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March 19, 2007

Mr. Nilesh C. Chokshi
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U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: EPRI Draft White Paper *"Considerations for NPP Equipment and Structures Subjected to Response Levels Caused by High Frequency Ground Motions"*

Project Number: 689

Dear Mr. Chokshi:

Enclosed for NRC review is the first draft of a white paper on the subject of considerations for NPP equipment and structures subjected to response levels caused by high frequency ground motions. It is the intent of the industry to have this document published when it is finalized.

We look forward to discussing this white paper with NRC staff in the near future so that we can reach a common understanding on the revised regulatory requirements for siting new nuclear facilities at CEUS sites.

If you have any questions on this letter or its enclosure, please contact Rick Hill at rahill@erineng.com.

Sincerely,

A.P. Heymer

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Considerations for NPP Equipment and Structures Subjected to Response Levels Caused by High Frequency Ground Motions

DRAFT

Considerations for NPP Equipment and Structures Subjected to Response Levels Caused by High Frequency Ground Motions

DRAFT Technical Update Report, March 2007

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ARES Corporation, Inc.

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EXECUTIVE SUMMARY

A resurgence of interest in nuclear siting has led to submittals for early site permits (ESP) and the preparation of combined license (COL) applications by several companies. A significant area of uncertainty for application approval is resolution of an appropriate treatment of the high frequency component of the site-specific seismic design response spectra being established for many potential nuclear plant sites in the Central and Eastern United States (CEUS).

Existing nuclear power plants have been designed using either the site-independent Regulatory Guide 1.60 design spectrum shape (normalized spectral acceleration as a function of frequency) or other site-independent spectra shapes (Housner, NUREG/CR-0098, etc.) that have dominant spectral amplification in the frequency range of 2-10 Hz. In contrast, site-specific uniform hazard-based response spectra for CEUS hard rock sites have dominant spectral amplification in the greater than 10 Hz frequency range. However, the site-specific CEUS response spectra at hard rock sites contain significantly less displacement and lower response spectra amplification in the frequency range less than 10 Hz and are, consequently, expected to be less damaging to plant components, structures, systems, and components (SSCs), than site-independent spectra shapes similar to the Regulatory Guide 1.60 design spectra. But CEUS site-specific spectra shapes may contain spectral amplification at frequencies higher than 10 Hz that exceed the spectral amplification contained in the standard Regulatory Guide 1.60 spectrum shape. These high frequency spectral exceedances are considered to cause negligible additional response stresses within typical nuclear plant SSCs, but may be significant to the functional performance of vibration sensitive components, such as relays.

In the context of this report, high frequency spectral accelerations are those that exceed the standard Regulatory Guide 1.60 spectral shape at high frequencies. Nuclear structures (existing plants and new designs) are very stiff with fundamental frequencies within the range 3-15 Hz. In general, most nuclear structures have fundamental modes less than 10 Hz in the horizontal directions and would not be expected to have significant horizontal response to site-specific spectral shapes that have high spectral accelerations in the frequency range above 10 Hz.

Historically, nuclear power regulation has considered the high frequency components of ground motion to be non-damaging. In the late 1970s and mid-1980s, small earthquakes occurred near two nuclear power plants (Perry and Summer) that were under construction. The Perry plant was undergoing startup procedures at the time of the earthquake. The plant seismic instrumentation recorded motion with high frequency content that yield response spectra that exceeded the SSE design response spectrum at frequencies larger than approximately 15 Hz, yet subsequent walkdown inspection and evaluation of the plant responses indicated that exceedance of the design response spectrum in the high frequency range caused no damage to structures and equipment and had no consequence on plant operation. A number of small magnitude reservoir induced earthquakes occurred near the Summer plant in 1978 and 1979 that were recorded by a nearby free-field USGS strong motion instrument. These recorded motions were of very short duration, but yielded spectral accelerations that exceeded the SSE design spectra for the plant at high frequencies. Both plants were subjected to extensive evaluations that concluded that the earthquakes did not have a significant effect on SSCs of either plant. These events demonstrated that nuclear plant structures and equipment have the capability to withstand high frequency motions that were not part of the plant design basis and prompted the USNRC to reconsider the adequacy of Regulatory Guide 1.60 (Bernero, 1988).

Analytically, structures with low fundamental frequencies can generally be shown to be unaffected by high frequency content in the input motion. Structures with high natural frequencies will have very low displacements and correspondingly low stresses. In general, it may be observed that relative displacement response causes structural damage and that high frequency motions are associated with very low, non-damaging relative displacements.

Empirically structures and equipment have been subjected to high frequency motions from a variety of different sources. Structures and mounted systems have sustained base input motion induced by mining/quarry or construction blasting operations without damage. The few instances of fossil-fired power plants subjected to local low magnitude earthquake ground motions have shown that plant structures and the associated equipment systems are not affected by high frequency motion content associated with close-in low magnitude seismic events.

Qualification testing of equipment systems has demonstrated that equipment can sustain unintentional high amplitude, high frequency motion associated with the operation of large shake tables. For some equipment systems, the high frequency dynamic environment is part of the qualification procedure to demonstrate that certain vibrations caused by operational transients do not affect the function of the equipment. Various test programs have subjected equipment to a variety of increasing levels of input motion to ascertain the functional limits or fragility level of the equipment.

This evidence has been used, both implicitly and explicitly, by the USNRC to justify their conclusion that any additional effort (testing or analysis) beyond the design basis to address high frequency response effects for operating nuclear power plants was not warranted. This conclusion and the associated regulatory actions by the USNRC are based on the following programs, initiatives, and publications:

- Individual Plant Examination for External Events (IPEEE) – GL 88-20, Supplement 4
- USNRC panel report on the implications of updated probabilistic seismic hazard analysis (PSHA) estimates that resulted in an increased high frequency hazard at Watts Bar
- Extensive inspection of the Perry Nuclear Power Plant following the 1986 earthquake with the conclusion that the exceedance of the design spectra in the high frequency range did not have engineering significance
- Seismic confirmatory program of the Summer plant following the reservoir induced earthquakes of 1978 and 1979, which satisfied the ASLB and ACRS requirements to document the lack of engineering significance

- Regulatory Guide 1.166, developed in response to the issue of OBE exceedance at high frequencies, which concluded that frequencies over 10 Hz do not need to be considered in the determination of whether shutdown is warranted following a felt earthquake

As discussed herein, the resolution of the effects of high frequency seismic motions have been extremely difficult to quantify within the numerous evaluations conducted; however, these analytical evaluations and aggregates of empirical evidence have consistently resulted in a qualitative assessment of the high frequency motions as non-significant. For the advanced reactor plants, quantification of high frequency issues will again be difficult to address, especially for those plant configurations that do not consider internally generated high frequency dynamic loads (e.g., hydrodynamic loads), potentially resulting in significant costs and schedule delays. Such efforts are considered unnecessary since the consensus of technical experts is that high frequency seismic motions in the greater than 20 Hz range are only significant for sensitive, non-ductile components such as relays. Limited analytical evaluations are proposed for typical structures and components, as applicable, to confirm the conclusion that structure and component design based on Regulatory Guide 1.60 spectra can also withstand the high frequency input typical of a hard rock CEUS site. In addition, a program has been proposed to identify potentially sensitive active components and to confirm their functionality for high frequency input. The issue of high frequency exceedances of in-structure design spectra should be resolved by the following efforts:

- To support the determination that limited high frequency exceedances are not potentially damaging to structures and components, a limited number of evaluations should be performed. These evaluations should include portions of building structures, primary systems, piping systems, and components evaluated by analysis. Structures and components should be selected to include locations where exceedances of the design in-structure response spectra occur. In addition, components should be selected based on which high frequency modes are deemed to have significant response. The discretization level of the structural models used may also need to be examined in order to obtain sufficient numerical accuracy for determination of high frequency response. Evaluations should compare results for input motion based on the current Regulatory Guide 1.60 based design spectra to results obtained for motions consistent with CEUS site-specific response spectra. These limited comparisons should demonstrate the adequacy of design based on the Regulatory Guide 1.60 spectra.

- A separate industry program, including (1) identification of high-frequency sensitive or non-ductile equipment and components, (2) establishment of screening criteria, (3) development of evaluation methods, and (4) recommendations for additional testing procedures, should be initiated to address the functional performance of equipment that could be sensitive to high frequency vibration input.

ACKNOWLEDGEMENTS

This report represents the consensus position of the nuclear industry on the effects of high frequency seismic ground motion and the recommended licensing approach to deal with any potential exceedances of the design certification basis of advanced plants due to high frequency earthquake motion. The following individuals are members of the NEI Seismic Issues Task Force (SITF) and have contributed to this report:

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A separate Technical Review and Advisory Group (TRAG) has been appointed by EPRI to provide peer review. The members of the TRAG are:

Robert Kennedy (Chair)	RPK Structural Consulting
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Don Moore	Southern Nuclear
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Carl Stepp	Earthquake Hazards Solutions

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LIST OF ACRONYMS

ABWR -	Advanced Boiling Water Reactor
ACRS -	Advisory Committee on Reactor Safeguards
ALWR -	Advanced Light Water Reactor
ASCE -	American Society of Civil Engineers
ASLB -	Atomic Safety and Licensing Board
BWR -	Boiling Water Reactor
CAV -	Cumulative Absolute Velocity
CEUS -	Central and Eastern United States
COL -	Combined License
EPRI -	Electric Power Research institute
ESP -	Early Site Permit
EUS -	Eastern United States
HCLPF-	High Confidence of Low Probability of Failure
IEEE -	Institute of Electrical and Electronics Engineers
INEL -	Idaho National Engineering Laboratory
IPEEE -	Individual Plant Examination for External Events
LLNL -	Lawrence Livermore National Laboratory
NEI -	Nuclear Energy Institute
NPPs -	Nuclear Power Plants
NRR -	Nuclear Reactor Regulation
OBE -	Operating Basis Earthquake
PRA -	Probabilistic Risk Assessment
PSHA -	Probabilistic Seismic Hazard Analysis
RLE -	Review Level Earthquake
RRS -	Required Response Spectrum
SDOF -	Single Degree of Freedom
SSE -	Safe Shutdown Earthquake
SSHAC-	Senior Seismic Hazard Analysis Committee
STIF -	Seismic Issues Task Force
TRAG -	Technical Review and Advisory Group
TRS -	Test Response Spectrum
UHRS -	Uniform Hazard Response Spectrum
USGS -	United States Geological Survey
USNRC-	United States Nuclear Regulatory Commission
WUS -	Western United States
ZPA -	Zero Period Acceleration

1
PURPOSE

This document provides a review of the response of structures and equipment to various dynamic environments that are rich in high frequency content. In the context of this report, high frequency ground motions are those caused by seismic events that produce exceedances of standard Regulatory Guide 1.60 spectra at high frequencies. However, these same events produce spectral responses that are significantly lower at the typical fundamental frequencies of nuclear structures than those generated using Regulatory Guide 1.60 spectra. There is substantial empirical evidence that such high frequency excitations are not damaging to power plant and heavy industrial structures and equipment; nor do they cause functional performance anomalies in power plant or heavy industrial equipment systems. In the past, evidence has been found that justifies that additional equipment dynamic qualification effort (testing or analysis) beyond the seismic design bases for operating nuclear power plants (NPPs) to address high frequency response effects is not warranted.

2
INTRODUCTION AND BACKGROUND

The recognition of differences between the frequency content of standard seismic design spectra shapes and the expected site-specific spectra shapes for Central and Eastern United States (CEUS) sites is not a new subject. Discussions of the appropriate high frequency cut-off for seismic motion were initiated during the development of the Regulatory Guide 1.60 design spectrum (USNRC, 1973). Based on studies using the available set of recorded Western United States (WUS) ground motions available at that time (1973), it was concluded that the higher frequency content of seismic motion could be represented as uniformly (on a log spectral acceleration-log frequency scale) decreasing from about 9 Hz to a cut-off value of 33 Hz. The choice of the 33 Hz cut-off was primarily motivated by the fact that the then available recorded ground motions yielded response spectra that indicated no amplification beyond about 30 Hz (Newmark, 1978). Also, it should be noted that ship-borne systems, at that time, were evaluated and tested for vibratory motion with 33 Hz being the upper frequency limit.

During late 1970s and early 1980s, the ACRS recommended that the USNRC consider risk-based regulation based on probabilistic design criteria. Since a major external initiating event for a given plant site was due to the regional seismic hazard, the USNRC focused on research during the 1980s which would identify the frequency and uncertainties associated with a seismic event and the accompanying response of the plant structures and the mounted equipment systems. Both the USNRC and EPRI conducted Probabilistic Seismic Hazard Analyses (PSHAs) for the sites of operating NPPs located in the central and eastern United States (CEUS). A set of Uniform Hazard Response Spectra (UHRS) were developed by both studies for each analyzed plant site. The published results of the two studies (LLNL, 1989; USNRC, 1994; and EPRI, 1989a) were extensively peer reviewed with general consensus of results reached (recognizing large parameter uncertainty) during the early 1990s. One of the major research results was the recognition that site-specific spectral shapes of the UHRS for CEUS sites was distinctively different from site-specific UHRS spectral shapes for WUS sites and from the Regulatory Guide 1.60 standard spectral shape. The UHRS for CEUS sites (particularly rock sites) tended to reach maximum acceleration values in the 20-30 Hz range while the WUS have maxima in the 2-9 Hz range.

Since the deterministic seismic design criteria used for design of the then operating plants was entirely based on the available seismic record base of the WUS, this noted difference between the expected UHRS and the seismic design spectra impacted the plant evaluation program which was initiated in 1985 by the USNRC to identify the seismic margin beyond the plant design basis. The program guidance contained in USNRC Generic Letter 88-20, Supplement 4 and NUREG-1407 (USNRC, 1991) for the Individual Plant Examination of External Events (IPEEE) recognized the results of the hazard studies which indicated the presence of relatively higher spectral amplitudes at frequencies greater than 10 Hz when compared to the plant design bases. However, the NUREG/CR-0098 (Newmark, 1978) median spectral shape was adopted for the review level earthquake (RLE) used in the required seismic margin evaluations. The IPEEE guidance concluded that no plant-specific response was necessary to address concerns related to high frequency spectral acceleration content as long as a special margin evaluation of non-ductile components, such as relays, was conducted. This conclusion was based upon the USNRC judgment that only brittle materials and devices employing electro-mechanical contacts are sensitive to high frequency spectral accelerations (USNRC, 1991).

During the late 1970s and 1980s, seismograph networks including strong motion instruments were placed at Canadian and CEUS locations. When Canadian and CEUS earthquake rock motions were recorded, they yielded high spectral amplitudes at high frequencies. The data recorded by the Canadian and CEUS networks formed the basis of a new generation of engineering ground motion prediction equations for Eastern North America (EPRI, 1993).

Small earthquakes occurred near two nuclear power plants (Perry and Summer) that were under construction in the late 1970s and mid 1980s. The Perry plant was undergoing startup procedures at the time of the earthquake in 1986. Although the seismic instrumentation recorded high frequency motion content that yielded response spectra which exceeded the OBE and SSE design response spectra of the plants, yet subsequent walkdown inspections and evaluation of the plant responses indicated that exceedance of design criteria in the high frequency range produced no damage to safety-related SSCs and had no adverse consequence on plant operation. The series of small magnitude reservoir induced earthquakes which occurred near the Summer plant in 1978 and 1979 were recorded by a nearby free-field USGS strong motion instrument. These recorded motions were of very short duration, but the response spectra contained high spectral accelerations at high frequencies which exceeded the OBE and SSE design response spectra of the plant. An extensive seismic confirmatory program was undertaken to resolve ASLB and ACRS concerns with resulting conclusions showing lack of engineering significance. Had these plants been fully operational, shutdown would have been required in accordance with USNRC regulations.

Evaluations of the significance of the high spectral accelerations from these small earthquakes occurring at high frequencies demonstrated that nuclear plant structures had the capability of sustaining high frequency motions that were not part of the plant design basis and prompted the USNRC to reconsider the adequacy of Regulatory Guide 1.60 (Bernero, 1988). The evaluations of these earthquakes also prompted EPRI to initiate a research program (EPRI, 1988 and EPRI, 1991c) to develop OBE exceedance criteria to address the future occurrence of CEUS earthquakes near nuclear power plant sites. The results of this study were reviewed by the USNRC and, after consensus was reached on changes to the recommended criteria (Bagchi, 1992), the USNRC formulated Regulatory Guide 1.166 (USNRC 1997b), which only checks for OBE exceedances of spectral acceleration levels (5% damping) greater than 0.2 g in the less than 10 Hz frequency range.

The USNRC has encouraged operating plants to adopt the provisions of Regulatory Guide 1.166 which includes the installation of free- field digital accelerometers, the capability to process the record and compare to the OBE spectrum within 4 hours, and to inspect the plant within 8 hours. Thus, for plants that meet these provisions, shutdown is not required for exceedance of the OBE spectrum by the spectral acceleration content of free-field motion in the frequency range greater than 10 Hz. Again, this conclusion was motivated by a consensus judgment that high frequency spectral accelerations (> 10 Hz) are not damaging to heavy industrial equipment and structures.

During the latter part of the 1990s, the USNRC revised their regulations to require formal quantification of uncertainty in assessments of SSE ground motion. The process of certification of advanced reactor designs was begun using 0.3g Regulatory Guide 1.60 seismic design spectra as the standard design basis. The design of the advanced reactors proceeded using Regulatory Guide 1.60 spectrum shape since it had been accepted by the USNRC for seismic design of nuclear plants licensed since 1973. Given this history, the utilities and vendors reasonably assumed that the site-independent Regulatory Guide 1.60 spectrum would continue to be accepted, as it indeed was accepted by the USNRC for the certified design of the advanced plants. The USNRC did not raise the issue of the adequacy of the Regulatory Guide 1.60 spectrum during the advanced plant design reviews.

The USNRC also developed Regulatory Guide 1.165 (USNRC, 1997a) as the recommended approach of deriving site-specific SSE ground motion using site-specific probabilistic seismic hazard results. Regulatory Guide 1.165 recommended that site-specific SSE ground motions for future nuclear plant sites be based on a hazard-based target reference probability of median 1E-5/yr. Following the adoption of Regulatory Guide 1.165, the USNRC initiated a research program for the purpose of developing procedures for determining site-specific response spectra (NUREG/CR-6728 [REI, 2001] and NUREG/CR-6769 [REI, 2002]). This research demonstrated procedures for deriving risk-consistent site-specific response spectra. During this same time period, a performance goal-based procedure for determining SSE response spectra was developed and adopted as ASCE Standard 43-05 (ASCE, 2005).

Given the recent interest in nuclear power, several utilities have applied for an early site permit (ESP) and, consequently, attempted to utilize the new guidance to develop site-specific SSE response spectra for CEUS sites. For deep soil sites, the high frequency content of the CEUS bedrock outcrop is attenuated, resulting in surface SSE response spectra similar in shape to the Regulatory Guide 1.60 design spectra shapes generally used for the certification of new plant designs. For rock and intermediate soil sites, the high frequency content of the CEUS bedrock outcrop is not attenuated, resulting in surface SSE response spectra that have spectral accelerations (for spectral frequencies above about 10 Hz) that are larger than the Regulatory Guide 1.60 design response spectrum accepted for advanced reactor designs. Based on these high frequency ground motion issues identified in the first ESP, the nuclear power industry developed a number of enhancements to determine site-specific SSE response spectra. These include 1) the use of a CAV filter to remove the effect of low magnitude earthquakes, that have negligible potential for causing damage to nuclear plants, from the PSHA calculations, 2) the use of revised CEUS ground motion models in the PSHA calculations, 3) use of a performance goal approach to determine the site-specific performance-based response spectra, and 4) a methodology to account for ground motion incoherence effects in seismic design analyses. These enhancements have improved the definition of high frequency ground motion by taking appropriate consideration of new data and of performance-based seismic design criteria. But these enhancements do not directly address the focus of this report which is the observation that high frequency motions are essentially non-damaging. For many sites, depending on the plant design, it is still expected that limited high frequency exceedances of in-structure design spectra, generated using motions compatible with Regulatory Guide 1.60 ground motion spectra, will occur when the current enhancements are incorporated to determine site-specific motion and the subsequent analyses to determine the response of the plant structures.

3
DEFINING HIGH FREQUENCY EARTHQUAKE GROUND MOTION

The concept of a 'high' frequency motion is dependent on the discipline that is considering the motion being described. In the vehicle design industry, the range 100-1000 Hz is considered as the mid–range for the specification of the spectral content of motion used for design. In structural engineering, commercial structures with fundamental frequencies greater than 4 Hz are often denoted as high frequency structures, while nuclear plant structures with fundamental frequencies greater than 10 Hz are considered as high frequency structures.

In earthquake engineering, the zero period acceleration (ZPA) frequency is associated with rigid-body response, such that there is insufficient frequency content in the input motion to cause a single-degree-of-freedom (SDOF) system with that ZPA or higher frequency to respond and the system simply transfers the ground motion without amplification. Within the last two decades, as noted previously, hazard analyses have shown that surface rock motion in the EUS has high spectral amplitude content in the 20-40 Hz range with declining frequency content approaching a ZPA value at 100 Hz. This high frequency surface rock spectral amplitude content, attributed to the increased hardness of basement rock in the EUS (EPRI, 1993), is supported by a relatively sparse set of ground motion records in the CEUS which are used to develop model-based ground motion prediction equations.

Figure 3-1 compares foundation design motion submitted as part of an ESP for a CEUS rock site with the design spectra used for new plant certifications based on the use of a site-independent Regulatory Guide 1.60 spectrum or an augmented Regulatory Guide 1.60 spectrum. As can be noted, the example ESP spectrum significantly exceeds the spectra used for design certification in the greater than 10 Hz frequency range. In this report, high frequency spectral accelerations will be defined as those that exceed the standard Regulatory Guide 1.60 spectral shape at high frequencies.

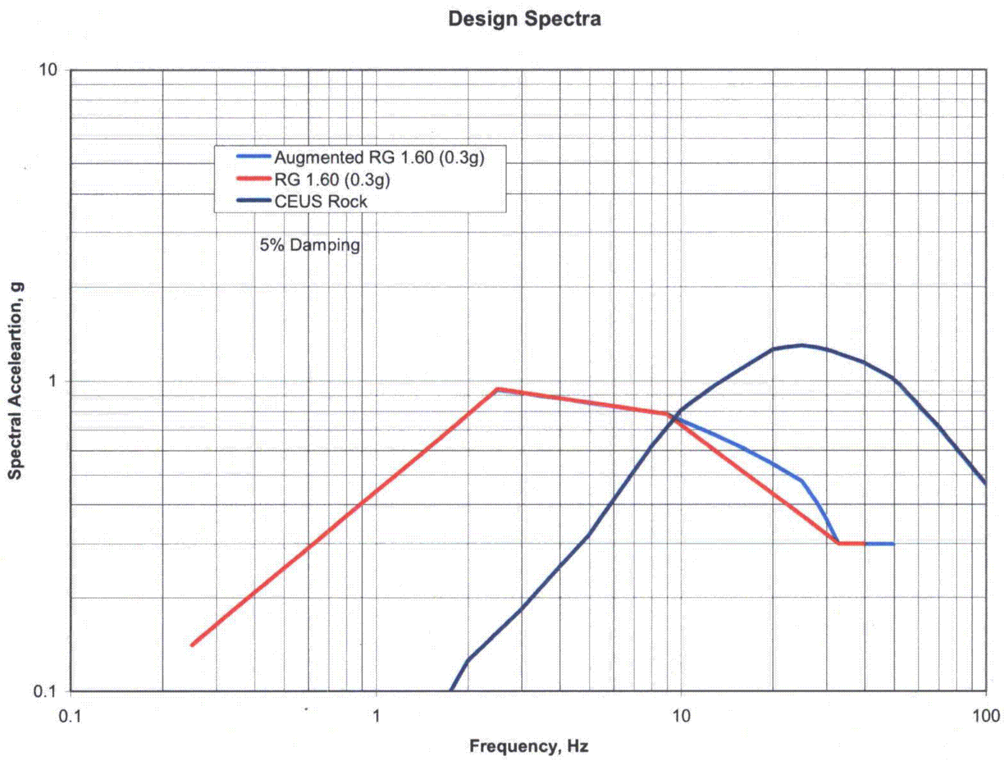


Figure 3-1
Comparison of an Design Motion Developed for a CEUS Rock Site and Design Motions Used for Design Certification (5% Damping)

Nuclear structures tend to be very stiff box-type concrete construction with wall thickness in the 2-3 feet range, and founded on thick base mats. The fundamental frequency of such structures can range from 3-15 Hz depending on the function of the structure and the wave speed of the foundation material (soil vs. rock vs. hard rock). Shield buildings and freestanding steel shells tend to have fixed base horizontal frequencies less than 10 Hz while the massive concrete internal structures providing shielding and support of the reactor vessel can have frequencies greater than 10 Hz. In general, most nuclear structures will have horizontal fundamental modes less than 10 Hz which implies that the major part of the in-structure response will be a filtered motion dominated by varying amplitude sinusoids that are controlled by the frequency content of the ground motion in the less than 10 Hz frequency range.

4 REGULATORY PRECEDENTS FOR THE ACCEPTANCE OF HIGH FREQUENCY MOTION

As initially noted, the USNRC has consistently accepted the design and evaluation of structures and systems that exclude the response effects of any high frequency content of ground motion. Based on the observation of structures and equipment systems subjected to high frequency motions, the USNRC staff has concluded that such motion is not damaging nor does it cause malfunction of control systems. The conclusions reached on the non-damaging effects of high frequency response for the IPEEE program and the issue of OBE exceedance are primary examples of USNRC acceptance of criteria that exclude the effects of high frequency ground motion on structures and systems.

For the conduct of the IPEEE program, the USNRC issued procedural guidance (USNRC, 1991). The following quote from NUREG-1407 provides the USNRC position on the consideration of high frequency ground motion effects:

> *"Because recent ground motion estimates, such as those included in the LLNL and EPRI hazard studies, indicate relatively higher ground motion at frequencies greater than 10 Hz than shown in the NUREG/CR-0098 spectrum, the margin evaluation of only non-ductile components – for instance, relays – that are sensitive to high frequencies should be performed as discussed(below). No plant-specific response analysis is anticipated to address concerns related to high frequency ground motion."*
>
> *"Attempts to address the concerns related to high-frequency ground motion by analysis is very likely to entail extensive efforts, including the development of new and much more complex building models that transmit and amplify high-frequency input and generate accurate and meaningful floor spectra at high frequencies. Estimates of high-frequency amplification in cabinets containing relays will also have to be developed. Rather than using analysis, the following approach is more suitable:*
>
> 1. *Prepare a list of relays that are known to have high-frequency sensitivity.*
> 2. *Screen relays that are known to have very high HCLPFs (that is, eliminate them from further consideration without performing specific response calculations).*
> 3. *Assume that the remaining relays will chatter at the review level earthquake.*
> 4. *Screen the remaining relays by showing either the circuitry is insensitive to high-frequency chatter or that they can be recovered from changes of state and associated false alarms.*

5. *Finally, replace the remaining relays with relays that are not sensitive to high frequency (an alternative approach is to show that the remaining relays are rugged by conducting tests)."*

The USNRC has conducted a trial implementation of the SSHAC (1997) guidance for conducting a PSHA at two existing reactor sites in the southeastern United States (LLNL, 2002). For one of these sites, Vogtle, the seismic hazard estimate was reduced from the previous (USNRC, 1994) hazard estimate while for the Watts Bar site the hazard increased particularly in the high frequency range. The reason for these changes was reportedly due to an increased understanding of seismic sources within the CEUS. The implication of an updated increased hazard estimate has been considered by the USNRC staff (USNRC, 2003) with the conclusion that the SSE exceedances in the high frequency range were considered to be non-damaging and had already been addressed by the IPEEE program. The following quote from this NRC letter summarized the USNRC position of the Watts Bar high frequency exceedance situation:

"Since the natural frequency range for most structures and equipment in nuclear power plants falls below 10 Hz, it is expected that the new hazard results will have a minimal effect on major structures, systems, and components at Watts Bar. High frequency ground motion above 10 Hz generally affects only active components, such as contact devices and relays, which are subject to chatter. Relays and components with high frequency sensitivity have been explicitly addressed in IPEEE evaluations."

"The panel discussed at length the basis for the IPEEE guidance on dealing with the high frequency issue and compared various ground motion spectra, including the latest models of NUREG/CR-6728 for the eastern United States. During the IPEEE guidance development, the issue of high frequency was explicitly addressed. As discussed above, the high frequency motion affects components, such as relays, and brittle components, e.g., potentially some anchorage. Based on tests conducted by NRC and the industry, a list of relays with known vulnerability was developed. During the IPEEE process, the plants were specifically addressing these relays. When identified, these relays were either replaced or shown not to have an adverse impact. The industry had also conducted tests to address the anchorage issue. Comparison of the ground motion results by NRC (NUREG-1488) and EPRI, and new results show differences in the ground motion level, but the frequency characteristics are essentially the same."

After the Northeast Ohio Earthquake of 1986 occurred near the Perry Plant, the USNRC conducted several investigations concerning the exceedance of the OBE by the response spectra computed from the plant recordings. The following quotes are from the Safety Evaluation Report on the Perry Plant issued by the USNRC (USNRC, 1986):

"The January 31 earthquake triggered the in-plant seismic monitoring instruments. Some of the recorded motions exceeded the design spectrum at high frequencies (above 15 Hz) for the Operating Basis Earthquake (OBE) and the Safe Shutdown Earthquake (SSE). The earthquake motion recorded at the reactor

building foundation was of short duration (about 1 second) and contained predominantly high-frequency elements"

"It is not unusual in an earthquake to have high-amplitude, high-frequency peak accelerations of limited duration."

"These high-frequency peak accelerations have not been used and should not be used in scaling and applying R.G. 1.60 design spectra because they are usually of short duration and little energy and are not representative of spectral response at lower, more significant frequencies."

"Preliminary analysis of data from the aftershocks suggests that the recorded ground motions in the free-field include high frequencies similar to ground motions recorded elsewhere in Arkansas, Anaz (California), New Brunswick, and at Monticello Reservoir. As at Perry, these earlier events did not result in any significant damage."

"On the basis of the results of detailed walkdowns conducted by the NRR staff and its consultants, Region III, and utility personnel which found no apparent equipment or structural damage that could be attributed to the Ohio earthquake of January 31, 1986, and on a reassessment of the seismic capability of a sampling of equipment types, it is the staff's opinion that the earthquake did not have any significance from an engineering view point on the equipment at the Perry plant. In other words, the design-basis earthquake may have been exceeded at some high, narrow frequency region of the response spectra, but the original overall plant seismic design was not affected. Therefore, the staff concludes that the previous conclusions regarding the adequacy of the applicant's seismic qualification program remain valid."

To address the OBE exceedance issue the USNRC issued Regulatory Guide 1.166 (USNRC, 1997b). In case of a seismic event which triggers plant free-field seismic instrumentation, Regulatory Guide 1.166 provides multi-step evaluation criteria to determine if the plant OBE has been exceeded. The following quote from Regulatory Guide 1.166 provides the primary check based on the response spectrum of the recorded free-field motion:

"The OBE response spectrum is exceeded if any one of the three components (two horizontal and one vertical) of the 5 percent of critical damping response spectra generated using the free-field ground motion is larger than:

1. *The corresponding design response spectral acceleration (OBE spectrum if used in the design, otherwise1/3 of the safe shutdown earthquake ground motion(SSE)spectrum) or 0.2g,whichever is greater, for frequencies between 2 to 10 Hz, or*

2. *The corresponding design response spectral velocity (OBE spectrum if used in the design, otherwise1/3 of the SSE spectrum) or a spectral velocity of 6 inches per second (15.24 centimeters per second), whichever is greater, for frequencies between 1 and 2 Hz."*

It can be noted that OBE spectral values are only checked for exceedance in the less than 10 Hz range. This is an implicit recognition that motion content in the greater than 10 Hz range is non-damaging and is also in agreement with those instances where actual recorded ground motion has exceeded a plant OBE in the greater than 10 Hz range without any damage or operational effects.

5
ANALYTIC STRUCTURAL RESPONSE CONSIDERATIONS

The response of a structural system to a base input motion is dependent on the separation of the fundamental frequency of the structure from the dominant frequency content of the input motion. First, consider a SDOF system with frequency f_n subjected to a base input motion of pure harmonic input motion with dominant frequency, f_i. Figure 5-1 shows the acceleration transfer function for a SDOF system with 7% damping.

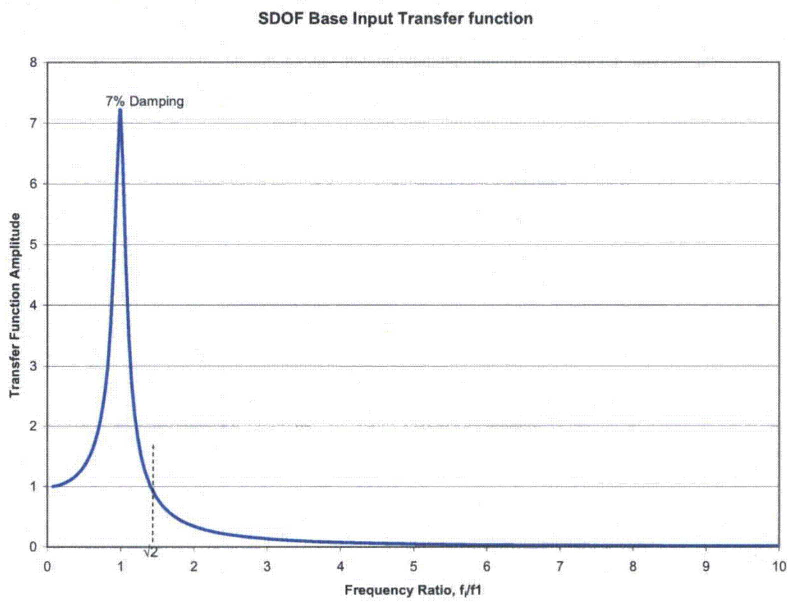


Figure 5-1
Acceleration Transfer Function for a SDOF System (7% Damping)

For $f_i > \sim\sqrt{2} \times f_n$, we have the classic case of the structure behaving as an isolation system with the acceleration response of the structure being attenuated (i.e., less than the ground motion). Thus, a low frequency SDOF structure does not fully respond to a high frequency base input motion. For $f_i << f_n$, the structure tends to respond as a rigid object with the ratio of the structure and ground motion approaching unity. For $f_i < \sim\sqrt{2} \times f_n$, the acceleration response of the structure is amplified with the tuned case ($f_i = f_n$) resulting in a maximum amplification factor of $1/(2\xi)$, where ξ is the fraction of critical damping for the SDOF system (resulting in a factor of 7.1 for a 7% damped system). If both f_n and f_i are close high frequencies, then this near tuned case will have high acceleration response but low resulting stresses, since the corresponding high frequency of the structure implies an excess of material in order to achieve the high structure frequency. In order to demonstrate this fact, it is useful to plot an acceleration spectrum as either pseudo-velocity or pseudo-displacement spectra. A response spectrum is a plot of the maximum SDOF response to a given base motion as a function of the SDOF oscillator frequency, f_n. In nuclear power engineering, it is traditional to compute the absolute spectral acceleration of the system, $Sa = Max|a + a_g|$, where a is the relative acceleration response of the SDOF mass and a_g is the input base acceleration. The pseudo-spectral velocity, PSv, is found by $PSv = Sa/\omega_n$, where ω_n is the circular frequency, $\omega_n = 2\pi f_n$. The pseudo-spectral displacement, PSd, is found by $PSd = Sa/(\omega_n)^2$. It can be shown that the pseudo-spectral displacement, PSd, is a close and conservative approximation to the maximum relative displacement, $\delta = Max|x|$, of the SDOF compliance element (effective spring), where x is the relative displacement of the SDOF system. Figures 5-2, 5-3, and 5-4 show the example CEUS rock spectrum (see Figure 3-1) plotted as separate SA, PSv, and PSd functions with abscissa values of SDOF frequency, f_n. Since $PSv = Sa/\omega_n = \omega_n PSd$, this information could be presented in a single tripartite plot, however, the frequency dependence of each variable would not be readily apparent. For example, reference to Figure 5-4 will indicate that the response displacement associated with the spectral frequency of 8 Hz is approximately $\delta \approx 0.10$ inch corresponding to a spectral acceleration of approximately 0.6g as indicated in Figure 5-2. At 33 Hz, the spectral displacement is approximately $\delta \approx 0.01$ inch corresponding to a spectral acceleration of approximately 1.2g. In terms of the behavior of structures and components, a deformation of 0.01 inch or less can be considered as negligible.

Figure 5-5 shows a simple structure, comprised of a low rise shear wall element supporting a floor mass, which may be idealized as a SDOF system with the system damping assumed to be 5%. Following the development of Figure 5-5, we can see that the maximum shear force, V, for a given frequency wall system is determined by product of the mass, $\underline{M}$, and spectral acceleration given by Figure 5-2, but that the stress in the wall element is determined by the spectral displacement given by Figure 5-4. For a low rise (H/L < 2) concrete wall, ASCE 43-05 indicates that the nominal wall capacity, in terms of maximum shear stress, may be taken as, $v_u = 5.3(f_c')^{1/2}$, assuming H/L = 1, zero vertical wall load, and considering concrete stress only (i.e., ignore reinforcing steel). Using the terms defined in Figure 5-5, we note that $G = E/[2(1+\nu)]$ and for concrete, $E = 57{,}000(f_c')^{1/2}$ and $\nu \sim 0.175$. Then, the apparent wall shear strain associated with wall capacity, δ_u/H, may be computed as $\delta_u/H = v_u/G = 2.185 \times 10^{-4}$. If the wall height is taken as H = 20 ft = 240 in, the displacement associated with wall capacity (ignoring the effect of reinforcing steel) is $\delta = 0.0524$ in. Referring to Figure 5-4 for the example CEUS site, we note that all SDOF walls (H= 20 ft), with frequency greater than ~14 Hz, will have displacement response levels less than 0.05 in., thus, the resulting wall shear stress level will be less than nominal capacity and be a decreasing function of frequency.

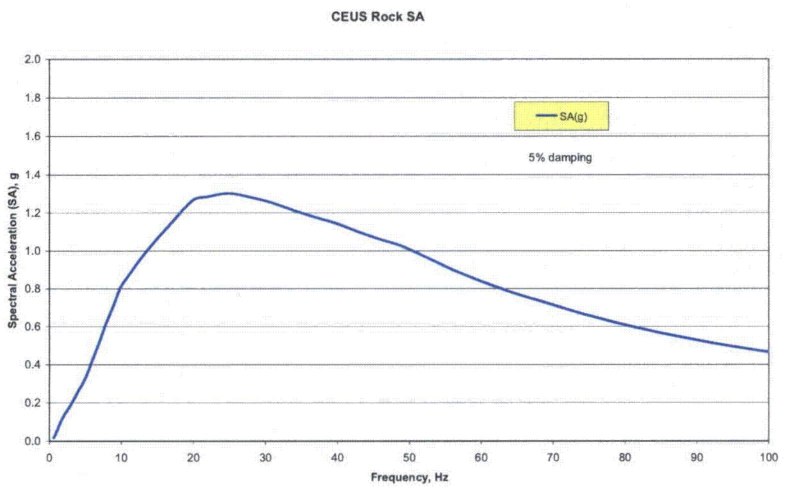


Figure 5-2
Spectral Acceleration Response Spectrum for CEUS Rock Site

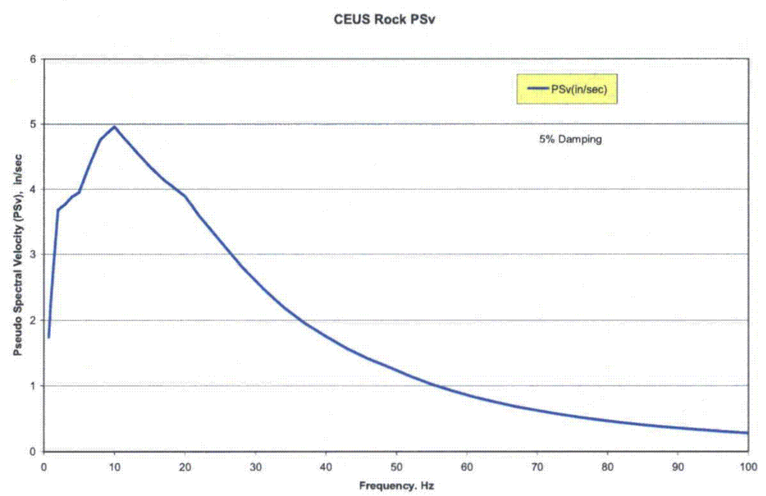


Figure 5-3
Pseudo-Spectral Velocity Response Spectrum for CEUS Rock Site

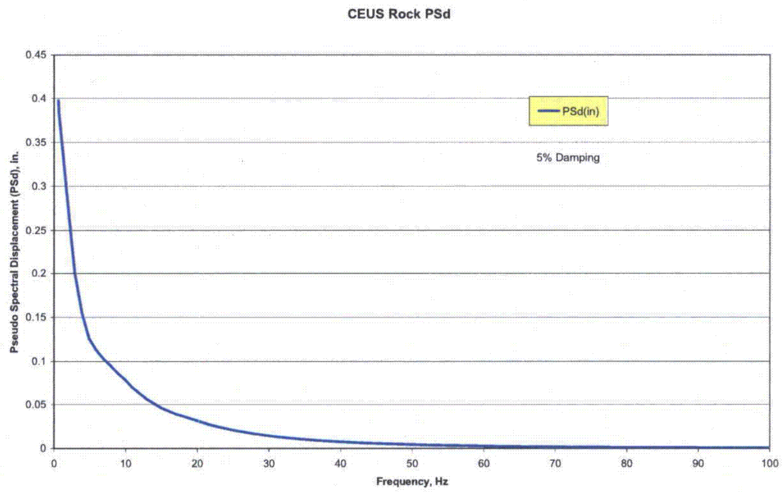
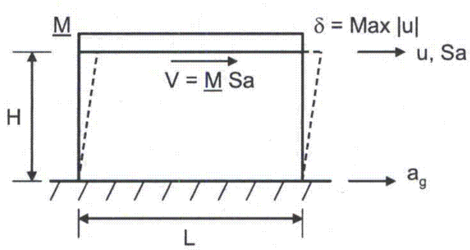


Figure 5-4
Pseudo-Spectral Displacement Response Spectrum for CEUS Rock Site



$Sa = \text{Max } |a + a_g|$

$PSv = Sa/\omega$

$PSd = Sa/\omega^2 \approx \delta$

u = wall displacement	K = wall stiffness = GA_s/H
H = wall height	G =Shear Modulus $=E/[2(1+\nu)]$
L = wall length	ν = Poison's ratio (≈ 0.175)
A_s = wall shear area	E = modulus of elasticity = $57000(f_c')^{1/2}$
$\underline{M}$ = supported floor mass	v_u = maximum shear stress = $5.3\ (f_c')^{1/2} = G\delta_u/H$
V = wall shear	f_c' = concrete compressive strength

wall frequency, $\omega^2 = K/\underline{M} = GA_s/H\underline{M}$

wall stress $= v_u = V/A_s = (\underline{M}\ Sa)/A_s = G\ Sa/(\omega^2 H) = G\delta/H$

Now, $\delta_u/H = v_u/G = 5.3\ [2(1+\nu)]/57000$, and if $\delta < \delta_u$ then $v < v_u$

Figure 5-5
Idealized Single-Degree-of-Freedom Shear Wall Structure

Most structures have actual behavior similar to idealized distributed mass beams, such as a shear beam, flexural beam, or the combined shear/flexural Timoshenko beam. For the flexure and shear beams, the eigenfunctions are simple analytic forms which can be readily integrated to obtain values of the participation factors, however, the eigenfunctions for the Timoshenko beam are algebraically complicated requiring numerical integration to obtain values of the participation factors. The Timoshenko beam requires specification of two parameters r^2/h^2 and E/(kG), where r is the cross-section radius of gyration, h is the beam height, E is the modulus of elasticity, k is the cross-section shear factor, and G is the shear modulus. For general details of the governing equations for determining the modal frequencies, eigenfunctions, and participation factors, the reader is referred to the large body of texts and technical review papers (e.g., Han (1999), Papadopoulos (1980), Jacobsen, (1938)) on this subject. Figure 5-6 shows the acceleration transfer function for the case of an example uniform Timoshenko beam (r^2/h^2=0.1, E/(kG) =4.6) with 7% damping in all modes. As can be noted from Figure 5-6, the general attenuation of motion for inputs with frequency content higher than the fundamental frequency, f_1, is similar to a SDOF system except each higher mode can locally amplify a given input motion. There are also differences in response depending upon the location, x, along the height of the beam. For systems with several modes, the general issue concerning high frequency input motion is the effect of increased response of the higher modes. While the Timoshenko beam is judged to be the more representative structural model, the behavior of distributed mass systems is similar and the resulting equations can be placed in the same general form. For purposes of simplicity, a uniform shear beam may be used as an illustrative example structure to demonstrate the effect of high frequency input motion on structure response. The use of the analytic mode shapes and frequencies of uniform shear beam allows an accurate assessment of the high frequency modal response components. In general, for modeling of actual structures using finite element codes, the discretization level of the structural model used may need to be examined in order to demonstrate that the high frequency portion of the structural response is numerically accurate.

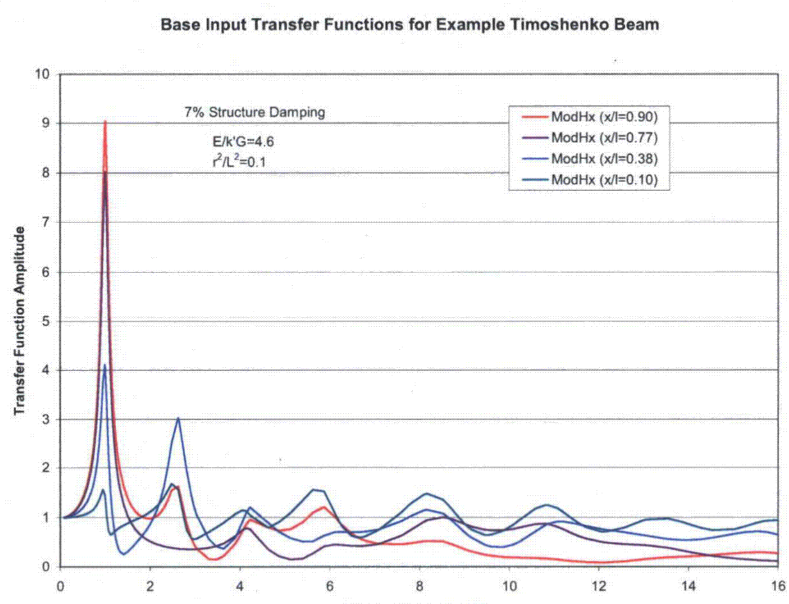
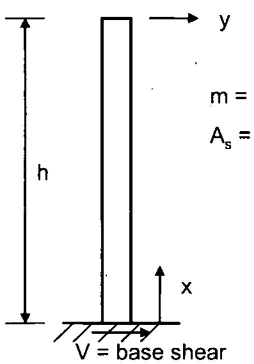


Figure 5-6
Acceleration Transfer Function for an Example Uniform Timoshenko Beam (7% Damping)

The development of Figure 5-7 shows that, for a uniform shear beam with a given fundamental frequency, each modal component of the base shear force in the beam is determined by the product of the total beam mass and the ratio $(\Gamma_n)^2$, where Γ_n is the modal participation factor, factored times the spectral acceleration shown in Figure 5-2 associated with each mode frequency. For a uniform shear beam, the ratios $(\Gamma_n)^2$ are 0.8106, 0.0901, 0.0324, 0.0165, and 0.0100 for the first five modes. Each modal component of the base section stress, however, would be determined by the product of a material and cross section related constant, $(G\rho/k)^{1/2}$, and the modal participation factor, Γ_n, factored times the pseudo-spectral velocity as given by Figure 5-3 associated with each mode frequency. For a uniform shear beam, the modal participation factor values Γ_n are 0.900, 0.300, 0.180, 0.1286, 0.100. and 0.082 for the first six modes. Figure 5-3 indicates that the pseudo-spectral velocity is a decreasing function of frequency for $f_n > 10$ Hz, thus when weighted by the decreasing modal participation factor, the modal components of the base section stress are a decreasing series. In the general case, the total base stress would be found using the appropriate procedure for combination of modal components (depending upon the closeness of mode frequencies). For a uniform shear beam, the mode frequencies are well separated ($f_n/f_1 = 1, 3, 5, 7$, etc.), thus the square-root-sum-of-squares (SRSS) procedure can be used to combined the components. A correction is included to account for the truncation of modes beyond the frequency associated with the ZPA.



h = height

ρ = mass density

A =cross section area

k = shear factor

G = shear modulus = $E/[2(1+\nu)]$

$\tau = V/A_s$ = shear stress

Modal frequency

$(\beta_n h) = \pi(2n-1)/2$, $\Gamma_n = (2)^{1/2}/(\beta_n h)$

$\omega_n^2 = (\beta_n h)^2 GA_s/(mh^2)$, $f_n = 2\pi\omega_n$

Mode shape (derivative)

$[y_{n,x}(x)] = (2)^{1/2}\beta_n\cos(\beta_n x)$

Modal response

$\delta_n = Sa/(\omega_n^2)$

Base shear (modal component)

$$V_n = GkA\,[y_{n,x}(x=0)]\,\Gamma_n\delta_n$$
$$= GkA\,(\beta_n h)(2)^{1/2}\Gamma_n/(h\omega_n^2)\,Sa$$
$$= mh\,\Gamma_n^2\,Sa$$

Base section stress (modal component)

$$\tau_n = V_n/(kA) = G(\beta_n h)(2)^{1/2}\Gamma_n/(h\omega_n^2)\,Sa$$
$$= (G\rho/k)^{1/2}(2)^{1/2}\Gamma_n\,PSv$$

ZPA correction

$$= \quad (1 - \sum_1^n \Gamma_n^2)(G\rho/k)^{1/2}(\pi/2)\,ZPA/\omega_1$$

Figure 5-7
Idealized Shear Beam Structure

The net effect of the higher modes on response can best be seen by an example problem using the CEUS rock spectrum given in Figure 5-3. Consider a concrete shear beam with a 9 Hz fundamental mode and 5% modal damping:

k(thick wall cylinder)=	0.52	
f_c'=	5000	psi
$E=57000(f_c')^{1/2}$=	4030508.653	psi
ν=	0.175	
G=E/2/(1+ν)=	1715110.065	psi
ρ=150 lb/ft$_3$/g=	0.000224652	lb*sec^2/in^4
$(G\rho)^{1/2}$=	19.629	psi/(in/sec)
$v_u=5.3(f_c')^{1/2}$=	374.767	psi
ZPA=	0.469	g

Mode	f(Hz)	PSv(in/sec)	Γ_n	τ_n(psi)
1	9	4.860	0.900	168.440
2	27	2.945	0.300	34.023
3	45	1.471	0.180	10.195
4	63	0.781	0.129	3.868
5	81	0.685	0.100	2.639
6	99	0.295	0.082	0.930
			ZPA Corr	4.617
			SRSS	172.272
			τ/v_u	0.460

As can be noted from the above table, the effect of the higher modes on the total base section stress is small with the total stress considerably less than the nominal shear strength taken as $v_u = 5.3(f_c')^{1/2}$ for this example using the CEUS rock input motion shown in Figure 5-3. Other examples can be considered, but, in general, structures with low fundamental frequencies will not be affected by input motions with high frequency content. Structures with high natural frequencies will have correspondingly lower stresses. This can be demonstrated with the above concrete shear beam model by considering a hypothetical 25 Hz fundamental mode:

Mode	f(Hz)	PSv(in/sec)	Γ_n	τ_n(psi)
1	25	3.204	0.900	111.040
2	75	0.542	0.300	6.264
			ZPA Corr	13.616
			SRSS	112.047
			τ/v_u	0.299

6
EMPIRICAL HIGH FREQUENCY RESPONSE OF STRUCTURES AND EQUIPMENT

Structures and equipment systems have been subjected to high frequency motions from a variety of different sources. Structures and mounted systems have sustained base input motions induced by mining, quarry, and construction blasting operations without damage. Where nuclear power plants have been subjected to local low magnitude earthquake ground motions, the resulting investigations have shown that plant structures and the associated equipment system are not affected by high frequency motion content. Qualification testing of equipment systems has demonstrated that equipment can sustain unintentional high frequency motion associated with the operation of large shake tables. For some equipment systems, the high frequency dynamic environment is part of the qualification procedure to demonstrate that certain vibrations caused by operational transients do not affect the function of the equipment. Various test programs have subjected equipment to a variety of increasing levels of input motion to ascertain the functional limits or fragility level of the equipment.

Mining, Quarry, and Construction Blasting Operations

EPRI documented the available data on the effects of blasting on structures as part of the research program conducted (EPRI, 1988) to develop the OBE exceedance criteria. A response spectrum associated with the threshold cracking of un-reinforced masonry walls was developed based on the prior research of Hendron (1974). This prior research had used spectra associated with 3% damping to correlate observed damage. It was argued that the masonry damage threshold would be a conservative surrogate for nuclear plant concrete structures. Figure 6-1 compares the masonry cracking threshold for blasting to the example CEUS rock motion (note that to be consistent with the cracking threshold spectrum, the rock spectrum is also associated with 3% damping). As can be noted from Figure 6-1, the high frequency content of the CEUS rock motion is not capable of causing cracks in a masonry wall. Only for frequencies less than 4 Hz does the rock motion have the potential of cracking a masonry wall.

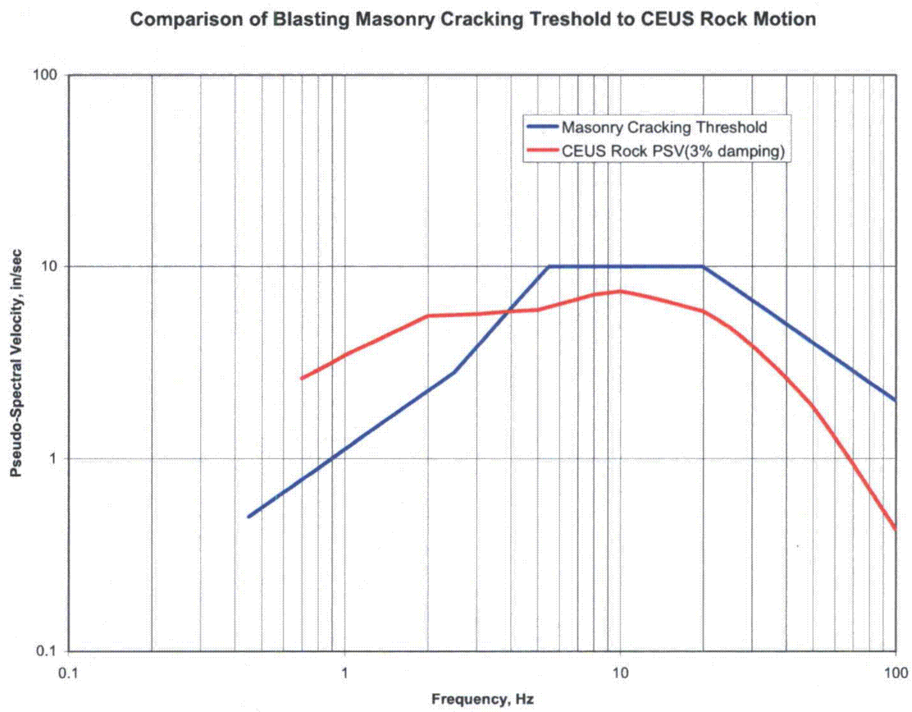


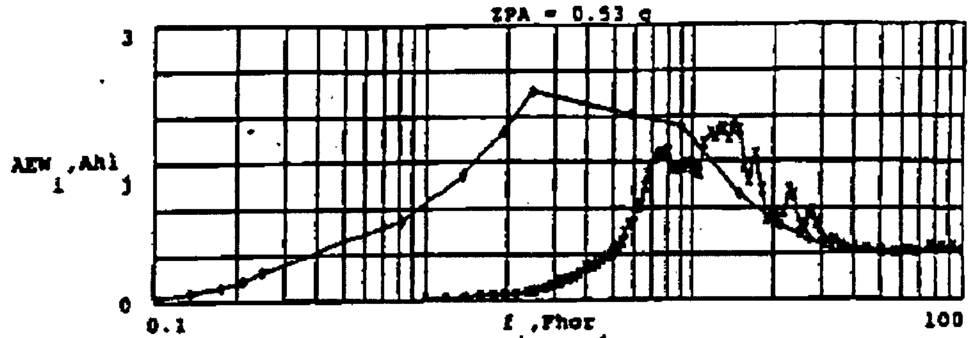
Figure 6-1
Masonry Cracking Threshold Due to Blasting Compared to CEUS Rock Motion (3% Damping)

Earthquake Experience

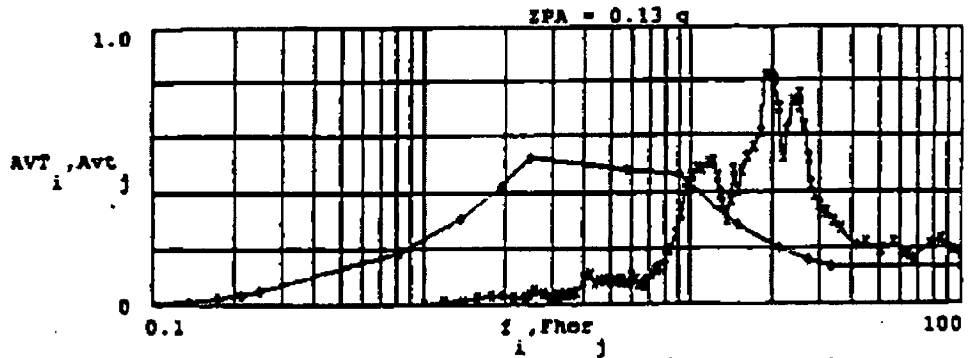
There are few documented occurrences of CEUS earthquakes occurring near power plants with seismic instrumentation. Most of the recordings which substantiate the ruggedness of power plant structures and equipment are from the WUS which does not have the same high frequency motion content found in the few available CEUS strong motion records. The most notable events that have occurred near CEUS NPPs are the Northeastern Ohio Earthquake of 1986 associated with the Perry Nuclear Power Plant (Chen, 1988) and the 1978/1979 South Carolina Monticello Reservoir induced events associated with the Summer Nuclear Station (Whorton, 1988). Strong motion instruments were activated at both plants; Perry had base mat and upper elevation instruments while Summer had only a free-field instrument. In both cases, the plants were under construction and there was no damage due to either event. However, both the OBE and SSE of each plant was exceeded by the recorded motions in the greater than 10 Hz range. Since the Perry Plant was undergoing operational testing prior to fuel load, the control circuits were powered and there was no spurious activation of plant safety-related controls. Three non-safety systems did experience trips due to relay activation. At the Summer plant, a significant seismic confirmatory program was undertaken to resolve ASLB and ACRS concerns about the exceedance of the design spectra in the high frequency range which were shown to lack engineering significance. These two cases were the primary motivation for the EPRI OBE exceedance research program and subsequent USNRC adoption of Regulatory Guide 1.166 using the EPRI developed criteria. The criteria excluded the portion of the OBE spectrum greater than 10 Hz from being considered primarily based on the observation that this high frequency content lacked damage potential (EPRI, 1988 and 1991c).

Several fossil-fired power plants were also subjected to the ground motion resulting from the 1986 Northeastern Ohio Earthquake. These plants were located at approximately the same distance from the epicenter as the Perry Nuclear Power Plant and all units experienced trips caused by turbine vibration sensors, switch activation, or operator action (EPRI, 1989b). All units were restarted and placed back into service.

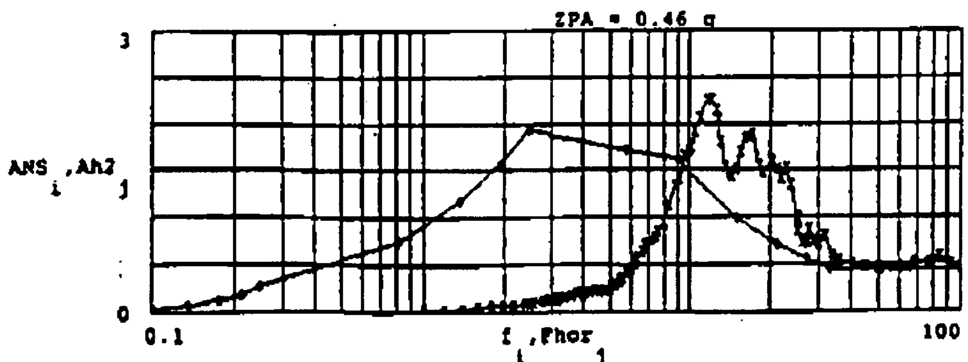
Looking beyond North America, there is one documented (Chen, 1992) low magnitude earthquake ground motion that has occurred in the vicinity of an operating nuclear power plant. The 1989 event near Krško, Slovenia subjected a US designed plant (the single unit plant is similar to the Robinson Plant in South Carolina) to an earthquake with magnitude M_D =3.9 (duration magnitude). The recorded free field acceleration time histories are characterized by motion durations less than one second but with horizontal peak acceleration values of 0.533 g and 0.456 g. Such short duration, high acceleration, records are typical of nearby low magnitude events. Other than spurious activation of non-safety-related level switches associated with the feed water reheaters, there was no physical damage or any spurious control activations of safety-rated circuits. The plant was manually shut down by the operators primarily due to the unfamiliar noises caused by the earthquake. The plant had several strong motion instruments that recorded the event. Figure 6-2 shows the response spectra computed from the free-field motion records. Each motion component is compared to a Regulatory Guide 1.60 Spectrum anchored to the ZPA of each recorded component in order to illustrate the difference in frequency content. Comparison of Figure 6-2 with Figure 3-1 shows the similarity of the frequency content of the recorded Krško, Slovenia, motion to the CEUS design motion. The Krško earthquake record provides direct evidence that such high frequency motions are not damaging to power plant structures nor are safety-related equipment functions impaired by the high frequency motion.



Direct comparison of Free-Field surface East-West spectrum with USNRC RG 1.60 Spectrum Units: g's, Hz.



Direct comparison of Free-Field surface Vertical spectrum with USNRC RG 1.60 Spectrum Units: g's, Hz.



Direct comparison of Free-Field surface North-South spectrum with USNRC RG 1.60 Spectrum Units: g's, Hz.

Figure 6-2
Free-Field Response Spectra (2% Damping) Associated with the Krško, Slovenia, Nuclear Power Plant Due to the 1989 Krško Earthquake
(2% damped RG 1.60 spectral shapes are anchored to the ZPA of each component to show the difference in frequency content)

Equipment Environmental Qualification Testing

There is a substantial database of equipment that has been qualified for the required response spectra (RRS) of operating plants. The dynamic portion of such qualification, in accordance with IEEE Std 323, is accomplished as a type test of aged equipment for the seismic RRS (in-structure motion due to plant SSE) and additional vibrations due to plant transients (such as BWR hydrodynamic loading). This type testing is accomplished using IEEE Std 344 and it should be noted that a large percentage of equipment seismic qualification is performed for mild environmental conditions that do not require the full application of IEEE Std 323 aging procedures. While the seismic RRS of operating plants do not, in general, have frequency content specified beyond 33 Hz (the Regulatory Guide 1.60 ZPA), shake table testing of equipment induces unintentional high frequency motion which is associated with the operation of large multi-axis shake tables. The spurious high frequency content is due to both actual table high natural frequencies and the ball joints/bearings used to achieve the multi-axis kinematic motion of the shake table. Figure 6-3 shows an example of a test response spectrum (TRS) produced by such a table motion. In the case shown, the equipment under test was a stationary battery rack with vented and flooded lead-acid aged batteries instrumented for voltage and current discontinuity (INEL, 1990). The primary functional test for aged batteries is the post-test cell discharge. For aged flooded lead-acid batteries with lead calcium cells, the additional high frequency content used in the qualification did not cause loss of rated function. Similar qualification test spectra with high frequency content can be found for electrical enclosures (battery chargers, inverters, etc.), instrumentation, and various mechanical components that show that such additional high frequency content does not adversely affect equipment function.

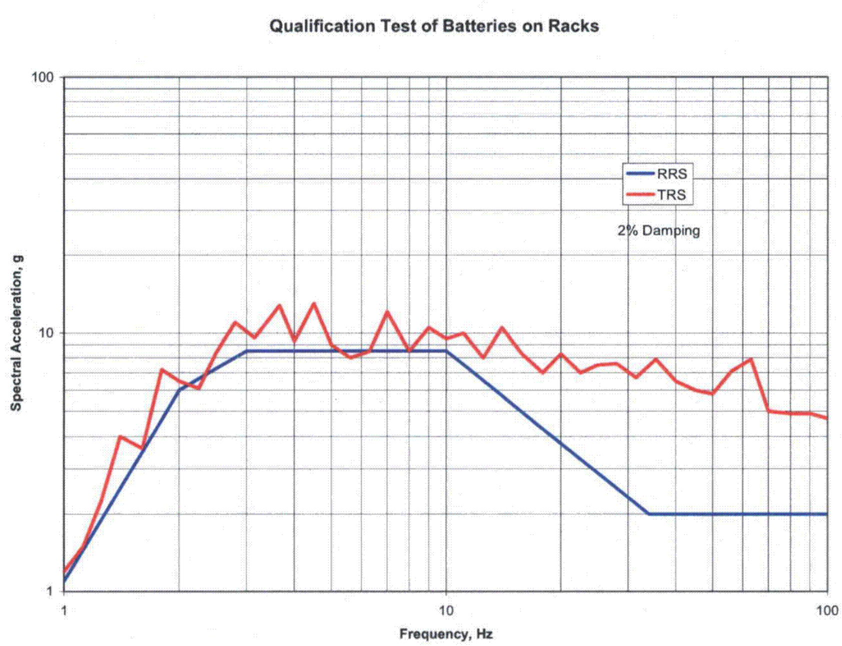


Figure 6-3
SSE Qualification Test of Lead-Acid Batteries on Racks

For some equipment systems, an additional high frequency dynamic environment is intentionally specified in the RRS to demonstrate that certain vibrations caused by operational transients (such as BWR hydrodynamic transients) do not affect the function of the equipment. Figure 6-4 shows a TRS from a valve operator qualification test for ABWR service (ARES, 2006). In this case, the valve operator is subjected to the "faulted" RRS motion (simultaneous SSE and hydrodynamic vibration). The valve operator is the same as used in other plant designs. Thus, these types of tests also show that additional high frequency content does not affect equipment function.

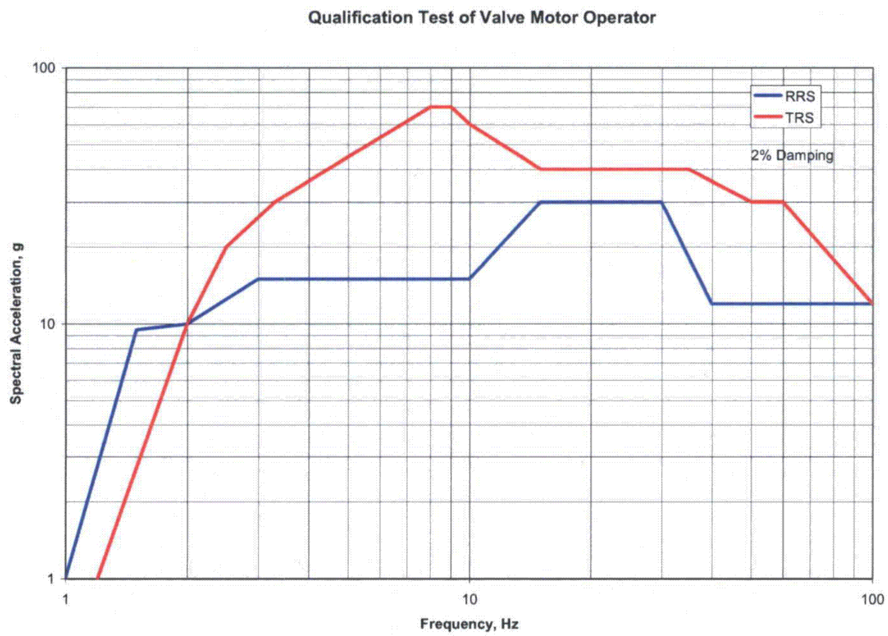


Figure 6-4
Faulted (Combined SSE and Hydrodynamic Loading) Qualification Test of Motorized Valve Operator

Operational Vibration Limitations for Equipment

Various test programs have subjected equipment to a variety of increasing levels of input motion to ascertain the functional limits or fragility level of the equipment. One of the early test programs was conducted under the military SAFEGUARD program (early 1970s) which sought to establish the fragility level of standard commercial mechanical and electrical equipment mounted in hardened structures and subjected to ground shock motions induced by nuclear weapons. This data was used to establish fragility levels for nuclear plant equipment in early seismic margin assessments and PRA studies. Much of the relevant data was summarized for the EPRI seismic margin study (EPRI NP-6041, 1991a). These tests tended to emphasize the high frequency range. The implications of this data with regard to high frequency input motion are also discussed in EPRI NP-7498 (EPRI, 1991b). Another study (EPRI, 1985), recognizing the high frequency emphasis of the test data, sought to use the data as an equipment qualification basis for BWR hydrodynamic loading. In general, this body of data demonstrates that high frequency input motion content does not adversely affect equipment structure or function.

7
CONCLUSIONS

There is both analytical and empirical evidence that short duration, high frequency excitations are not damaging to power plant and heavy industrial structures and equipment. The analytical evidence provided within Section 5 of this report demonstrates the lack of significant response of structural systems to these high frequency motions based on studies of a range of idealized distributed mass beams. The empirical evidence presented in Section 6 of this report is extensive and broad in its origins:

- Mining, Quarry and Construction Blasting Data Support the Lack of High Frequency Effects
- Earthquake Experience Data at NPPs Support the Lack of High Frequency Effects
  - Northeast Ohio Earthquake of 1986 (Perry Plant)
  - South Carolina Monticello Reservoir Events of 1978/1979 (Summer Plant)
  - 1989 Slovenia Earthquake (Krško Plant)
- Shake Table Equipment Qualification Data Support the Lack of High Frequency Effects
  - BWR Hydrodynamic and Seismic Test Data
- Operational Vibration Test Data Support the Lack of High Frequency Effects

In the past, this evidence has been used, both implicitly and explicitly, by the USNRC to justify that any additional effort (testing or analysis) beyond the design basis to address high frequency response effects for operating NPPs is not warranted. These regulatory actions by the USNRC have included the following programs, initiatives and publications:

- Individual Plant Examination for External Events (IPEEE) - GL 88-20, Supplement 4
- USNRC panel report on the implications of updated PSHA estimates that resulted in increased high frequency hazard at Watts Bar
- Extensive inspection of the Perry plant following the 1986 earthquake with the conclusion that the exceedance of the design spectra in the high frequency range did not have engineering significance
- Seismic confirmatory program of the Summer plant following the reservoir induced earthquakes of 1978 and 1979, which satisfied the ASLB and ACRS requirements to document the lack of engineering significance
- Development of Regulatory Guide 1.166 in response to the issue of OBE exceedance at high frequencies

As a result of the material summarized within this report, it is concluded that additional seismic qualification effort to address the high frequency content of seismic motions is not warranted with the exception of certain potentially high-frequency vibration sensitive components such as relays.

However, since it is recognized that the high frequency content of the seismic ground motion can potentially propagate within a structure and potentially affect mounted components, limited analytical evaluations are proposed for typical structures and components, as applicable, to confirm the conclusion that structure and component design based on Regulatory Guide 1.60 spectra can also withstand the high frequency input typical of a hard rock CEUS site. In addition, a program has been proposed to identify potentially sensitive active components and to confirm their functionality for high frequency input. The issue of high frequency exceedances of in-structure design spectra should be resolved by the following efforts:

- To support the determination that limited high frequency exceedances are not potentially damaging to structures and components, a limited number of evaluations should be performed. These evaluations should include portions of building structures, primary systems, piping systems, and components evaluated by analysis. Structures and components should be selected to include locations where exceedances of the design in-structure response spectra occur. In addition, components should be selected based on which high frequency modes are deemed to have significant response. The discretization level of the structural models used may also need to be examined in order to obtain sufficient numerical accuracy for determination of high frequency response. Evaluations should compare results for input motion based on the current Regulatory Guide 1.60 based design spectra to results obtained for motions consistent with CEUS site-specific response spectra. These limited comparisons should demonstrate the adequacy of design based on the Regulatory Guide 1.60 spectra.

- A separate industry program, including (1) identification of high-frequency sensitive or non-ductile equipment and components, (2) establishment of screening criteria, (3) development of evaluation methods, and (4) recommendations for additional testing procedures, should be initiated to address the functional performance of equipment that could be sensitive to high frequency vibration input.

8 REFERENCES

ARES (2006), "Review of ABWR Test Qualification Data," GE San Jose site visit by K. L. Merz, ARES Corporation, August 2006.

ASCE (2005), American Society of Civil Engineers, "Seismic Design for Structures, Systems, and Components in Nuclear Facilities and Commentary," ASCE Standard 43-05, 2005

Bagchi (1992), G. and Giese-Koch, G. V., "Determination of OBE Exceedance for Operating Reactors," Proceedings of the Fourth Symposium on Current Issues Related to nuclear Power Plant structures, Equipment, and Piping, Orlando, Florida, December, 1992.

Bernero (1988), R. M., et al, "High Frequency, High Amplitude, and Low Energy Earthquake Study of Nuclear Power Plants," *Nuclear Engineering and Design*, Vol. 107, Nos. 1 & 2, pp. 141-148, April 1988.

Chen (1988), C., et al, "Studies of Equipment Response to Low Energy, Low Velocity, High Amplitude, and High Frequency Seismic Events," *Nuclear Engineering and Design*, Vol. 107, Nos. 1 & 2, pp. 127-139, April 1988.

Chen (1992), C., et al, "Experience Data and analytical Results of High Frequency Earthquakes," Proceedings of the Fourth Symposium on Current Issues Related to Nuclear Power Plant structures, Equipment, and Piping, Orlando, Florida, December, 1992.

EPRI (1985), Electric Power Research Institute, "Equipment Operability Under High-Frequency Excitation," NP-3946, April 1985.

EPRI (1988), Electric Power Research Institute, "A Criterion for Determining Exceedance of the Operating Basis Earthquake," NP-5930, July 1988.

EPRI (1989a), Electric Power Research Institute, "Probabilistic Seismic Hazard Evaluations at Nuclear Power Plant Sites in the Central and Eastern United States," NP-4726, 1989.

EPRI (1989b), Electric Power Research Institute, "The 1986 Leroy, Ohio Earthquake: Performance of Power and Industrial Facilities," NP-6558, November 1989.

EPRI (1991a), Electric Power Research Institute, "A Methodology for Assessment of Nuclear Power Plant Seismic Margin, (Revision 1)," EPRI NP-6041-SL, August 1991.

EPRI (1991b), Electric Power Research Institute, "Recommended Procedures to Address High frequency Ground Motions in Seismic Margin Assessment for Severe Accident Policy Resolution," *Appendix B of Industry Approach to Seismic Severe Accident Policy Implementation*, EPRI NP-7498, November 1991.

EPRI (1991c), Electric Power Research Institute, "Standardization of the Cumulative Absolute Velocity," EPRI TR-100082, December 1991.

EPRI (1993), Electric Power Research Institute, "Guidelines for Determining Design Basis Ground Motions, Volume 1: Method and Guidelines for Estimating Earthquake Ground Motion in Eastern North America," EPRI TR-102293, November 1993.

Han (1974), S. M., et al, "Dynamics of Transversely Vibrating Beams Using Four Engineering Theories," Journal of Sound and Vibration, Vol. 225, p.p. 935-988, 1999.

Hendron (1974), A. J. and Dowding, C. H., "Ground and Structural Response DUE to Blasting," Proceedings, 3rd Congress of the International Society of Rock Mechanics, Vol. II-B, National Academy of Sciences, Washington, D. C., 1974.

INEL (1990), Idaho National Engineering Laboratory, "Aging Evaluation of Class 1E Batteries: Seismic Testing," NUREG/CR-5448, August, 1990.

Jacobsen (1938), L. S., "Natural Frequencies of Uniform Cantilever Beams of Symmetrical Cross Section," Journal of Applied Mechanics, American Society of Mechanical Engineers, p.p. A1-6, March 1938.

LLNL (1989) Lawrence Livermore National Laboratory, "Seismic hazard Characterization of 69 Nuclear Plant Sites East of the Rocky Mountains," NUREG/CR-5250, January, 1989

LLNL (2002), Lawrence Livermore National Laboratory, "Guidance for Performing Probabilistic Seismic Hazard Analysis for a Nuclear Plant Site: Example Application to the Southeastern United States," NUREG/CR-6607, October 2002.

Newmark (1978), Nathan N. Newmark Consulting Engineering Services, "Development of Criteria for Seismic Review of Selected Nuclear Power Plants," NUREG/CR-0098, May 1978.

Papadopoulos (1980), A. P. and Trujillo, D. M., "Natural Frequency of Timoshenko Beam on Flexible Base," Journal of the Engineering Mechanics Division, American Society of Civil Engineers, Vol. 106, p.p. 307-321, April 1980.

REI (2001), Risk Engineering, Inc., "Technical Basis for Revision of Regulatory Guidance on Design ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines," NUREG/CR-6728, October 2001.

REI (2002), Risk Engineering, Inc., "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Development of Hazard- and Risk-Consistent Seismic Spectra for Two Sites," NUREG/CR-6769, April 2002

SSHAC (1997), Senior Seismic Hazard Analysis Committee, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," NUREG/CR-6372, USNRC, 1997.

USNRC (1973), US Nuclear Regulatory Commission, "Design Response Spectra for Seismic Design of Nuclear Power Plants," Regulatory Guide 1.60, December 1973.

USNRC (1986), US Nuclear Regulatory Commission, "Safety Evaluation Report Related to the Operation of Perry Nuclear Power Plant, Units 1 and 2," NUREG-0887, Supplement No. 9, March 1986.

USNRC (1991), US Nuclear Regulatory Commission, "Procedural and Submittal Guidance for the Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities," NUREG-1407, June 1991.

USNRC (1994), US Nuclear Regulatory Commission, "Revised Livermore Seismic Hazard Estimates for Sixty-Nine Nuclear Power plant sites East of the Rocky Mountains," NUREG-1488, April 1994.

USNRC (1997a), US Nuclear Regulatory Commission, ""Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," Regulatory Guide 1.165, March 1997

USNRC (1997b), US Nuclear Regulatory Commission, "Pre-Earthquake Planning and Immediate Nuclear Power Plant Operator Postearthquake Actions," Regulatory Guide 1.166, March 1997.

USNRC (2003), US Nuclear Regulatory Commission, "Panel Report on Initial Screening of GI-194, 'Implication of Updated Probabilistic Hazard Estimates'," Staff Memorandum, September, 2003 (Accession Number ML032680979 in NRC Public Document Room)

Whorton (1988), R. B., "High Frequency, High Amplitude and Low Energy Earthquake Study at V.C. Summer Nuclear Station," *Nuclear Engineering and Design*, Vol. 107, Nos. 1 & 2, pp. 109-125, April 1988.