = kH/(EA)$.

The corresponding mode shape is Blevins [36]:

$$\phi = Cot(\lambda_k)\ Cos(\lambda_k[x/h]) + Sin(\lambda_k[x/h]) \qquad \textit{Eq. C-14}$$

The normalized mode shape is given by:

$$\overline{\emptyset} = \phi N$$

where N is given by:

$$N = 1/([1/(2\, Sin^2(\lambda_k)) + [2/(\lambda_k)]\, Cos(\lambda_k)\, Sin(\lambda_k)])^{1/2}$$

Then the participation factor for base input is $\Gamma = \frac{N}{\lambda_k}$ and

$$\Gamma\overline{\emptyset} = \Gamma N[Cot(\lambda_k)\, Cos(\lambda_k[x/h]) + Sin(\lambda_k[x/h])] \qquad \text{Eq. C-15}$$

The frequency equation for the first mode frequency, λ_1, is plotted in Figure C-4 as a function of γ.

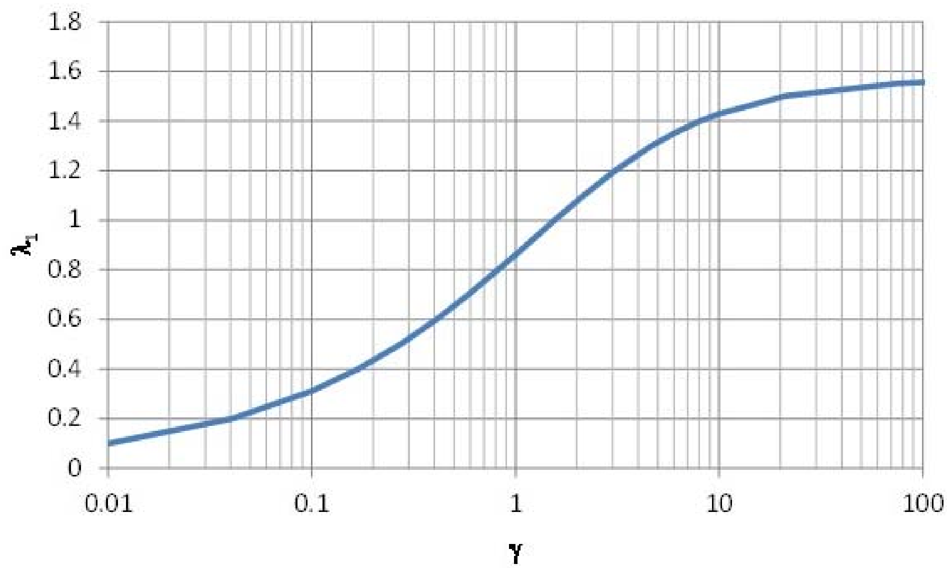
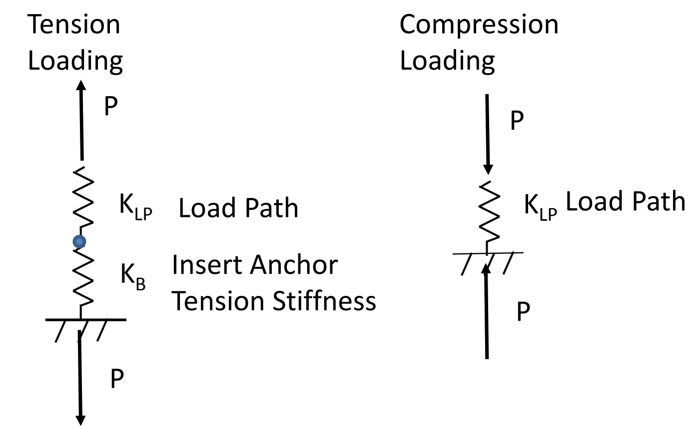


Figure C-4
Frequency Equation for Vertical Bar with Base Compliance

For typical cabinet installations, the parameter $\gamma = kH/(EA)$ will span the range of values from 1 to 10. To demonstrate this, consider the following example of base compliance. Each cabinet anchor point can be idealized with the cabinet load path stiffness shown in Figure C-5. The tension stiffness of a concrete insert anchor is given by K_B and the load path stiffness of the cabinet base is given by K_{LP}. For tension loading (i.e., cabinet uplift), the composite tension stiffness for the series pair is given by $K_t^* = [\alpha/(1+\alpha)]\, K_B$ where $\alpha = K_{LP}/K_B$. For compression loading of the cabinet anchor point, only the cabinet load path stiffness is active since the cabinet is bearing directly on a concrete floor. Thus, the composite compression stiffness is simply, $K_c^* = K_{LP} = \alpha\, K_B$, where the anchor tension stiffness is used as a proxy reference stiffness value. The effective anchor stiffness for vibratory loading is taken as the average of the tension and compression stiffness, or $K^* = [K_t^*+K_c^*]/2 = ½\, [\alpha/(1+\alpha)+\alpha]\, K_B$.



$$1/K_t^* = 1/K_{LP} + 1/K_B$$
$$= (K_B + K_{LP})/(K_{LP}\,K_B)$$
Let $K_{LP} = \alpha K_B$
$$1/K_t^* = (K_B + \alpha K_B)/(\alpha K_B\,K_B)$$
$$K_t^* = [\alpha/(1+\alpha)]K_B$$

$$K_c^* = K_{LP} = \alpha K_B$$
(using K_B as a reference value)

Effective Vibratory Stiffness
$$K^* = (K_c^* + K_t^*)/2$$

Figure C-5
Base Load Path Composite Stiffness

Per EPRI TR-103960 [33], the approximate tension stiffness of a 1/2 in. diameter insert anchor is about 500 Kip/in. Assuming that, due to the eccentricity of the anchor from the cabinet corners and the flexibility of the base members in the load path from the anchor point to the vertical cabinet corner posts, the load path stiffness is approximately 1/4 of the anchor bolt stiffness, or α =0.25, then the composite anchor point stiffness is K* =[0.25/(1+0.25) + 0.25](500)/2 = 112.5 Kip/in. There are four anchor bolt locations, but the anchors in the cabinet front are assumed to be only one-half effective due the presence of the door. Then, the effective base compliance is k = 3K* = 337.5 Kip/in. Referring to NUREG/CR-4659 [34], a typical single bay control cabinet has a weight of about W=1450 lbs and has dimensions of 30 in. x 30 in. x 90 in. (H). To estimate the effective parameter (EA), consider that the fixed-base frequency of the example cabinet is f_∞ = 33 Hz. Equation (11) may be rewritten as $f_\infty = (1/4)\sqrt{EA/H)(g/W)}$, then EA/H may be computed as (EA/H) = $4^2(33)^2(1450)/386.4$ = 65.4 Kip/in and the resulting γ is calculated as γ=k/(EA/H) = 337.5/65.4 or γ= 5.16. Using Figure C-4, or the frequency equation, $Tan(\lambda_k) = \gamma/\lambda_k$, the resulting λ_1 is 1.32. For a cabinet with base stiffness, Equation (13) can be written as $f_1 = [\lambda_1/(2\pi)]\sqrt{k/\gamma)(g/W)}$ and the cabinet frequency estimate is:

$$f_1 = [1.32/(2\pi)]\sqrt{337.5x1000/5.16)(386.4/1450)} = 27.7 \text{ Hz}.$$

Thus, the estimated cabinet frequency is within the 25 to 35 Hz range of peak GMRS motions that have resulted from the new hazard studies conducted for the plant sites. Further, the vertical building structures that have been reanalyzed for the GMRS as part of ongoing SPRAs have shown that vertical in-structure spectra can have frequencies in the 20 to 30 Hz range. Thus, the clipped region of the in-structure spectrum is within the frequency bandwidth of the in-cabinet response, which validates the assumption that the clipped in-structure spectrum value should be directly factored by the cabinet amplification factor.

Figure C-6 plots the associated mode shapes over the cabinet height for a range of the parameter values assigned to γ. At various heights within the cabinet, the acceleration level will be given by the product [$\Gamma\bar{\phi}$ SA_c]. For values of $\gamma < 10$, the maximum values of $\Gamma\bar{\phi}$ are less than 1.0.

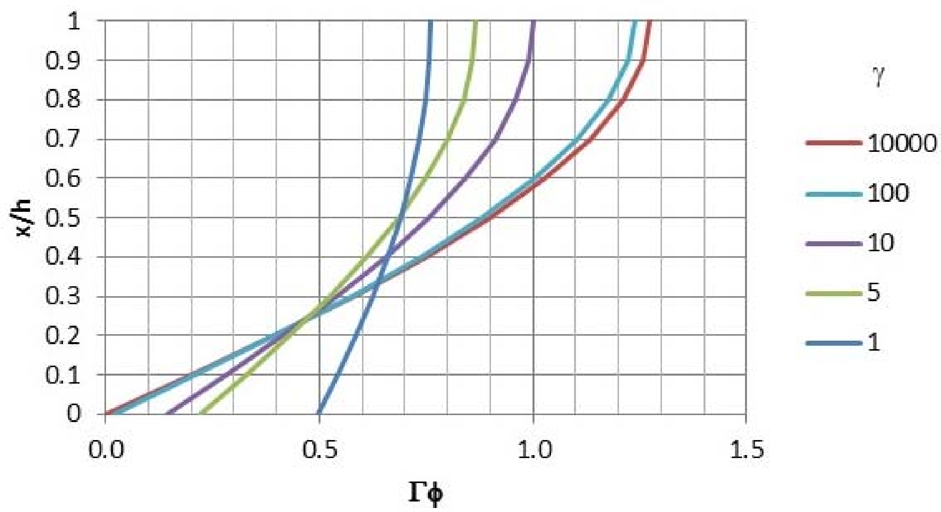


Figure C-6
Base Load Path Composite Stiffness

C.4.2 Determination of Vertical Cabinet Amplification Factor

By considering an in-cabinet response spectrum as the result of a cascade of single degree of freedom (SDOF) responses, the resulting cabinet amplification may be estimated by using random vibration theory. For an in-cabinet oscillator located at a given cabinet position, each cabinet mode component may be considered as an independent input to the in-cabinet oscillator, and thus the contribution of each mode component to the in-cabinet oscillator response can be considered as the response of two cascaded SDOF systems. The output of the first stage with frequency f_1, or cabinet modal response of the vertical mode, is used as input to the second stage, which is the response spectrum oscillator (on the cabinet) with frequency f_2. The output of the second stage is the cabinet response spectrum ordinate. Now, given that the base input motion for the first stage (or cabinet) is characterized as white noise, the root-mean-square (RMS) response of the first and second stage may be obtained from the white noise results presented in the text by Crandall and Mark [35] for a two-SDOF cascade.

Denoting the first stage response as the RMS value A_{1RMS}, and the second stage response as A_{2RMS}, the functional relations presented by Crandall and Mark (1963) [35] may be utilized to obtain a normalized amplification function which compares the uncoupled response of the in-cabinet oscillator to the cabinet response at the point of attachment. This cascade amplification function is denoted as the response ratio:

$$AF_T = \frac{A_{2RMS}}{A_{1RMS}}\left(\frac{f_2}{f_1}, \xi_1, \xi_2\right)$$

which is a function of the frequency ratio and damping values of the two SDOF systems. This function is essentially a transmissibility function, which, when clipped, will provide the desired effective cabinet amplification factor. The peak mounting point demand is given by the value $SA_{mp} = (\Gamma\phi)\ AF_T\ SA_c$. Since $(\Gamma\phi)$ will be a maximum of unity at the cabinet top for $\gamma < 10$, $SA_{mp} = AF_T\ SA_c$ is assumed to be the worst-case mounting point peak demand. The clipped mounting point demand is then $SA_{mpc} = C_c\ AF_T\ SA_c = AF_c\ SA_c$.

We will begin by estimating the vertical cabinet amplification factor for fragility evaluations. Figure C-7 shows a normalized amplification function for the case of 7% cabinet damping and 5% in-cabinet response spectra damping. A cabinet damping of 7% is judged to be consistent with the fragility methodology. The peak value $\breve{AF}_T = 6.5$ and the resulting clipping factor is $\breve{C}_c$ = 0.46 using Equation 6a (B = 0.183). The clipped level value is $\breve{AF}_c$ = 3.0 for determining the vertical demand for components mounted in all cabinets. The randomness associated with the amplification factor is estimated as $\beta_{r,AF}$ = 0.11. The clipping uncertainty $\beta_{u,cf}$ = 0.28 is determined using Equation 7a. Based on Appendix I to EPRI NP-6041 [21] the uncertainty in the peak factor $\breve{AF}_T$ is estimated as $\beta_{u,pf} \sim 0.23$. The combined uncertainty for the amplification factor is then given by $\beta_{u,AF} = [\beta^2_{u,cf} + \beta^2_{u,pf}]^{1/2} = 0.36$. Summarizing, for fragility evaluations, the vertical cabinet amplification factor is:

$\breve{AF}_c$ = 3.0, $\beta_{r,AF}$ = 0.11, $\beta_{u,AF}$ = 0.36

Now, given $\breve{AF}_c$ = 3.0, $\beta_{r,AF}$ = 0.11, and $\beta_{u,AF}$ =0.36, the CDFM amplification factor may be determined by using Equation I-4 in Appendix I to EPRI NP-6041 [21] with the four device capacity variability cases identified in Appendix I:

Case 1: $\beta_{u,D} = 0.18$ $\beta_{r,D} = 0.09$, resulting $AF_{c,\,HCLPF}$ = 4.72

Case 2: $\beta_{u,D} = 0.21$ $\beta_{r,D} = 0.09$, resulting $AF_{c,\,HCLPF}$ = 4.59

Case 3: $\beta_{u,D} = 0.27$ $\beta_{r,D} = 0.135$ resulting $AF_{c,\,HCLPF}$ = 4.30

Case 4: $\beta_{u,D} = 0.21$ $\beta_{r,D} = 0.04$, resulting $AF_{c,\,HCLPF}$ = 4.84

Since $AF_{c,\,CDFM} = AF_{c,\,HCLPF}$, the clipped level value of broad frequency input spectrum device capacity factor for determining the vertical demand for components mounted in all cabinets is reasonably estimated as $AF_{c,\,CDFM} = 4.7$. This resulting vertical AF_c for use in CDFM evaluations was determined in the same manner as was done for the horizontal amplification factor for Motor Control Centers and Switchgear, and thus consistently reflects the same level of conservatism.

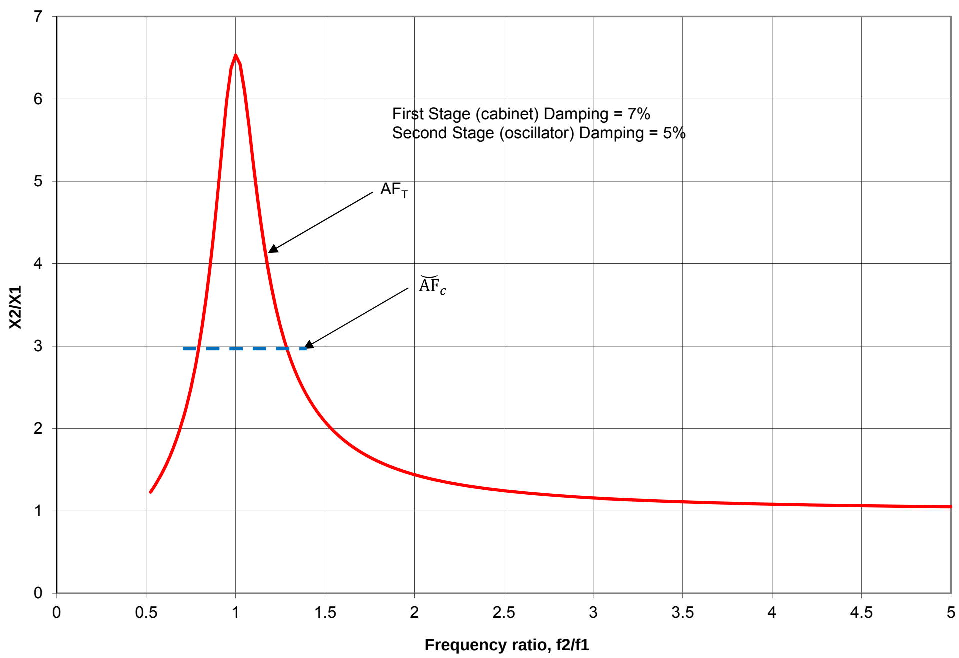


Figure C-7
Fragility Vertical Cabinet Amplification Function with Clipped Level Indicated

Appendix D: Example Characterization of Seal-In and Lockout Impacts

Table D-1
Example Characterization of Seal-In and Lockout Impacts to be Assessed in High Frequency Confirmation Evaluations

Function	Objective	Seal-In and Lockout Impacts to Be Assessed
Reactor Trip/Scram	No impact on reactor scram signal	N/A – No plant-specific assessment required. Design of reactor protection systems does not include seal-in and lockout relays that prevent successful scram.
RCS/Reactor Vessel Inventory Control	Confirm reactor coolant system integrity is not challenged, i.e., no induced LOCA.	PWRs: • Pressurizer PORV logic • Letdown isolation valve logic BWRs: • SRV actuation circuits • ADS actuation logic
RCS/Reactor Vessel Pressure Control	No impact on RPV/RCS pressure control.	N/A – No plant-specific assessment required. Pressure control is assured through passive components (e.g., relief valves)
Core Cooling	Confirm one train of AC-independent core cooling not challenged.	PWRs: • AC-independent EFW/AFW pump • Steam supply valve circuits/diesel fuel oil supply, as applicable. • EFW/AFW pump trip circuits • Valve logic for flow path from water source to Steam Generator BWRs: • AC-independent core cooling pump, e.g., HPCI/RCIC or Isolation condenser isolation valve logics, as applicable. • Steam supply valve circuits for HPCI/RCIC, as applicable. • HPCI/RCIC pump trip circuits, as applicable • Valve logic for flow path from water source to RPV

Table D-1 (continued)
Example Characterization of Seal-in and Lockout Impacts to be Assessed in High Frequency Confirmation Evaluations

Function	Objective	Seal-In and Lockout Impacts to Be Assessed
AC/DC Power Support Systems	Confirm EDG start and load on medium voltage buses and DC power provided to maintain battery charging.	• EDG start logic • EDG trip logic • EDG output breaker logic • Required EDG support system trip logic and valve logic • Medium voltage bus lockout circuits • Bus lockout circuits that would prevent supplying battery charger • Battery charger • Inverters required for instrumentation • Circuits that would prevent supplying power from charger to batteries/inverters • Circuits that would prevent battery from supplying DC bus, if necessary for instrumentation or AC-independent core cooling

Program:

Risk and Safety Management

3002004396

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