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March 9, 2009

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: Duke Energy Carolinas, LLC.
William States Lee III Nuclear Station - Docket Nos. 52-018 and 52-019
AP1000 Combined License Application for the
William States Lee III Nuclear Station Units 1 and 2
Response to Request for Additional Information
(RAI No. 1244)
Ltr# WLG2009.03-02

Reference: Letter from Brian Hughes (NRC) to Peter Hastings (Duke Energy), *Request for Additional Information Letter No. 055 Related To SRP 02.05.02 for the William States Lee III Units 1 And 2 Combined License Application*, dated December 3, 2008

This letter provides the Duke Energy response to the Nuclear Regulatory Commission's requests for additional information (RAIs) included in the referenced letter.

Responses to the NRC information requests described in the referenced letter are addressed in separate enclosures, which also identify associated changes, when appropriate, that will be made in a future revision of the Final Safety Analysis Report for the Lee Nuclear Station.

If you have any questions or need any additional information, please contact Peter S. Hastings, Nuclear Plant Development Licensing Manager, at 980-373-7820.

Bryan J. Dolan
Vice President
Nuclear Plant Development

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NRO

Enclosures:

1) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-006
2) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-007
3) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-008
4) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-009
5) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-010
6) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-011
7) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-012
8) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-013
9) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-014
10) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-015
11) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-016
12) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-017
13) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-018
14) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-019
15) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-020
16) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-021
17) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-022
18) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-023
19) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-024

Enclosures (cont'd):

20) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-025
21) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-026
22) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-027
23) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-028
24) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-029
25) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-030
26) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-031
27) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-032
28) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-033
29) Duke Energy Response to Request for Additional Information Letter 055, RAI 02.05.02-034

AFFIDAVIT OF BRYAN J. DOLAN

Bryan J. Dolan, being duly sworn, states that he is Vice President, Nuclear Plant Development, Duke Energy Carolinas, LLC, that he is authorized on the part of said Company to sign and file with the U. S. Nuclear Regulatory Commission this supplement to the combined license application for the William States Lee III Nuclear Station and that all the matter and facts set forth herein are true and correct to the best of his knowledge.

Bryan J. Dolan

Bryan J. Dolan

Subscribed and sworn to me on March 9, 2009

Kim N Slays

Notary Public

My commission expires: April 19, 2010

SEAL

KIM N. SLAYS NOTARY PUBLIC NEW HANOVER COUNTY, N.C.

xc (w/o enclosures):

Loren Plisco, Deputy Regional Administrator, Region II
Mark Tonacci, Acting Branch Chief, DNRL

xc (w/ enclosures):

Brian Hughes, Senior Project Manager, DNRL

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-006**

**NRC RAI:**

On April 30, 2008, you submitted a letter to the NRC along with an enclosed report that details the methodology used to develop the horizontal and vertical site-specific hazard consistent UHRS at the Lee Unit 1 site. The purpose of this report is to supplement information presented in FSAR Section 2.5.2.7 "Development of FIRS for Unit 1".

Please reference this report in the appropriate subsection in your next FSAR Revision.

**Duke Energy Response:**

As requested, COLA Part 2, FSAR, Chapter 2, Subsection 2.5.2.7.1, Revision 1, includes a new second paragraph as shown in Attachment 1 that includes a reference to the supplemental technical report as provided in Enclosure 1 of the April 30, 2008, letter (Reference 1) titled "Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1." In addition, Subsection 2.5.2.8, Revision 1, includes a new reference to the April 30, 2008, letter (Reference 1) as shown in Attachment 2.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

1) FSAR Subsection 2.5.2.7.1, Revision 1
2) FSAR Subsection 2.5.2.8, Revision 1

# Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-006

## FSAR Subsection 2.5.2.7.1, Revision 1

COLA Part 2, FSAR, Chapter 2, Subsection 2.5.2.7.1, was revised in Revision 1 by adding a new second paragraph as follows:

The analysis methodology presented in this subsection is described in a supplemental technical report (Reference 299). The report describes, in detail, the analysis methodology used to develop horizontal and vertical site-specific FIRS that are hazard-consistent and incorporate both aleatory and epistemic variabilities in dynamic material properties at the Lee Nuclear Station Unit 1. The report addresses, in detail, the Random Vibration Theory (RVT) approach to equivalent-linear site response, as well as the fully probabilistic method used to incorporate the effects of site-specific dynamic material properties and their variabilities into the hard rock UHRS.

# Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 2 to RAI 02.05.02-006

## FSAR Subsection 2.5.2.8, Revision 1

COLA Part 2, FSAR, Chapter 2, Subsection 2.5.2.8, was revised in Revision 1 by adding a new reference as follows:

299. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch: Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s): RAI 02.05.02-007**

**NRC RAI:**

In Section 2.1 of Enclosure 1 (submitted April 30, 2008), the following statement is made regarding RVT durations:

> For both applications, i.e. estimating spectral accelerations and peak particle velocities as well as peak shear-strains, durations are taken as the inverse of the source corner frequency (Boore, 1983) with a distance dependent term to accommodate the increase in duration due to wave scattering (Herrmann, 1985).

The duration inverse to the source corner frequency corresponds to the duration of one wave (e.g., S-). The correction of Herrmann (1985)

$$T = 1/fc + 0.05R$$

is supposed to take into account an increase in duration due to the appearance of surface waves. The above formula (used by the applicant and shown in Table 2 of Enclosure 1) is relatively simplistic and does not take into account the source depth or additional factors. In addition, strong motion records include P-waves that usually have more high frequency content than S- and surface waves.

a.) Please provide examples and/or references that demonstrate an adequate comparison of duration of actual strong-motion time histories with those modeled by Boore (1983) method with Herrmann (1985) correction.

There are also limitations on the low-frequency portion of the spectra. Boore and Joyner (1984) specifically addressed the issue of duration for calculation of response spectra when period of oscillator is longer than the duration of record (i.e. reaction of SDF can be longer than the duration used).

b.) Please provide more information on calculation of the low frequency part of the response spectra that can potentially be affected by non-adequate duration.

**Duke Energy Response:**

The response presented below addresses both items a.) and b.) of this RAI.

In the context of random vibration theory (RVT) as well as structural dynamics, duration is not a uniquely defined parameter. Duration is the time over which the signal is stationary (statistics remain reasonably constant) and the power spectrum remains relatively constant (an additional weak constraint in practice). Since the RVT estimate of peak motion is weakly dependent on duration, a 50% change in duration reflects only about a 10% to 20% change in expected peak motion due to the square root log dependence [e.g., Equations 24 and 25, Boore, 1983 (Reference 1)]. Consequently, minimal additional effort has been put forth to characterize either a strict definition of duration or duration dependencies on details of crustal models and/or source spectral shape. The reasonable assumption that source duration taken as the point-source inverse corner frequency (low-frequency corner for double corner source models) with a distance dependent increase due to contributions of an increased number of arrivals and/or scattering, was based on comparisons with the magnitude and distance dependencies of recorded motions and motions simulated with numerical source and wave propagation models. This empirical approach obviated the need for a definition and direct measurement of RVT duration going directly to evaluating the model predictions of motions.

Refinements have been made to the model with definitions and measurements of the 5% to 75% of the cumulative power [Ou and Herrmann, 1990 (Reference 2)] as well as Central Eastern United States (CEUS) empirical models [see references in Boore, 2003 (Reference 3)]. The Electric Power Research Institute (EPRI) [1993 (FSAR Reference 2.5.2-273)] and Silva et al. [1996 (FSAR Reference 2.5.2-288)] extended the effective calibration of the duration model to site response [EPRI, 1993 (FSAR Reference 2.5.2-273)] and an extensive suite of earthquake recordings [over 500 sites and about 15 earthquakes; Silva et al., 1996 (FSAR Reference 2.5.2-288)] by showing consistency of predicted motions with recorded motions over a wide range in magnitude and distance [e.g., the comparison with empirical attenuation relations in Silva et al., 1996 (FSAR Reference 2.5.2-288) covered rock and deep firm soil, magnitudes from 5.5 to 7.5, and Joyner-Boore (JB) distances from 1 to 200 km]. The simple model for RVT duration of $1/f_C + 0.05R$, where $f_C$ is the source corner frequency and R is JB distances, adequately captures the magnitude and distance dependencies of recorded motions and, by inference, the corresponding dependencies on duration for the point-source model [(FSAR Reference 2.5.2-273); (FSAR Reference 2.5.2-288); (Reference 3 including references therein); (FSAR Reference 2.5.2-202)] provided the appropriate stress drop is used in computing $f_C$.

The more difficult issue is the definition of duration to apply to an actual time history (synthetic or recorded) whose power spectrum is used for an RVT based analysis. For finite fault simulations which produce time histories, the 5% to 75% time interval for the cumulative power or Arias Intensity [Ou and Herrmann, 1990 (Reference 2)] has been shown to provide good estimates of recorded motions [Silva et al., 1996 (FSAR Reference 2.5.2-288)]. In this approach, to provide improved statistical stability, RVT estimates of peak motions and strains were used in lieu of time domain values. Validation exercises which included RVT equivalent-linear site response compared very favorably with recorded motions over a large magnitude and source distance range [Silva et al., 1996 (FSAR Reference 2.5.2-288)], suggesting the appropriateness of the Ou and Herrmann [1990 (Reference 2)] definition of RVT duration as the time interval of 5% to 75% of total cumulative power, or where the shape of the Arias Intensity buildup is relatively constant.

Considering the response spectra low-frequency duration correction for RVT, Boore [2003 (Reference 3)] gives an excellent illustration and summary of several correction procedures. Because RVT has a long history of use in structural dynamics, correction procedures have been developed for structural (oscillator) duration in terms of non-stationary and clumping or clustering of peaks in time [Udwadia and Trifumac, 1974 (Reference 4); Vanmarcke, 1976 (Reference 5)] as well as scaling factors to adjust damping ratios from 5% to lower and higher damping [Rosenbluth, 1980 (Reference 6)].

While the empirical oscillator duration correction of Boore and Joyner [1984 (Reference 7)] works well, Duke Energy's testing by comparing SDF (computed from time histories) response spectra (5% damping) with RVT response spectra lead us to favor the more classical approach of

Vanmarcke [1976 (Reference 5)]. This approach generally resulted in slightly closer estimates of median spectra, the estimate of main interest in developing transfer functions. The classical correction is performed separately on the RMS (root mean square) and on estimates of the number of zero crossings, SNZ. For the RMS, the correction has the form

$$RMS_C = RMS\ (1 - e^{2\eta\omega T})^{0.5},$$

where $RMS_C$ is the corrected RMS (computed via Parseval's relation and integrating the PSD), $\eta$ is the oscillator damping (decimal), $\omega$ is the oscillator angular frequency, and T is the strong motion duration ($1/f_C + 0.05R$) or 5% to 75% cumulative power (Arias Intensity) interval. The peak factor (ratio of the expected peak in the time domain to RMS) is computed using Equation 24 in Boore [1983 (Reference 1)] with the SNZ computed using Equations 19 and 27 [Boore, 1983 (Reference 1)] and corrected as follows:

$$SNZ_C = SNZ\ (1.63\ \beta^{0.45} - 0.38),$$

Where $SNZ_C$ is the corrected number of zero crossings and

$$\beta = 1 - \frac{m_1^2}{m_o m_2}$$

is Vanmarcke's [1976 (Reference 5)] measure of the PSD bandwidth and $m_j$ reflects the $j^{th}$ moment of the PSD

$$m_j = \frac{1}{\pi}\int_0^\infty \omega^j \left|A(\omega)\right|^2 d\omega,$$ $\omega$ is the angular frequency [Boore, 1983 (Reference 1)].

The minimum estimate of $SNZ_C$ is 1.33 [Vanmarcke, 1976 (Reference 5)].

**References:**

1. Boore, D.M. (1983). "Stochastic Simulation of High-frequency Ground Motions Based on Seismological Models of the Radiated Spectra." *Bull. Seism. Soc. Am.,* 73(6), 1865-1894.
2. Ou, G.B., and Herrmann, R.B. (1990). "Estimation Theory for Strong Ground Motion." *Seism. Res. Letters.* 61(2), 99-107.
3. Boore, D.M. (2003) "Simulation of Ground Motions Using the Stochastic Method" *Pure and Applied Geophysics,* 160(2003); 635-676.
4. Upwadia, F.E. and M. D. Trifunac (1974). "Characterization of Response Spectra through the Statistics of Oscillator Response." *Bull. Seism. Soc. Am.,* 64(1), 205-219.
5. Vanmarcke, E.H (1976). "Structural Response to Earthquakes." In *Seismic Risk and Engineering Decisions.* Chapter 8, Ed. by C. Lomnitz and E. Rosenblueth, Elsevier Publishing Co., Amsterdam, NY., pp 287-337.
6. Rosenblueth, E. (1980). "Characteristics of Earthquakes." In E. Rosenblueth, editor, *Design of Earthquake Resistant Structures,* Chapter 1, Wiley.
7. Boore, D.M. and Joyner, W.B. (1984). "A Note on the Use of Random Vibration Theory to Predict Peak Amplitudes of Transient Signals." *Bull. Seism. Soc. Am.,* 74, 2035-2039.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-008**

**NRC RAI:**

Table 2 of Enclosure 1 (submitted April 30, 2008), relating to FSAR Figure 2.5.2-221, lists the point-source model parameters and durations used in developing site-specific V/H ratios.

Please provide more information on this table. Specifically, please explain why parameters are identical at 1.50 and 1.25 PGA.

**Duke Energy Response:**

The single corner-frequency point-source model parameters, used in developing both the reference site motions as well as site-specific motions, are listed in Table 2 (Reference 1). In developing site-specific transfer functions, the crustal model listed in Table 2 (Reference 1) was used for the reference (hard rock) site while for the William States Lee III Unit 1 Foundation Input Response Spectra (FIRS) profile, the concrete layer was simply placed on top. Specifically, the identical entries at 1.50g and 1.25g reflect round-off as well as typographical errors. At 1.50g and 1.25g, the source depths are 1.890 km and 2.100 km respectively. The corresponding path durations are 0.0445 sec and 0.0550 sec, respectively. For 1.00g the total duration should be 1.04 sec with a path duration of 0.08 sec.

In addition, the formula for the path component of the duration should be R-1 instead of simply R. In this case $R \geq 1$. For Western North America (WNA) the R-1 becomes R-10 as durations are not seen to increase within about 10 km (Silva et al., 1996 (Reference 2.5.2-288)). However, for Central Eastern North America (CENA), durations appear to increase within 10 km due to scattering, as evidenced by the close-in recordings of the Nahanni, Canada main shock. Attachment 1 contains a mark-up of Table 2 that will be incorporated into a future revision of the supplemental technical report.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

Table 2. Hard Rock Expected Horizontal Peak Acceleration Levels, Point Source Distances, and Durations

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachment:**

1) Revised Supplemental Technical Report, Table 2. Hard Rock Expected Horizontal Peak Acceleration Levels, Point Source Distances, and Durations

# Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-008

## Revised Supplemental Technical Report, Table 2. Hard Rock Expected Horizontal Peak Acceleration Levels, Point Source Distances, and Durations

Supplemental Technical Report, "Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1," Table 2, is revised as follows:

| Table 2<br>Hard Rock Expected Horizontal Peak Acceleration Levels,<br>Point Source Distances, and Durations | | | | | |
|---|---|---|---|---|---|
| **M** 5.1, single-corner | | | | | |
| G(g) | Distance (km) | Depth (km) | $T_{source}$ (sec) | $T_{path}$ (sec) | $T_{total}$ (sec) |
| 1.50 | 0 | 2 | 0.96 | 0.04 | 1.00 |
| 1.25 | 0 | 2 | 0.96 | 0.046 | 1.002 |
| 1.00 | 0 | 3 | 0.96 | 0.058 | 1.014 |
| 0.75 | 0 | 4 | 0.96 | 0.12 | 1.08 |
| 0.50 | 0 | 5 | 0.96 | 0.20 | 1.16 |
| 0.40 | 0 | 6 | 0.96 | 0.25 | 1.21 |
| 0.30 | 0 | 8 | 0.96 | 0.34 | 1.30 |
| 0.20 | 7 | 8 | 0.96 | 0.47 | 1.43 |
| 0.10 | 16 | 8 | 0.96 | 0.84 | 1.80 |
| 0.05 | 27 | 8 | 0.96 | 1.43 | 2.39 |
| 0.01 | 80 | 8 | 0.96 | 3.97 | 4.93 |

Notes: Additional parameters used in the point-source model are:
$Q = 670 f^{0.33}$
$\Delta\sigma$ (1c) = 110 bars
$\kappa = 0.006$ sec, hard rock
$\rho = 2.71$ cgs
$\beta = 3.52$ km/sec
Rc = 60 km, crossover hypocentral distance to $R^{-0.5}$ geometrical attenuation
T = 1/fc + 0.05 (R-1), R>1 ; RVT duration, R = hypocentral distance (km)

| CENA Generic Hard Rock Crustal Model | | | |
|---|---|---|---|
| Thickness (km) | Vs (km/sec) | Vp (km/sec) | ρ (cgs) |
| 1 | 2.83 | 4.90 | 2.52 |
| 11 | 3.52 | 6.10 | 2.71 |
| 28 | 3.75 | 6.50 | 2.78 |
| [infinite] | 4.62 | 8.00 | 3.35 |

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-009**

**NRC RAI:**

Paragraph 2 of Section 2.1.1 of the Enclosure 1 report, describes the process for integrating the PSD. The following statement is made regarding the integration range used for the Lee Unit 1 site:

> To integrate the PSD, numerical integration is performed rather than analytical integration, as the PSD includes site response in addition to FAS of the simple point-source model. Because the PSD is reasonably smooth, a simple and rapid Simpson's three-point scheme is implemented but with a very dense sampling to fully accommodate the presence of peaks and troughs. Typically (e.g. Lee Nuclear Station Unit 1) 25,000 points are used from 0.007 Hz (about 150 sec) to 150 Hz. The wide integration rate is to ensure inclusion of potential high- and low-frequency amplification. Additionally, the RMS is sensitive to the integration over low-frequency so it is prudent to extend its range to at-least an order of magnitude below the lowest frequency of interest, 0.1 Hz for nuclear applications (e.g. Lee Nuclear Station Unit 1).

Data used in strong motion seismology are based on records obtained using film (mostly SMA-1) or digital (SSA-2, Etna, and others) accelerographs. Older-style film instruments had typical flat frequency response characteristics from DC to 20-25 Hz. The new generation digital accelerometers have flat frequency response characteristics that range from DC to either ~50 or ~100 Hz. The sampling rate of strong motion records used by the USGS or CGS networks (the main sources for strong motion data in the U.S.) is 200 samples/sec. Combining those parameters limits the reliable frequency response of existing data to 100 Hz at the most, for the high-frequency end.

Almost all existing data are processed with the low-frequency cut-off filter of 0.1 Hz or higher (10 second period or lower). Usually it is a 4-pole Butterworth filter. The most recent PEER NGA database contains a very limited number of data confident up to 10 sec, with most data confident up to 5 sec-period (0.2 Hz).

As a result, the confident frequency response of strong motion data in current databases varies from 0.2 to 25 Hz (typical for film instruments) to 0.1 to 100 Hz (typical for digital instruments). The frequency band used by the applicant is much beyond those limits: 0.007 to 150 Hz.

Please clarify what procedures are used to extend the frequency band to such values. How are you confident that results from frequencies 0.007 to 150 Hz (well beyond the confidence level of strong-motion recordings) are reliable and not contaminated by noise? If your response is based on theoretical results, please provide information on constrains at both low and high frequency ends of the spectrum, and validation of your model at both low- and high-frequency ends beyond the empirical data.

**Duke Energy Response:**

It is certainly true that the majority of strong motion data contain reliable information on Fourier amplitude spectra (FAS) over a restricted frequency range of about 0.1 hertz (Hz) to about 50 Hz for digital data and about 0.2 Hz to about 25 Hz for film records, all depending on magnitude, distance, and, to some extent, site conditions. For high frequencies Boore (1983, Reference 1) has demonstrated that the point-source model works well for magnitudes (M) down to M 0.4 with Fourier amplitude frequencies up to about 400 Hz. For typical strong motion data, the contribution to response spectra at peak acceleration (e.g., 100 Hz) from FAS beyond about 25 Hz to 50 Hz in Western North America (WNA) and about 50 Hz to 70 Hz at hard rock sites in Central Eastern North America (CENA) is small.

To compute control motions, low-pass filters at 50 Hz in WNA and about 60 Hz in CENA were applied and reflect our typical corner frequencies for the Butterworth filters. The filter for CENA simulations is simply to force saturation to peak acceleration at 100 Hz for convenience (convention). The extension of the integration to 150 Hz is done for cases with kappa (κ) less than 0.006 sec and without low-pass filters. As an extreme case to illustrate the contribution to high-frequency response spectra by the FAS at high-frequency, Figure 1 (Attachment 1) shows results computed for M 7.0 at a Joyner-Boore (JB) distance of 1 km for CENA hard rock conditions (Reference 2.5.2-287). For the nominal FAS integration to 150 Hz, the corresponding response spectrum (5% damped pseudo absolute acceleration) peaks near 30 Hz and saturates monotonically to peak acceleration near 150 Hz (no filters applied). Restricting the FAS integration to 100 Hz shows an impact in the response spectrum beginning near 90 Hz and quickly saturating to peak acceleration just beyond 100 Hz. While Boore (1983, Reference 1) has shown the point-source model works well beyond 100 Hz, high-frequency response spectra (beyond the peak) are controlled by lower frequencies in the FAS. This sensitivity to lower-frequency and saturation to peak acceleration is a consequence of the width of the oscillator transfer function increasing directly with oscillator frequency. At high-frequency, where the FAS is depleted, the oscillators incorporate lower-frequency energy where the FAS has a broad peak, finally saturating to peak acceleration as the oscillator transfer function increases width with increasing oscillator frequency. As a result, validations of response spectra for frequencies up to and including peak acceleration, the highest frequency of interest for engineering design, indirectly validates the FAS to slightly higher frequencies, beyond which integration has no effect.

At low-frequency however, as Figure 2 (Attachment 2) illustrates, the response spectrum is sensitive not only at the low-frequency integration limit but to lower-frequency as well, not reaching a saturation to peak displacement, for pseudo absolute acceleration. This sensitivity is opposite to that at high-frequency, as the width of the oscillator transfer function, being proportional to oscillator frequency, is quite narrow at low-frequency. As a result, the low-frequency response spectrum is sensitive to a fairly narrow frequency range in the FAS about the oscillator frequency. In the integration, the low-frequency range is typically taken at about 0.007 Hz (0.006 Hz in the illustration presented in Figures 1 and 2) and the response spectra depend directly on the model FAS for frequencies below the peak in the response spectra, about 30 Hz in this example case (Figure 2). However, as Figure 2 illustrates, for the lowest frequency of interest to nuclear facilities (0.1 Hz to 0.2 Hz), the response spectrum is controlled by the FAS to frequencies somewhat below 0.1 Hz and above 0.05 Hz, with little impact on response spectra at 0.1 Hz for FAS integrations below 0.05 Hz. As a result, model validation for response spectra for oscillator frequencies extending to 0.1 Hz indirectly validates the model generated FAS to somewhat lower-frequencies (between 0.05 Hz and 0.10 Hz), additionally integrations to lower-frequency have little impact for 0.1 Hz oscillators. The integration to 0.007 Hz is performed to conservatively accommodate very large magnitude sources with high-amplitude low-frequency site amplification. Such cases may have local FAS peaks near 0.1 Hz or below, potentially extending the impact on 0.1 Hz oscillators for FAS well below 0.1 Hz. Since no validation earthquakes and sites are currently available for such extreme cases for crustal sources, computed results will depend on the validity of the model FAS to frequencies somewhat below the lowest oscillator frequency of interest. It should be noted this is not a limitation exclusively of Random Vibration Theory (RVT), as the computation of response spectra directly from time histories exhibits the exact same issues.

Based on the validations and effective frequency ranges for Fourier amplitude and response spectra discussed above, there is confidence the theoretical computation of response spectra over the frequency range of interest to nuclear facilities is reliable.

**Reference:**

1. Boore, D.M. (1983). "Stochastic Simulation of High frequency Ground Motions Based on Seismological Models of the Radiated Spectra." Bulletin of the Seismological Society of America, 73(6), 1865 1894.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

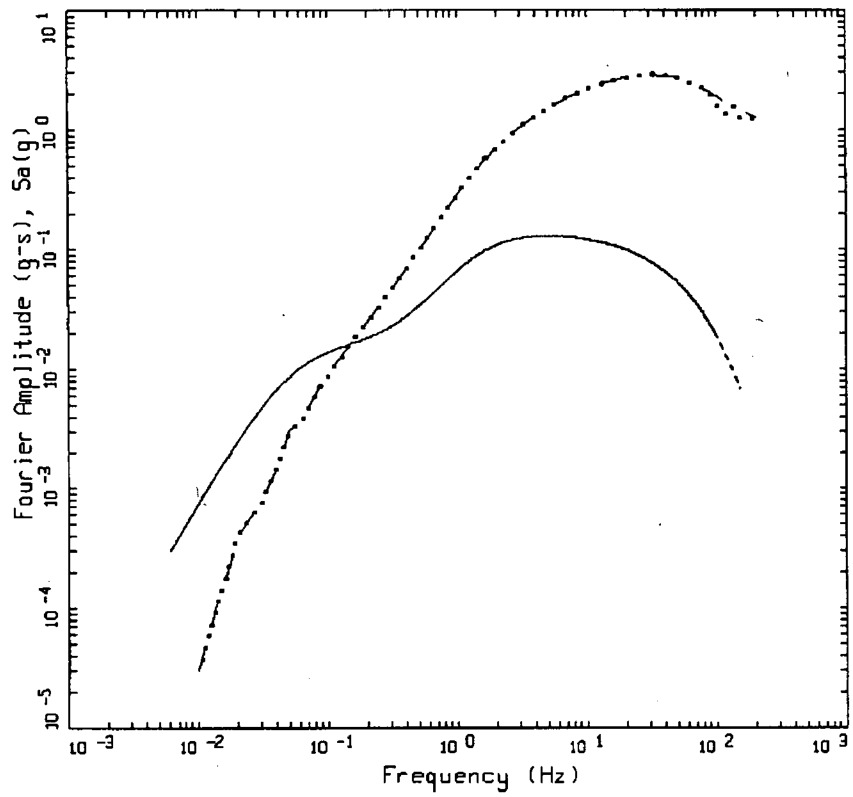
**Attachments:**

1) Figure 1. Effects of Fourier Amplitude Spectrum Integration Range at High-Frequency
2) Figure 2. Effects of Fourier Amplitude Spectrum Integration Range at Low-Frequency

## Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-009

## Figure 1. Effects of Fourier Amplitude Spectrum Integration Range at High-Frequency




M = 7.0, D = 1 KM
CENA HARD ROCK, 2-CORNER SOURCE MODEL

LEGEND

| | |
|---|---|
| ----- | FAS, FAS INTEGRATION 0.006 Hz-150 Hz |
| — · — | Sa(g), FAS INTEGRATION 0.006 Hz-150 Hz |
| ——— | FAS, FAS INTEGRATION 0.006 Hz-100 Hz |
| • • • • | Sa(g), FAS INTEGRATION 0.006 Hz-100 Hz |

**Figure 1. Effects of Fourier Amplitude Spectrum Integration Range at High-Frequency**

Nominal FAS integration frequency range of 0.006 Hz to 150 Hz (dashed line) and corresponding 5% damped pseudo absolute acceleration spectrum (dashed-dotted line). Limiting the integration to 100 Hz (solid line) has a minor impact on the response spectrum beginning at about 90 Hz but little effect on peak acceleration (150 Hz), which is controlled by the broad peak in the FAS from about 2 Hz to about 30 Hz – 40 Hz. Note FAS is unfiltered. Model parameters: CENA hard rock, double-corner source model [FSAR Reference 2.5.2-287 (Atkinson, 1993)], $\kappa = 0.006$ sec, $Q(f) = 670\ f^{0.33}$, no site amplification.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 2 to RAI 02.05.02-009**

**Figure 2. Effects of Fourier Amplitude Spectrum Integration Range at Low-Frequency**

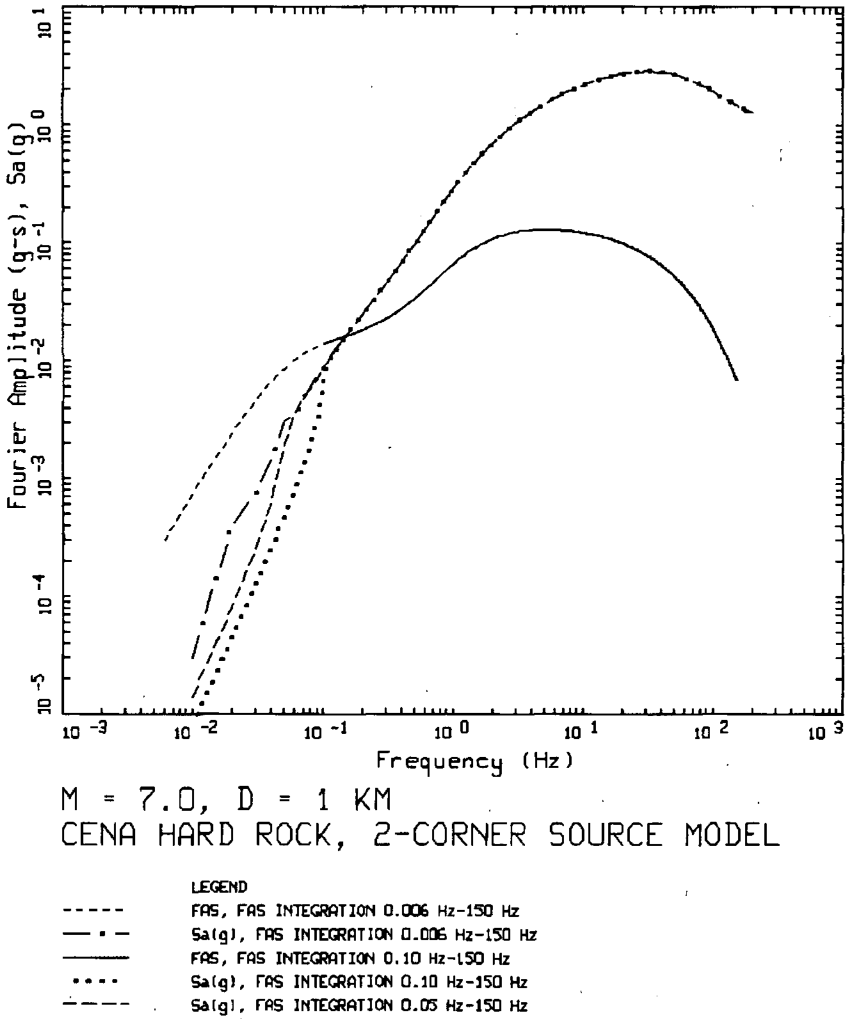



**Figure 2. Effects of Fourier Amplitude Spectrum Integration Range at Low-Frequency**

Nominal FAS integration frequency range of 0.006 Hz to 150 Hz (dashed line) and corresponding 5% damped pseudo absolute acceleration spectrum (dashed-dotted line). Beginning the integration at 0.10 Hz (solid line) has a significant impact on the response spectrum beginning at about 0.10 Hz and lower-frequency, but little effect at higher-frequency. Also shown is the impact on the response spectrum for FAS integration beginning at 0.05 Hz, showing little effect on the response spectrum at 0.1 Hz. Model parameters: CENA hard rock, double-corner source model [FSAR Reference 2.5.2-287 (Atkinson, 1993)], $\kappa = 0.006$ sec, $Q(f) = 670\ f^{0.33}$, no site amplification.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-010**

**NRC RAI:**

Paragraph 1 of Section 2.1.2 of the Enclosure 1 report states that for application to transfer functions differences in response spectra due to different corrections at low-frequency are cancelled through taking ratios.

Please clarify why corrections to the duration of the time series (time domain) can be cancelled by taking ratios (frequency domain). Please clarify if response (not Fourier) spectral ratios are used.

**Duke Energy Response:**

The response (not Fourier) spectral ratios are used. Both of the corrections for oscillator duration at low-frequency, nonstationarity and clumping of peaks in the time domain, become quite significant for oscillator periods that are longer than the source plus propagation path duration and neither is directly cancelled by taking ratios. More properly stated, the process of taking ratios minimizes the effects or differences in either the reference site response spectra or the soil site (site-specific) response spectra due to different correction procedures. Additionally, for typical stress drops of about 100 bars, source corner-periods are about 1, 3, and 9 seconds for moment magnitude (**M**) 5, 6, and 7 earthquakes and are therefore the shortest periods where corrections have a significant impact. Because the oscillator duration corrections are significant (≥ 30% to 40%) for oscillator periods near the source corner-periods and longer and long periods are typically controlled by large magnitude sources (**M** ≥ 6.5), the practical implications of the duration corrections for nuclear power plants with periods of interest extending to several seconds are not considered a significant issue.

Please refer to Table 1 and Figures 1, 2 and 3, attached. To demonstrate the effects of alternate correction factors on computed transfer functions, Figure 1 compares amplification factors computed for **M** 6.0 (Table 1) and a deep firm soil site in Central Eastern North America (CENA) (Figure 7, Reference 1) using both the Vanmarcke (1976) (Reference 2) approach (correction 1) and that of Boore and Joyner (1984) (Reference 3). Over the entire frequency range (0.1 hertz (Hz) to 100.0 Hz), as Figure 1 illustrates, there is little difference in the amplification factors computed using the two correction factors. In general the differences are less than about 5% and occur principally at high-frequency, beyond about 2 Hz. With a total duration of about 3 seconds (0.33 Hz) for 1.50g (Table 1), the corrections have the largest impact at low-frequency (below 0.33 Hz), where the difference is quite small.

To compare the two correction procedures in the computation of response spectral estimates, Figures 2 and 3 show the reference and soil site spectra computed for 0.01g and 1.50g respectively using both procedures. In Figure 2, with a reference site (hard rock) expected peak acceleration of 0.01g and a duration of about 11 sec (Table 1), the two correction procedures result in very similar (≤ 5% difference) response spectra for frequencies exceeding about 0.5 Hz. At lower frequency some divergence is evident increasing from about 5% to 10% at 0.2 Hz to perhaps 10% to 15% at 0.1 Hz. However for the corresponding amplification factors in Figure 1 (0.01g), the differences are much smaller. At the highest loading level, Figure 3, the differences in computed response spectra between the two correction procedures is much larger, particularly for very low frequencies (≤ 0.2 Hz). However, as with 0.01g, the corresponding amplification factors in Figure 1 (1.50g) show very small differences, even at very low frequency, illustrating the effective or approximate "cancelling" of oscillator duration corrections in taking ratios of response spectra at 5% damping. For lower damping, the effective cancellation may be expected to be more effective due to the decreased width of the oscillator transfer function. Conversely, for higher damping, the effective cancellation may be expected to be less effective due to the increased width of the oscillator transfer function.

**References:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
2. Vanmarcke, E.H (1976). "Structural Response to Earthquakes." In Seismic Risk and Engineering Decisions. Ch. 8, Ed. by C. Lomnitz and E. Rosenblueth, Elsevier Publishing Co., Amsterdam, NY., pp 287-337.
3. Boore, D.M. and Joyner, W.B. (1984). "A Note on the Use of Random Vibration Theory to Predict Peak Amplitudes of Transient Signals." Bulletin Seismological Society of America, 74, 2035-2039.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

1) Table 1. Model Parameters
2) Figure 1. Median Estimates of Amplification Factors (5% Damped Response Spectra) Computed for **M** 6.0 and a Deep Firm Soil Site in the CENA Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves
3) Figure 2. Median Estimates of Reference Site (Hard CENA Rock) and Soil Site (Deep Firm CENA Soil) Response Spectra (5% Damped) Computed for **M** 6.0 Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves (Soil Site), Reference Site Median Peak Acceleration is 0.01g

4) Figure 3. Median Estimates of Reference Site (Hard CENA Rock) and Soil Site (Deep Firm CENA Soil) Response Spectra (5% Damped) Computed for **M** 6.0 Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves (Soil Site), Reference Site Median Peak Acceleration is 1.50g

# Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-010

## Table 1. Model Parameters

**Table 1. Model Parameters**

| PGA(g) | Distance (km) | $T_{source}$ (sec) | $T_{path}$ (sec) | $T_{total}$ (sec) |
|---|---|---|---|---|
| 0.01 | 163, 8.0* | 2.7 | 8.1 | 10.8 |
| 1.50 | 0.1, 3.5* | 2.7 | 0.1 | 2.8 |

$\Delta\sigma$ = 110 bars

Q(f) = 670 $f^{0.33}$

K = 0.006 sec

$\rho$ = 2.71 cgs

$\beta$ = 3.52 km/sec

$R_C$ = 60 km

T = 1/fc + 0.05 (R-1), R>1; RVT duration, R = hypocentral distance (km)

*Source depth

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 2 to RAI 02.05.02-010**

**Figure 1. Median Estimates of Amplification Factors (5% Damped Response Spectra) Computed for M 6.0 and a Deep Firm Soil Site in the CENA Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves**

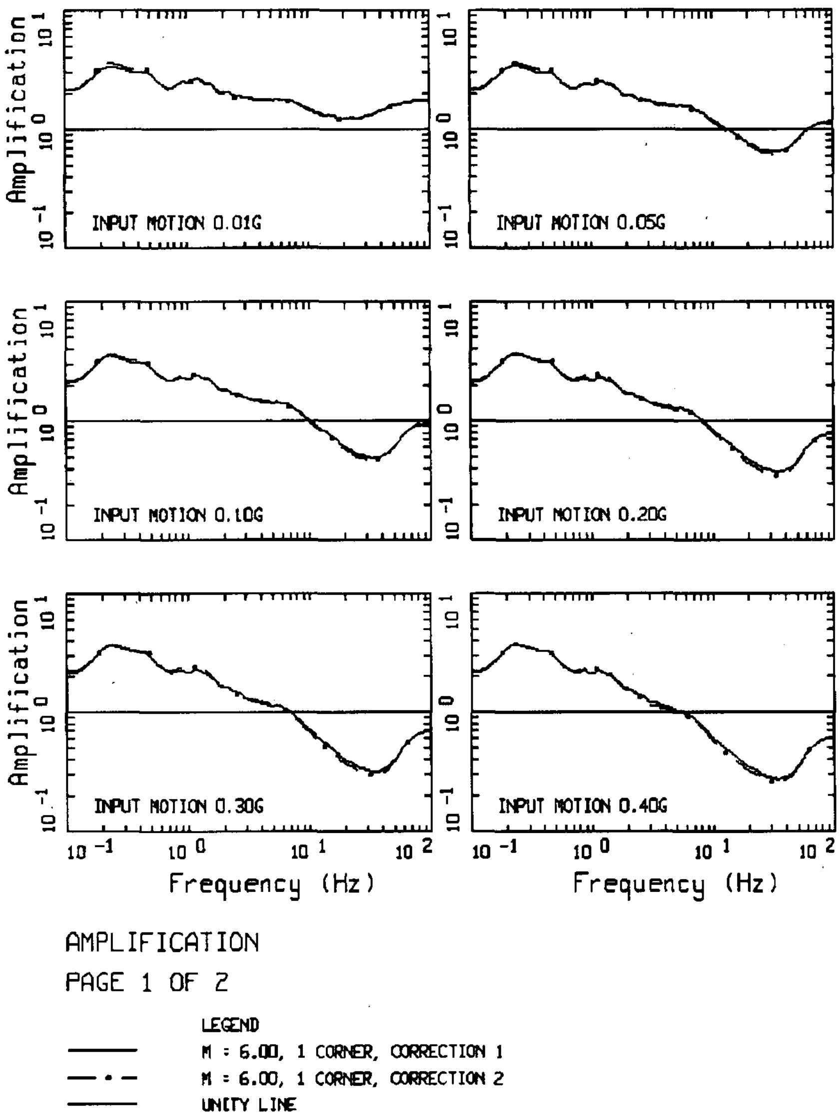



**Figure 1 (Sheet 1 of 2). Median Estimates of Amplification Factors (5% Damped Response Spectra) Computed for M 6.0 and a Deep Firm Soil Site in the CENA Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves**

Oscillator duration correction 1 from Vanmarcke (1976) and correction 2 is from Boore and Joyner (1984).

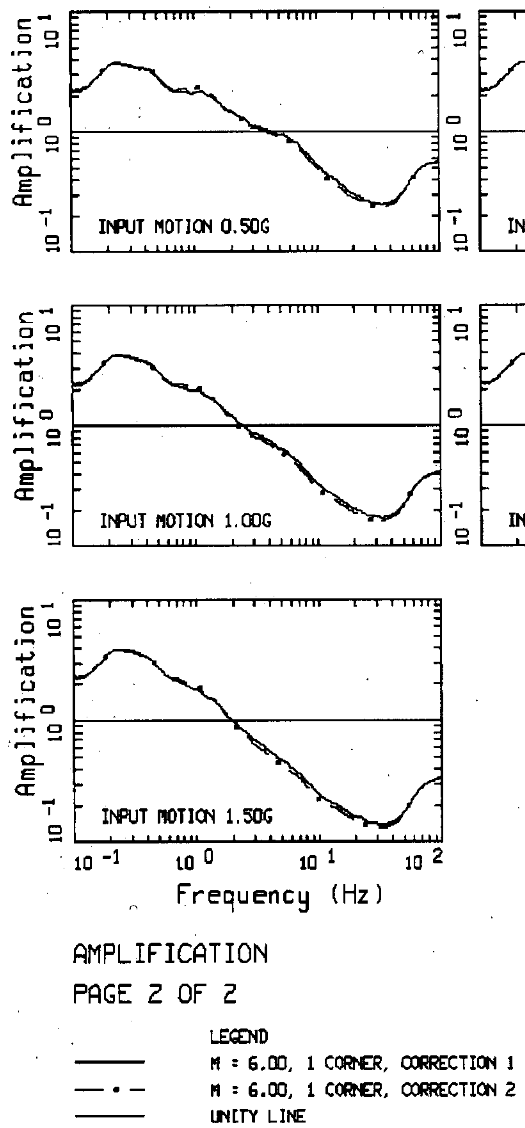



**Figure 1 (Sheet 2 of 2). Median Estimates of Amplification Factors (5% Damped Response Spectra) Computed for M 6.0 and a Deep Firm Soil Site in the CENA Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves**

Oscillator duration correction 1 from Vanmarcke (1976) and correction 2 is from Boore and Joyner (1984).

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 3 to RAI 02.05.02-010**

**Figure 2. Median Estimates of Reference Site (Hard CENA Rock) and Soil Site (Deep Firm CENA Soil) Response Spectra (5% Damped) Computed for M 6.0 Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves (Soil Site), Reference Site Median Peak Acceleration is 0.01g**

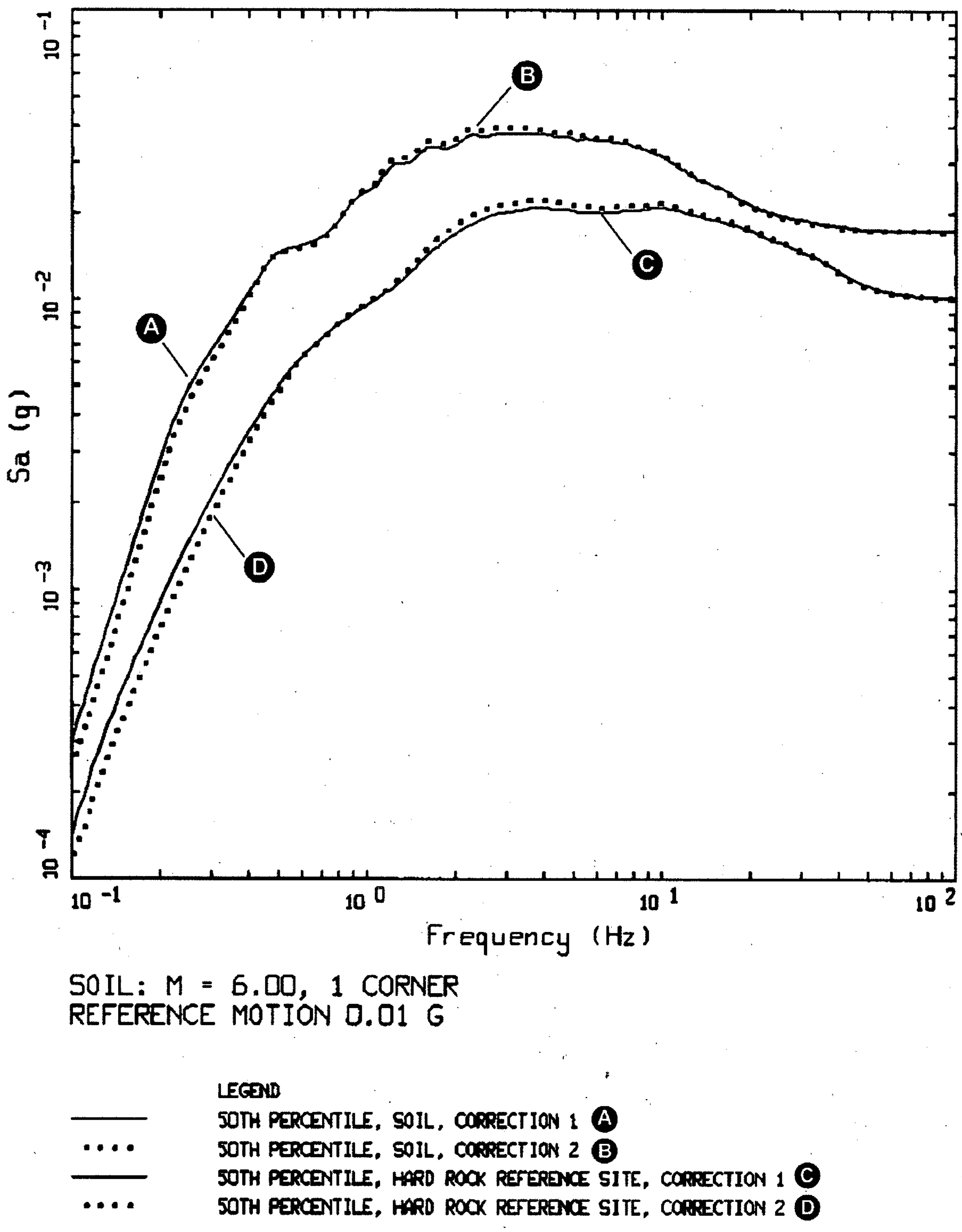



**Figure 2. Median Estimates of Reference Site (Hard CENA Rock) and Soil Site (Deep Firm CENA Soil) Response Spectra (5% Damped) Computed for M 6.0 Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves (Soil Site), Reference Site Median Peak Acceleration is 0.01g**

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 4 to RAI 02.05.02-010**

**Figure 3. Median Estimates of Reference Site (Hard CENA Rock) and Soil Site (Deep Firm CENA Soil) Response Spectra (5% Damped) Computed for M 6.0 Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves (Soil Site), Reference Site Median Peak Acceleration is 1.50g**

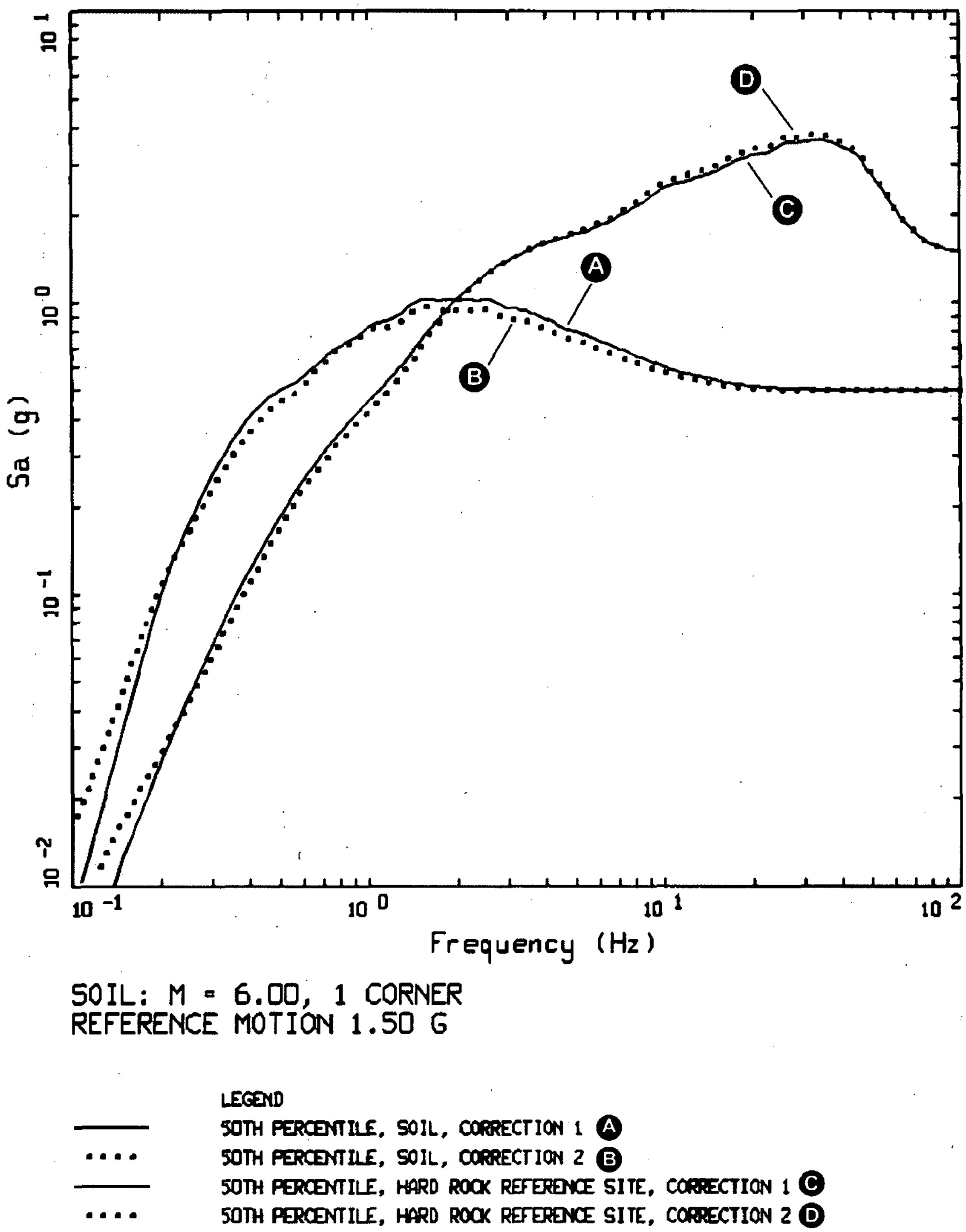



**Figure 3. Median Estimates of Reference Site (Hard CENA Rock) and Soil Site (Deep Firm CENA Soil) Response Spectra (5% Damped) Computed for M 6.0 Using the EPRI [1993 (FSAR Reference 2.5.2-273)] Modulus Reduction and Hysteretic Damping Curves (Soil Site), Reference Site Median Peak Acceleration is 1.50g**

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-011**

**NRC RAI:**

Paragraph 2 of Section 2.1.2 of the Enclosure 1 report states the following:

> In typical WNA and CENA, source durations scale with magnitude (M) such that for M 5, 6, and 7, durations are approximately 1, 3, and 9 seconds respectively. As a result, corrections only become important for oscillator periods below 1, 3, or 9 seconds, depending on the magnitude used in generating the transfer functions.

The correction elongates duration of the time history, therefore the correction is important for oscillator periods longer than the ground motion duration. Please provide additional information to justify your statement. Maybe it is just a typo?

**Duke Energy Response:**

In the supplemental technical report as provided in Enclosure 1 of the April 30, 2008, letter (Reference 1) titled "Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1," the intent of the word "below" in paragraph 2 of Section 2.1.2 was indeed meant to refer to longer periods, and is revised to "longer than" for clarity. Attachment 1 contains a mark-up of Section 2.1.2 that will be incorporated into a future revision of the supplemental technical report.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

Section 2.1.2

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachment:**

1) Revised Supplemental Technical Report, Section 2.1.2

# Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-011

## Revised Supplemental Technical Report, Section 2.1.2

Supplemental Technical Report, "Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1," Section 2.1.2, paragraph 2, is revised as follows:

In typical Western North America (WNA) and CENA, source durations (inverse corner frequency) scale with moment magnitude (**M**) such that for **M** 5, 6, and 7, durations are approximately 1, 3, and 9 seconds respectively. As a result, corrections only become important for oscillator periods ~~below~~longer than 1, 3, or 9 seconds, depending on the magnitude used in generating the transfer functions.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-012**

**NRC RAI:**

Paragraph 3 of Section 2.1.2 of the Enclosure 1 report states the following regarding figure 1 of the report:

> Figure 1 shows an example comparison using 30 time histories from a finite fault simulation reflecting randomly selected model parameters (e.g. slip model, nucleation point, shear-wave velocity profiles etc.).

Figure 1 of the report shows only response spectra, not time series. Please provide example comparisons of simulated records with actual earthquake time series from appropriate magnitude and distances in order to demonstrate reliability of method.

**Duke Energy Response:**

Figure 1 of Enclosure 1 of the April 30, 2008, letter (Reference 1) titled "Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1," was shown as an example of our own unpublished and limited verification of Random Vibration Theory (RVT). Additional validation may be found in Boore (2003) (Reference 2), and references therein, as well as in Ou and Herrmann (1990a and 1990b) (References 3 and 4).

**References:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
2. Boore, D.M. (2003) "Simulation of Ground Motions Using the Stochastic Method" Pure and Applied Geophysics, 160(2003); 635-676.
3. Ou, G.B., and Herrmann, R.B. (1990a). "A Statistical Model for Ground Motion Produced by Earthquakes at Local and Regional Distances." Bulletin Seismological of the Society America, 80, 1397-1417.
4. Ou, G.B., and Herrmann, R.B. (1990b). "Estimation Theory for Strong Ground Motion." Seismological Research of Letters, 61(2), 99-107.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-013**

**NRC RAI:**

Paragraph 3 of Section 2.2 of the Enclosure 1 report states the following:

> The vertically propagating shear-wave approach cannot successfully model amplitudes to arbitrary long periods at deep soil sites at large source distances, as this formulation does not consider horizontally propagating surface waves. It is not clear, however, under what circumstances (profile depth, source size and distance, and structural frequency) the 1D vertically propagating shear-wave model would result in unconservative motions. Validation exercises consisting of modeling recorded motions using the 1D approximation at deep soil sites in tectonically active regions suggest the simple model performs well in terms of spectral amplitudes to periods of at least several seconds (EPRI, 1993; Silva et al., 1997; Hartzell et al., 1999), periods long enough to accommodate nuclear facilities.

You state that validation exercises were performed. You also state that it is not clear under what circumstances the 1D vertically propagating shear-wave model would produce unconservative results. These statements appear contradictory. Please provide specific information on the limitations of applying the 1D approximation in Approach 3.

**Duke Energy Response:**

To clarify, the possible limitation of the vertically propagating shear-wave model at long periods due to the presence of horizontally propagating surface waves is not restricted to Approach 3, and applies equally well to Approaches 1, 2, and 4. The issue of specifically how long period vertical propagating shear-waves adequately accommodate amplification at deep soil sites has not been resolved, to our knowledge. The relative contributions between surface waves and shear-waves at periods beyond several seconds depends upon the specific shear-wave velocity profile, depth to basement material, and source properties such as magnitude, distance, and, to some extent, source depth. Published validation exercises suggest vertically propagating shear-waves perform as well as full 3-D analyses (which incorporate surface waves) for periods extending to 10 seconds [Hartzell et al., 1999 (Reference 1)]. Other validation exercises indicate 1-D analyses generally perform well for sources located within basins for periods extending to about 3 to 5 seconds but, over the same period range, underpredict recorded motions for sources located outside of basins and at large distances (> 100 km, Silva et al., 1996, FSAR Reference 2.5.2-288). Alternatively, a recent extensive modeling effort for Southern California suggests significantly greater 3-D amplification over 1-D amplification for periods greater than about 2 to 3 seconds for deep basins (e.g., depth to 1.5 km/sec material ≥ 1 km) [Day et al., 2008 (Reference 2)].

While there is general agreement that 1-D simulations significantly underpredict the time domain durations of long period motions at deep soil sites [Hartzell et al., 1999 (Reference 1)], there is presently little agreement among strong motion seismologists regarding the precise conditions under which 1-D analyses may become inappropriate at long periods for deep soil sites. Fortunately, this is an issue of little concern for response spectra computations. In Central Eastern North America (CENA), the longest period typically defined by the reference site hazard is 2 seconds (0.5 Hz) [EPRI, 2004 (FSAR Reference 2.5.2-219)]. In this case the potential limitation of 1-D analyses is addressed by extrapolating design spectra beyond two seconds using a constant spectral velocity for periods extending to the controlling source (modal) corner-period and constant spectral displacement beyond [BSSC, 2004 (FSAR Reference 2.5.2-294)]. This approach was developed partially to accommodate this potential issue, being based on recorded motions at predominately soil sites. Such an extrapolation, applied to the Lee Nuclear Station Unit 1, likely reflects conservative estimates of long period design motions due to the very stiff (i.e., concrete over hard rock) site conditions.

Specific guidelines regarding the appropriateness or limitations of 1-D analyses at long periods that reflects a consensus among the strong ground motion community is currently lacking, and extrapolation methods intended to result in conservative design levels is considered a reasonable approach.

**References:**

1. Hartzell, S., S. Harmsen, A. Frankel, and S. Larsen (1999). "Calculation of Broadband Time Histories of Ground Motion: Comparison of Methods and Validation Using Strong-Ground Motion." *Bull. Seism. Soc. Am.,* 89(6), 1484-1504.
2. Day, S. M., R. Graves, J. Bielak, D. Dreger, S. Larsen, K.B. Solsen, A. Pitarka, and L. Ramirez-Guzman (2008). "Model for Basin Effects on Long-Period Response Spectra in Southern California." *Earthquake Spectra* 24, 257-277.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-014**

**NRC RAI:**

The last sentence in paragraph 3 of Section 2.2 in the Enclosure 1 report says:

> The stacking (averaging) of responses necessary to achieve stability over multiple input time histories (all matched to the same control motion spectrum) renders the time domain (SHAKE) approach difficult to properly develop fully probabilistic response spectra.

It is not clear if you are discussing Approach 2B, although it appears that you are. However, Approach 2B is shown to work well with a large enough number of realizations (60). It is also transparent. Please clarify the approach being discussed.

**Duke Energy Response:**

The discussion in Section 2.2 of Enclosure 1 of the April 30, 2008, letter (Reference 1) titled "Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1," (Reference 1) is generic in that it applies to the development of site-specific amplification factors (mean in the case of Approach 2, median and $\sigma_{ln}$ in the case of Approach 3) using control motion time histories as opposed to Random Vibration Theory (RVT), which typically uses a smooth power spectrum as a control motion.

Typically in a time history approach, for each random set of site-specific dynamic material properties, multiple control motion time histories must be run to develop amplification factors due to the record-to-record and frequency-to-frequency variability. The variability in the control motion time histories results in a variability in response (site-specific motions) for each realization of dynamic material properties that do not cancel in developing amplification factors. This random variability is not due to variability in site-specific dynamic material properties and may dominate the variability of the amplification factors [Bazzuro and Cornell, 2004 (FSAR Reference 2.5.2-275)]. Since the frequency-to-frequency as well as record-to-record randomness has already been accommodated in the reference site hazard through the aleatory variability about the median attenuation relations [even for Central Eastern North America (CENA) Ground Motions Prediction Equations (GRMPEs), refer to the response to RAI 02.05.02-015 in Enclosure 10 of this letter], its inclusion may result in unnecessarily conservative estimates in mean amplification factors in Approach 2 (in developing mean amplification factors for a lognormal distribution mean = median $\sigma^2 / e^2$) or conservative site-specific hazard in Approach 3 (which directly includes $\sigma_{ln}$ of the amplification factors).

In contrast, with the RVT equivalent-linear approach, a power spectrum is used in lieu of time histories as control motions. Because of RVT, the response then reflects a mean overall possible (entire population) phase spectra (time histories) which have the same power spectrum, provided they meet the RVT criteria of stationary random noise [Boore, 1983 (Reference 2)], which has been demonstrated through extensive validations for magnitude **M** 2 to **M** 7+ earthquakes [Boore, 1983 (Reference 2), 1986 (Reference 3); EPRI, 1993 (FSAR Reference 2.5.2-273); Silva et al., 1996 (FSAR Reference 2.5.2-288)]. With the use of RVT, site-specific spectra computed with each realization of dynamic material properties reflect a mean over analyses done with all possible time histories, each with the power spectrum used in the single RVT analysis. Averaging over RVT analyses performed using multiple realizations of site-specific dynamic material properties then reflects an appropriate estimate of the aleatory variability about median amplification due to the aleatory variability in site-specific dynamic material properties.

**References:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
2. Boore, D.M. (1983). "Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models of the Radiated Spectra." Bulletin of the Seismological Society of America, 73(6), 1865-1894.
3. Boore, D.M. (1986). "Short-period P- and S-wave Radiation from Large Earthquakes: Implications for Spectral Scaling Relations." Bulletin of the Seismological Society of America, 76(1) 43-64.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-015**

**NRC RAI:**

Paragraph 5 of Section 2.2 (Enclosure 1 report) discusses the potential for double-counting of variability when developing amplification factors using a time domain procedure. The additional variability (frequency-to-frequency and record-to-record variability in the computed soil response due to time history propagation) reflects a double-counting since this is intrinsically included in the ground motion prediction equations (GRMPEs) used to develop the reference PSHA. This conclusion may be a true for the western U.S. where the GRMPEs are based almost entirely on recorded data that does contain this variability. However, it is not clear if this is true for CEUS GRMPEs that are based almost entirely on simulations using point-source models, RVT, and fixed values of kappa. Please provide clarification on this point.

**Duke Energy Response:**

The issue as to whether or not the aleatory variabilities in Central Eastern North America (CENA) ground motion prediction equations (GRMPEs) include frequency-to-frequency and record-to-record randomness is quite valid and a bit subtle. In general this variability is really the intra-event component of the variability and may be thought of as principally due to path and site effects. The source component may contribute as radiating somewhat different spectral shapes with azimuth and distance (e.g., rupture directivity, hanging-wall verses foot-wall). The intra-event is typically the larger component of the aleatory variability and, consequently, is intended to be included in all GRMPEs. For the EPRI [1993 (FSAR Reference 2.5.2-273)] and Silva et al. [2003 (Reference 1)] relations, this component of aleatory variability was explicitly included by combining the modeling variability with the parametric variability. The modeling variability was computed by comparing recorded and computed motions for a number of earthquakes and sites [Silva et al., 1996 (FSAR Reference 2.5.2-288)]. The modeling variability then includes the observed frequency-to-frequency and record-to-record variability that is not accommodated by the model. The remainder is included via the parametric variability by randomizing model parameters not optimized in the modeling of each validation earthquake.

For the hybrid CENA models [e.g., EPRI, 2004 (FSAR Reference 2.5.2-202)], as they begin with Western North America (WNA) aleatory variability, it is reasonable to assume they transfer the frequency-to-frequency and site-to-site component from WNA observation to the CENA. Also for the CENA models that use an "empirical" geometrical attenuation [e.g., Atkinson and Boore, 1995 (FSAR Reference 2.5.2-208) and 2006 (Reference 2)], the aleatory variability in the recordings is brought along in the GRMPE. Finally, because the CENA aleatory variability is similar or greater than the empirical WNA aleatory variability for all the GRMPEs [EPRI, 2004 (FSAR Reference 2.5.2-202)], it is very likely the intent of the GRMPEs was to capture a realistic record-to-record and frequency-to-frequency aleatory variability in the CENA GRMPEs.

**References:**

1. Silva, W.J., N. Gregor, R. Darragh (2003). "Development of Regional Hard Rock Attenuation Relations for Central and Eastern North America, Mid-Continent and Gulf Coast Areas." Unpublished report prepared by Pacific Engineering and Analysis (available on the Pacific Engineering and Analysis website), 2003. (Pacific Engineering and Analysis, 311 Pomona Ave., El Cerrito, CA 94530, www.pacificengineering.org; e-mail: pacificengineering@juno.com).
2. Atkinson, G.M. and D.M Boore (2006). "Earthquake Ground-motion Prediction Equations for Eastern North America." *Bull. Seism. Soc. Am,* 96(6), 2181-2205.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-016**

**NRC RAI:**

Paragraph 1 of section 2.2.1 "Amplification Factors" of the Enclosure 1 report needs further clarification. Paragraph 1 states the following:

> The correlation and layering model prevents unconservative profile realizations with uncorrelated velocity fluctuations over depth resulting in increased effective overall damping due to wave scattering at impedance boundaries (scattering kappa). This condition is exacerbated at high loading levels due to nonlinearity, concentrating shear strain in low velocity layers. As a check on this possibility it is important to compare the median response spectrum over multiple realizations with that from a single analysis with base-case properties, at low (linear) loading levels. If the median spectrum falls below that computed using the base-case dynamic material properties at high frequency by more than about 5%, a significant amount of scattering kappa has been added in the velocity randomization, resulting in an overall larger kappa value than desired and unconservative high-frequency motions at low loading levels. This should be then compensated by appropriately lowering the kappa value in the control motions, another advantage of using a point-source model to generate control motions as it is not an unambiguous endeavor to adjust control motions developed from attenuation relations of spectral shapes (NUREG/GR-6728) [sic] for lower (or larger) kappa values.

a.) In the above discussion you suggest lowering the kappa value in the control motions to compensate for the shortcomings of the randomization. Please specify what kappa value was used and the quantitative rationale for using this value. Also, please provide references.

b.) You suggest the correlation and layering model as a means to prevent unconservative profile realizations. You then discuss a means of checking for unconservative realizations in the profile. The process of checking for unconservative profiles is different from the process of preventing the unconservative profiles. Please provide a description of the preventative aspects of the model rather than just the secondary check for unconservative realizations in the profile.

c.) Please discuss any physical reason why profiles with significant "scattering kappa" should not exist in the real world. If there are physical limitations, then does the correlation and layering model generate unrealistic profiles? If there are no physical limitations, then are the motions only being modified so as to be conservative?

d.) Please explain if the results are consistently conservative. If the strains within the layers change with the modification of the control motion, then the site amplification will occur at different frequencies. This change in the frequency of amplification may result in conservatism at some frequencies, and unconservatism at other frequencies.

e.) If the correlation and layering model generates problematic profiles, then the correction should be made to the layering model, not the motion. How is the kappa adjusted? Is it specific for each site realization? In the calculation of the spectral ratio, is the ratio between the "corrected" surface and the "uncorrected" bedrock, or the "corrected" surface and the "corrected" bedrock?

**Duke Energy Response:**

The following response begins with a general discussion followed by specific elaborations of the five questions (parts a to e) posed in the RAI.

The intent of the profile randomization, necessitated by a desire to achieve fully probabilistic site-specific design motions with a defined Annual Exceedance Frequency (AEF), was to approximate the effects of changes in dynamic material properties which vary slowly across a site (e.g., give rise to spatial incoherence). The profile randomization scheme and 1-D wave propagation model implicitly assume each profile has an infinite lateral extent. As a result, any scattering due to vertically alternating velocities (fluctuations) that are laterally continuous is more pronounced than would occur with lateral variability.

To the extent random velocity fluctuations are not believed to be laterally continuous, any artificial effects induced by model limitations should be compensated in a physically reasonable manner. Since velocity fluctuations, if the lateral extent is great enough, can mimic energy absorption by reflecting high-frequency waves downward, a reasonable approach is to generally preserve the overall amplification, on average, which results from either a smooth base-case profile (typical) or a base-case profile which reflects laterally continuous velocity fluctuations (e.g., a single or multiple low-velocity zones which are continuous across a site). Since the base-case profile(s) are developed from low-strain measurements, it is appropriate to perform the adjustment (reduce kappa in the control motion) at low-strain. The assumption being the equivalent-linear approximation remains valid for velocity fluctuations which exist in the random profiles (Silva et al. (1996) (FSAR Reference 2.5.2-288)). It is important then to have equivalent-linear validations with recorded motions as well as fully nonlinear codes for profiles which have significant velocity fluctuations as well as high levels of motions (EPRI (1993) (FSAR Reference 2.5.2-273)).

For velocity fluctuations (i.e., low-velocity zones) which are large enough to be laterally continuous across a site (e.g., footprint and somewhat beyond), the 1-D model would be appropriate and randomly generated profiles may be expected to preserve such features. Laterally stable velocity fluctuations would be expected to result in stable resonances or possible depletion of energy over a frequency range, in the case of significant low-velocity zones. For such cases the layering model has an option which fixes layer thicknesses to those of the base-case (input) model, preserving layer boundaries. The issue then becomes one of judgment as to which velocity fluctuation features that appear laterally continuous and should be preserved in the randomization process. Such occurrences are generally treated with multiple base-cases which span the range in laterally continuous features, corresponding hazard curves computed, and weights applied based on judgment reflecting actual in-situ conditions.

a.) For the Unit 1 profile, which consisted of 20 ft of concrete, the scattering kappa ($\kappa$) was negligible. For the example soil profile, the profile kappa was 0.0158 sec with a hard rock value of 0.006 sec for a total value of about 0.02 sec. In this case, the median spectrum came very close to that computed with the base-case profile so the correction, reduction in the hard rock value, was neglected. Since this scattering kappa correction reflects a reasonable assumption, there is no quantitative rationale other than an assumption of about a 5% amplitude tolerance for the effects of an increased effective damping at low strain due to scattering in the random profiles.

No references are known on this correction apart from the discussion of scattering damping due to profile randomization in validation exercises (Silva et al. (1996) (FSAR Reference 2.5.2-288)).

b.) The profile randomization model is a statistical model that was based on an analysis of variance of measured shear-wave velocity profiles. It consists of a distribution for velocity at a given depth coupled with a correlation of velocity with depth, as well as a layering model which randomizes layer thickness and which increases random layer thickness with depth to model the observed decrease in fluctuations with increasing depth (EPRI (1993) (FSAR Reference 2.5.2-273); Silva et al. (1996) (FSAR Reference 2.5.2-288)). While the intent of the model was to produce random profiles with the same statistics as actual profiles, it is a model with limitations. Both the layering and correlation models were intended to reflect the characteristics of actual 1-D profiles and inhibit unnatural velocity fluctuations. A feature built into the model is the ability to include minimum and maximum velocities for each layer. This was intended as a possible means to limit unconservative or non-realistic realizations but this requires an objective assessment (judgment) of maximum and minimum values. Such constraints would also change the statistical model as it then becomes artificially bounded (truncated). Such an approach would necessarily be site-specific and necessitate very extensive site investigations. As a practical alternative, it was decided to compensate for the effects of the model limitations directly, at low strain, relying on the equivalent-linear approximation to adequately accommodate velocity fluctuations at higher strains. It is recommended the reviewer examine the model development by Dr. Gabriel Toro provided in EPRI (1993) (FSAR Reference 2.5.2-273) and Silva et al. (1996) (FSAR Reference 2.5.2-288).

c.) Significant "scattering kappa" can exist in the real world. Along these lines, the Central Eastern North America (CENA) nominal hard rock kappa value of about 0.006 sec may be mostly scattering due to random velocity fluctuations (laterally as well as vertically) with little to no intrinsic energy absorption or hysteretic damping. The motions are only being modified so as not to be unconservative.

d.) The decrease in kappa in the control motion or profile below the nonlinear or randomized zone is typically quite small, 10% to 25%. For example, the low-strain kappa in a given profile due to the hysteretic damping curves may total 0.01 sec, depending on profile thickness, and if the desired total kappa is 0.04 sec, an additional 0.03 sec is added below the soil or randomized zone or to the source spectrum. Typically scattering kappa may be about 0.002 sec to 0.004 sec, depending on the profile, reducing the 0.03 sec in this example to about 0.026 sec to about 0.028 sec. This is a relatively small change and not likely to result in significantly different frequencies of amplification.

e.) It is always possible for a statistical model to generate problematic profiles (e.g., a layer reflecting multiple standard deviations in velocity). When it is obvious this has occurred, a different random seed is selected. As with all models, a more sophisticated profile randomization model would be welcome but, in reality, it would reflect a considerable effort in development and perhaps require prohibitively extensive site investigations (i.e., truncated distributions developed for each site characterized).

As previously discussed, the kappa is adjusted (reduced) in materials below the profile randomization or in the control motion and the spectral ratio computed between the "corrected" soil motion and uncorrected reference motion, unless the reference site motion required its own correction, as median estimates are used for the reference site spectra.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-017**

**NRC RAI:**

Paragraph 3 of Section 2.2.1 of the Enclosure 1 report discusses perturbation tapering at the ends of the modulus reduction and damping curves in order to preserve the shape of the base-case curves.

Please clarify the following:

a) what causes these perturbations,

b) what type of tapering was used and the length of the tapering windows.

**Duke Energy Response:**

The Lee Nuclear Station Unit 1 Foundation Input Response Spectra (FIRS) consists of 20 ft of concrete with a base-case shear-wave velocity of 7500 feet per second (ft/sec) on hard rock (≈ 9300 ft/sec) as described in FSAR Figure 2.5.4-252. For such stiff conditions linear site response is adequate, even to loading levels of 1.50g because of the low cyclic shear strains. For linear site response analyses, amplification factors are independent of spectral shape (e.g., effects of magnitude; see Figure 2, Reference 1). The discussion below addresses the general problem of developing FIRS when nonlinear site response analysis is necessary. Since a linear site response analysis was used to develop the Lee Nuclear Station Unit 1 FIRS, this discussion does not specifically pertain to the Lee Nuclear Station Unit 1 FIRS.

In nonlinear site response analyses, each randomized modulus reduction and hysteretic damping curve is based on three curves: the base-case curve and upper and lower envelopes, which are taken as inviolable bounds on the random values. In addition, the width of the distribution is controlled by the standard deviation. The randomization is accomplished by randomizing one point on the median curve (rejecting and resampling it if it violates the envelope) and then generating a smooth curve through the random point. The single point randomized is taken at a strain of 0.03%, typically about where the envelope is widest. The smooth curve is generated by measuring the distance from the base-case value to the random value as a fraction of the distance to the upper (or lower) envelope. All of the other points on the random curve are then assigned to be the same fraction between the standard curve and the upper (or lower) envelope (bound). Thus, each random curve is a randomly weighted average of the standard curve and one of the envelopes.

In answer to specific questions a) and b), the fraction or random perturbation is tapered if necessary at low- and high-strains to force the random curve to remain within the bounds. The strain range over which the fraction or perturbation is tapered varies depending on the size of the fractional perturbation and the proximity of the random curve to the bounds. Because the randomization process uses a fractional perturbation between the base-case curve and the bounds, which are themselves based on the shapes of the base-case curves, the resulting randomized curves have shapes similar to those of the base-cases. Figure 1 shows an example of several random curves as well as the base-case curves using a natural-log variability, $\sigma_{ln}$, of 0.15 and 0.30 at a shear-strain of 0.03% [analyses by Dr. Carl Costantino, Silva et al., 1996 (FSAR Reference 2.5.2-288)]. As Figure 1 shows, the random curves have shapes similar to the base-case curves [EPRI, 1993 (FSAR Reference 2.5.2-273); 251 ft to 500 ft]. Note the cluster of G/Gmax curves due to the small aleatory variability. For a $\sigma_{ln}$ of 0.15, the 84th percentile is only about 15% above the median (base-case). Provided the randomized curves have shapes similar to that of the base-case, this process is not likely to produce a biased set of mean curves with a correspondingly biased suite of mean (log) amplification factors.

For deep stiff soil sites in Central Eastern North America (CENA), to illustrate that biases do not exist, Figure 2 compares median amplification factors computed with all site dynamic material properties randomized (velocities, depth to basement, G/Gmax and hysteretic damping curves) with median factors computed with only velocities and depth to basement randomized (base-case G/Gmax and hysteretic damping curves). In general, Figure 2 shows close agreement over the entire frequency range and for all loading levels. The agreement suggests the randomization process for the G/Gmax and hysteretic damping curves produces suites of curves which are unbiased in the mean. That is, the randomly generated modulus reduction and hysteretic damping curves have shapes similar to those of the base-case and are approximately evenly distributed (log) about the base-case over a wide range in strain.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

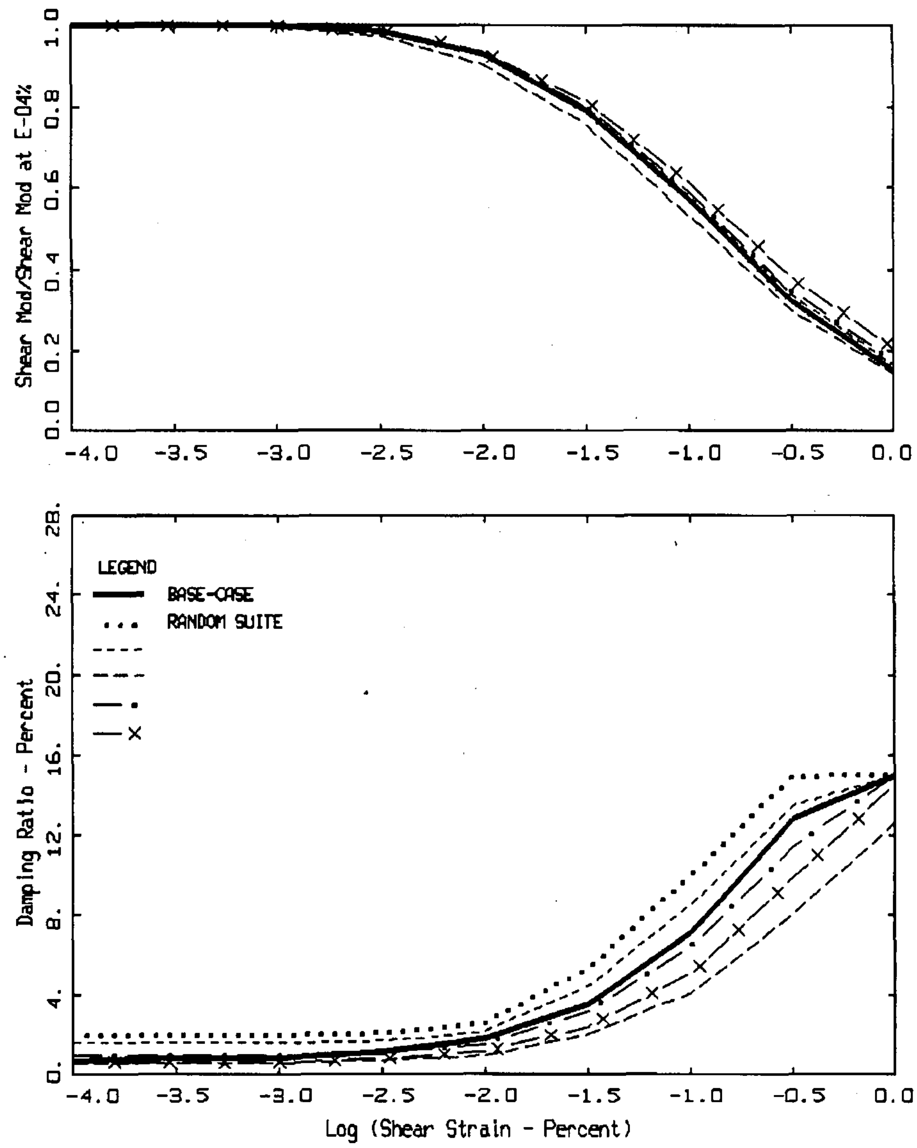
**Attachments:**

1) Figure 1. Comparison of a Suite of 5 Randomly Generated Modulus Reduction and Hysteretic Damping Curves With the Base-Case Curves
2) Figure 2. Comparison of Median Amplification Factors for a Deep Stiff Soil Site in the CENA Computed With All Site Parameters Varied (Shear-Wave Velocities, Depth to Basement, and Modulus Reduction as well as Hysteretic Damping Curves) With Only Shear-Wave Velocities Varied

## Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-017

## Figure 1. Comparison of a Suite of 5 Randomly Generated Modulus Reduction and Hysteretic Damping Curves With the Base-Case Curves




MODULUS REDUCTION AND DAMPING CURVES FOR SAND
EPRISRZ.MAT AND FIVE RATIONALIZATIONS

**Figure 1. Comparison of a Suite of 5 Randomly Generated Modulus Reduction and Hysteretic Damping Curves With the Base-Case Curves**

A log-normal distribution was assumed with standard deviations ($\sigma_{ln}$) of 0.15 and 0.30 at a shear-strain of 0.03% for G/Gmax and hysteretic damping respectively. Base-case curves are from EPRI [1993 (FSAR Reference 2.5.2-273)] 251 ft to 500 ft. Damping is limited to a maximum of 15%.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 2 to RAI 02.05.02-017**

**Figure 2. Comparison of Median Amplification Factors for a Deep Stiff Soil Site in the CENA Computed With All Site Parameters Varied (Shear-Wave Velocities, Depth to Basement, and Modulus Reduction as well as Hysteretic Damping Curves) With Only Shear-Wave Velocities Varied**

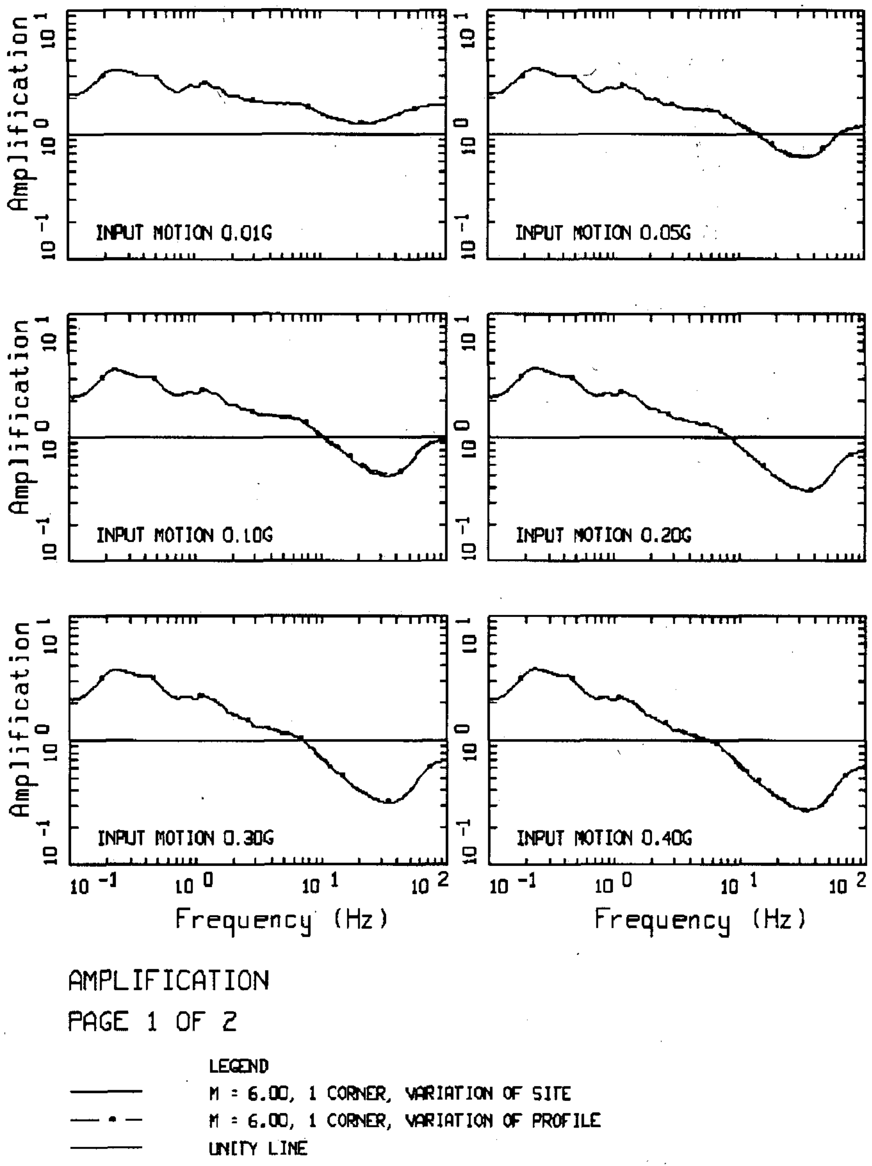



**Figure 2. Comparison of Median Amplification Factors for a Deep Stiff Soil Site in the CENA Computed With All Site Parameters Varied (Shear-Wave Velocities, Depth to Basement, and Modulus Reduction as well as Hysteretic Damping Curves) With Only Shear-Wave Velocities Varied (Page 1 of 2)**

Magnitude is **M** 6.0 and the single-corner model was used.

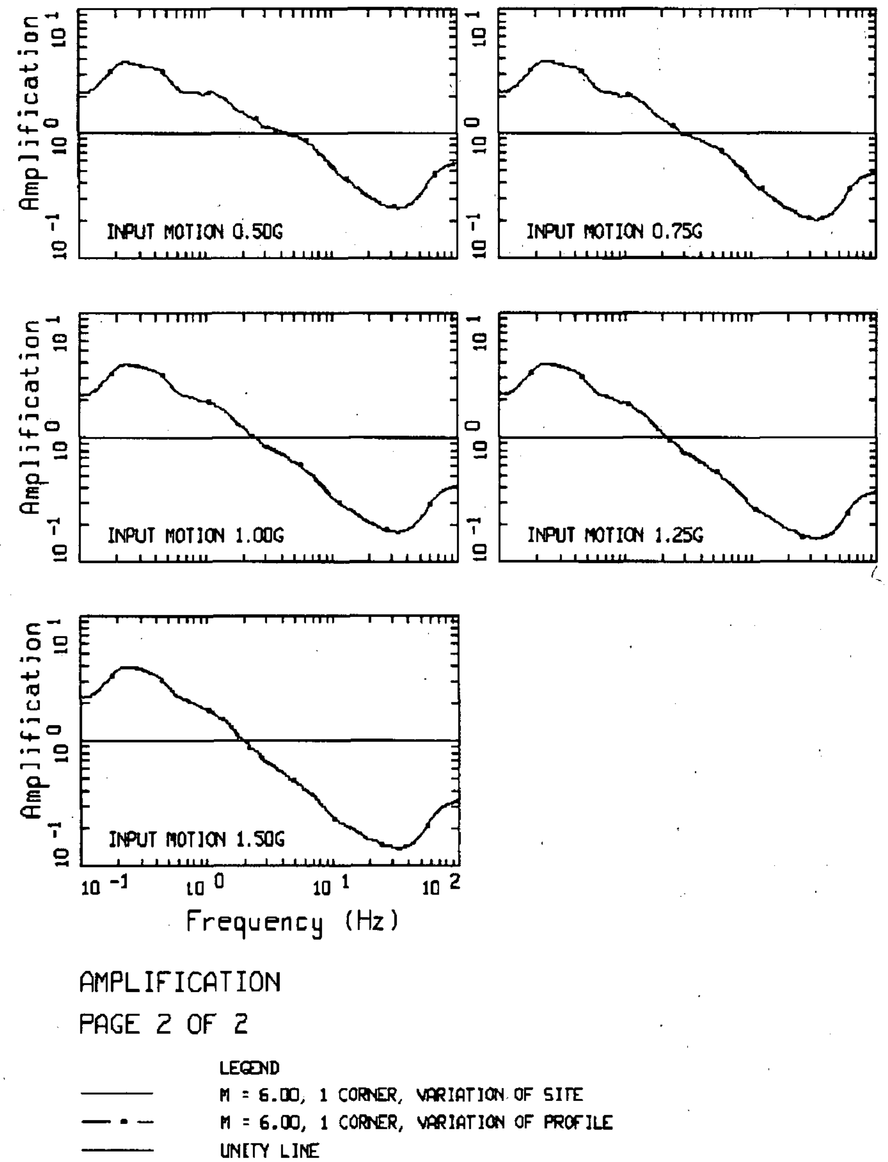



**Figure 2. Comparison of Median Amplification Factors for a Deep Stiff Soil Site in the CENA Computed With All Site Parameters Varied (Shear-Wave Velocities, Depth to Basement, and Modulus Reduction as well as Hysteretic Damping Curves) With Only Shear-Wave Velocities Varied (Page 2 of 2)**

Magnitude is **M** 6.0 and the single-corner model was used.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-018**

**NRC RAI:**

Paragraph 3 of Section 2.2.1 (Enclosure 1 report) states the following:

> Empirical sigma values, based on laboratory test of materials of the same general type (e.g. gravely sands) such that the G/Gmax and hysteretic damping curves would be applied over depth ranges which boring logs or laboratory index property tests indicate are appropriate, are 0.15 ($\sigma_{ln}$) and 0.30 ($\sigma_{ln}$) for modulus reduction and hysteretic damping respectively.

Please provide a reference for this assumption.

**Duke Energy Response:**

Statistical analyses performed on a limited data set of laboratory dynamic tests by Dr. Carl Constantino [Silva et al., 1996 (FSAR Reference 2.5.2-288)] resulted in the $\sigma_{ln}$ estimates of 0.15 and 0.30 for modulus reduction and hysteretic damping, respectively. More complete statistical analyses on a larger number of samples showed similar levels of aleatory variability [Darendeli, 2001 (Reference 1)].

**Reference:**

1. Darendeli, M.B. (2001). "*Development of a New Family of Normalized Modulus Reduction and Material Damping Curves.*" Ph.D. thesis, *Geotechnical Engineering Report GD01-1*, University of Texas, Austin, Texas.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-019**

**NRC RAI:**

The last sentence of Paragraph 1, Section 2.2.2 (Enclosure 1 report) suggests the development of amplification factors using both single and double-corner models and combining results with the same weights used in the development of the reference PSHA. This will require a detailed assessment of the different sub-models used in the development of the reference PSHA (assuming use of the 2004 EPRI GMPE where the weights for single and double-corner models vary for source types (i.e. general area sources vs. non-general area sources)). Please provide a discussion of how this GMPE deaggregation would be performed.

**Duke Energy Response:**

The EPRI (2004) (FSAR Reference 2.5.2-219) Ground Motion Prediction Equations (GRMPEs) are divided into four general clusters or model types: 1, single-corner; 2, double-corner; 3, hybrid [based on Western North America (WNA) empirical GRMPEs]; and 4, finite-source. All four are appropriate for both areal and fault sources, provided that the appropriate distance metric and associated variability is employed [EPRI, 2004 (FSAR Reference 2.5.2-219)]. Clearly models 1 and 2 separate into single- and double-corner while models 3 and 4 are likely double-corner as well. Model 3 is based on WNA empirical scaled to Central Eastern North America (CENA) and WNA strong ground motions appear to strongly reflect a double-corner source model [Atkinson and Silva, 1997 (Reference 1)]. Model 4, based on finite-fault simulations is expected to naturally result in a two-corner source as a consequence of summing point-sources [Joyner and Boore, 1986 (Reference 2)]. Recommended weights for the four models are: 0.275, 0.312, 0.196, and 0.217 for clusters 1 to 4 respectively [EPRI, 2004 (FSAR Reference 2.5.2-219)].

The EPRI (2004, FSAR Reference 2.5.2-219) hard rock spectral shapes could then be used as control motions reflecting clusters 1 to 4: single-corner shape for cluster 1 and double-corner shape for clusters 2, 3, and 4. For clusters 3 and 4, the double-corner shape reflects a reasonable assumption and should result in sufficiently accurate amplification factors.

A more general and preferred approach would be to develop amplification factors using each GRMPE (reference site) as control motions. With this approach each cluster GRMPE would generate cluster specific amplification factors and reference site hazard computed for each cluster (or GRMPE) [EPRI, 2004 (FSAR Reference 2.5.2-219)]. Approach 3 would then be applied to condition each hazard curve, weights applied, and final hazard curves computed perhaps with the Cumulative Absolute Velocity (CAV) filter applied as part of the Approach 3 implementation. The use of the GRMPE and its implementation of the CAV filter are described in EPRI, 2004 (FSAR Reference 2.5.2-219).

**References:**

1. Atkinson, G.M and W.J. Silva (1997). "An empirical study of earthquake source spectra for California earthquakes." *Bull. Seism. Soc. Am.* 87(1), 97-113.
2. Joyner, W.B., and Boore, D.M. (1986). "On simulating large earthquakes by Green's-function addition of smaller earthquakes." *Earthquake Source Mechanics,* edited by S. Das, J. Boatwright and C.H. Scholz (AGU Geophys. Monogr. 37, M. Ewing), vol. 6, 269-274.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-020**

**NRC RAI:**

Section 2.2.2 "Control Motions" of the Enclosure 1 report does not specifically describe the methods applied to the Lee site. Please describe what models were used, whether point-source, single- or double-corner, or a combination. Please describe the weighting factors used for the Lee COLA site.

**Duke Energy Response:**

For the Lee Nuclear Station Unit 1 Foundation Input Response Spectra, which consists of a thin (mean thickness of 20 ft) concrete layer over hard Central Eastern North America (CENA) rock, with a shear-wave velocity of about 9,300 feet per second (ft/sec), linear site response was assumed due to the stiffness of the materials. Note that Table 2 of Reference 1 is updated as part of the response to RAI 02.05.02-008 in Enclosure 3 of this letter. At loading levels of 1.50g, somewhat above Annual Exceedance Frequency (AEF) $10^{-6}$ loading levels, the maximum effective cyclic shear strains are only about $10^{-3}$%, reflecting linear response. Because of the assumed linearity, the transfer functions are independent of the spectral shape of the control motion, provided there is sufficient energy at high frequency to excite the resonance of the thin concrete layer.

Specifically, the single corner-frequency point-source model was used (weight = 1.0) with the parameters listed in the revised Table 2 of Reference 1 shown in Enclosure 3 of this letter. Moment magnitude (**M**) 5.1 was used and was based on a finer deaggregation at high frequency than that shown in Figure 16 of Reference 1. Although computations performed for the horizontal and vertical components were with linear analyses and are therefore independent of spectral shape, computation of vertical motions depends upon source depth as well as distance due to the incidence angle of the inclined P-SV wavefields. Because the high (structural) frequency hazard was dominated by relatively close-in small-magnitude sources, **M** 5.1 only was used to compute the V/H ratios (vertical and horizontal motions). At low frequency, it was not necessary to use **M** 7.0 and **M** 8.0 in the model V/H ratios because the minimum (water level) of 0.7 controls the low-frequency V/H ratios. As discussed in Section 4.2.2 of Reference 1, it was considered important to use the larger magnitudes (**M** 7.0, **M** 8.0) in the empirical soft rock V/H ratios because they showed significant magnitude dependence. Relative weights for V/H ratios are listed in Table 4 of Reference 1.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-021**

## NRC RAI:

Paragraph 2 of Section 2.2.2 "Control Motions" of the Enclosure 1 report states that "Use of the point-source models is computationally efficient as it avoids intermediate step of spectral matching to the empirical spectra, which are not well constrained for all **M** at distances exceeding about 100 km."

Please clarify that computational effectiveness of using point-source model instead of empirical spectra does not compromise the reliability of results.

## Duke Energy Response:

The point-source model produces spectra consistent with target rock response spectra, which Bazzurro and Cornell (2004) (Reference 1) identify as the most important requirement to achieve performance consistent results. Specifically, Bazzurro and Cornell (2004) (Reference 1) found that once the rock spectrum is known, the additional knowledge of magnitude and distance, which implicitly define its average response spectrum shape, do not appreciably improve the estimation of amplification as a function of frequency. The point-source model provides a realistic prediction of spectra and mean time-domain parameters including peak particle velocity over a wide range of magnitudes and distances (Boore (1983) (Reference 2); Boore (2003) (Reference 3)). More recent extensive validations with the point-source model have shown it produces good agreement with motions recorded in Western North America (WNA) over a wide range in magnitude (**M** 4.2 to **M** 7.4), distance (2 km to 150 km), and site conditions (Silva et al. (1996) (Reference 7)). A potential single-corner model limitation resulting from the validations revealed that it over predicts low-frequency rock site motions by about 25% for frequencies lower than about 0.6 Hz. Similar observations led to the development of the double-corner point-source model in the WNA (Atkinson and Silva (1997) (Reference 4)). Due to the limitation of nonlinearity in the top 500 ft of soil profiles, and based on validations using finite-source simulations, the low-frequency over-prediction of the single corner-frequency model is not considered to result in overly nonlinear site response. This observation is illustrated by the comparison of three figures showing median amplification factors computed with the single- and double-corner source models for a deep firm soil site in the Central Eastern North America (CENA). Figure 5 of the Enclosure 1 Report (Reference 5) indicates that at 0.40g the difference in median amplification factors between the single- and double-corner reference site motions is about 25%. However, the attached Figure 1, with a fundamental column resonance near 0.2 Hz, shows more than 100% difference in reference site (in the case of CENA hard rock) motions. This is in general agreement with the observations of Bazzurro and Cornell (2004) (Reference 1) of a weak effect of control motion spectral shape on computed amplification, conditional on control motion peak acceleration.

To illustrate more recent WNA spectral shapes, the attached Figure 2 compares four PEER (2008) spectral shapes with both the single- and double-corner point source models for **M** 6.5 at a distance of 25 km, distances where the Ground Motion Prediction Equations (GRMPEs) are well constrained by recordings. In general, the two numerical point source models do reasonably well in capturing the spectral shapes from empirical models. At long period (T > 1 sec) the two models generally span the empirical GRMPEs.

As a further note, the use of the empirical GRMPEs as control motions is complicated by the observations that rock conditions beneath soils in WNA are quite different from outcropping rock (NUREG/CR-6728 (Reference 8)). Typically, rock overlain by soils does not have a substantial weathered zone, which can have a significant effect at high-frequency through a smaller kappa value, as well as steeper velocity gradient (NUREG/CR-6728, (Reference 8, Page J-3)). Adjustment of empirical GRMPEs for base-of-soil conditions is more difficult than generating point-source (or finite source) motions for a given rock profile as well as kappa value.

**References:**

1. Bazzurro, P., and C. A. Cornell (2004), "Nonlinear Soil-Site Effects in Probabilistic Seismic-Hazard Analysis," Bulletin of Seismological Society of America, 94(6), 2110–2123.
2. Boore, D. M (1983), "Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models of the Radiated Spectra," Bulletin of Seismological Society of America, 73, 1865-1894.
3. Boore, D.M. (2003), "Simulation of Ground Motions Using the Stochastic Method," Pure and Applied Geophysics, 160, 635-676.
4. Atkinson, G.M and W.J. Silva (1997). "An Empirical Study of Earthquake Source Spectra for California Earthquakes." Bulletin of Seismological Society of America, 87(1), 97-113.
5. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
6. Pacific Engineering Research Center (PEER) (2008), Next Generation of Ground Motion Attenuation Models (NGA), "Special Issue on the Next Generation Attenuation Project," Technical editors, J. Stewart, R. Archuleta, M. Power, Earthquake Spectra, vol. 24(1).
7. Silva, W.J., Abrahamson, N., Toro, G., and Costantino, C. (1996), "Description and Validation of the Stochastic Ground Motion Model," Unpublished report prepared by Pacific Engineering and Analysis for Brookhaven National Laboratory, Associated Universities, Inc., Upton, New York 11973.
8. McGuire, R.K., Silva, W.J., and Constantino, C.J. "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard and Risk-Consistent Ground Motions Spectra Guidelines," U.S. Nuclear Regulatory Commission Report Prepared for Division of Engineering Technology, Washington, D.C., NUREG/CR-6728, 2001.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

1) Figure 1. Example of Single- and Double-Corner Median Reference Site Response Spectra (5% Damped) Computed for **M** 7.0 and 0.40g
2) Figure 2. Comparison of Empirical WNA Spectral Shapes (PEER, 2008 (Reference 6)) with those Computed using the Single- and Double-Corner Source Models

## Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-021

## Figure 1. Example of Single- and Double-Corner Median Reference Site Response Spectra (5% Damped) Computed for M 7.0 and 0.40g

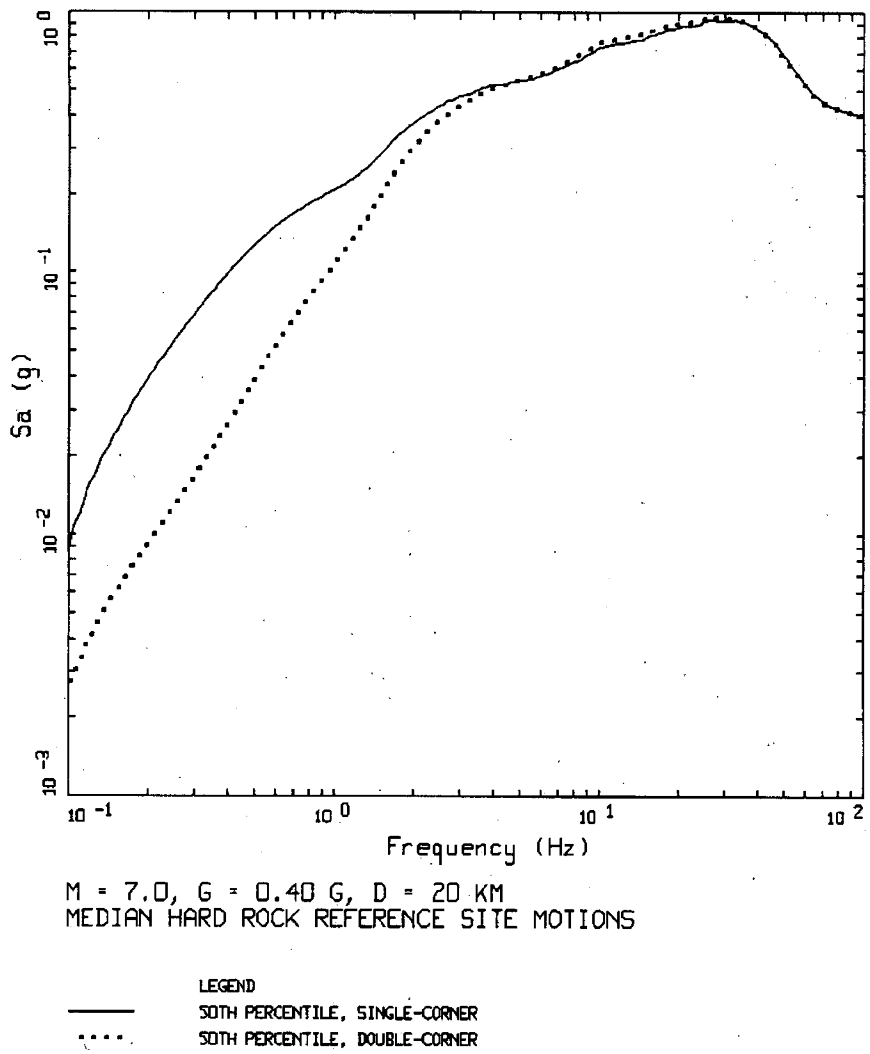



**Figure 1. Example of Single- and Double-Corner Median Reference Site Response Spectra (5% Damped) Computed for M 7.0 and 0.40g**

These spectra illustrate the differences in control motions used in developing the soil site amplification factors shown in Figure 5 of Reference 5.

## Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 2 to RAI 02.05.02-021

## Figure 2. Comparison of Empirical WNA Spectral Shapes (PEER, 2008 (Reference 6)) with those Computed using the Single- and Double-Corner Source Models

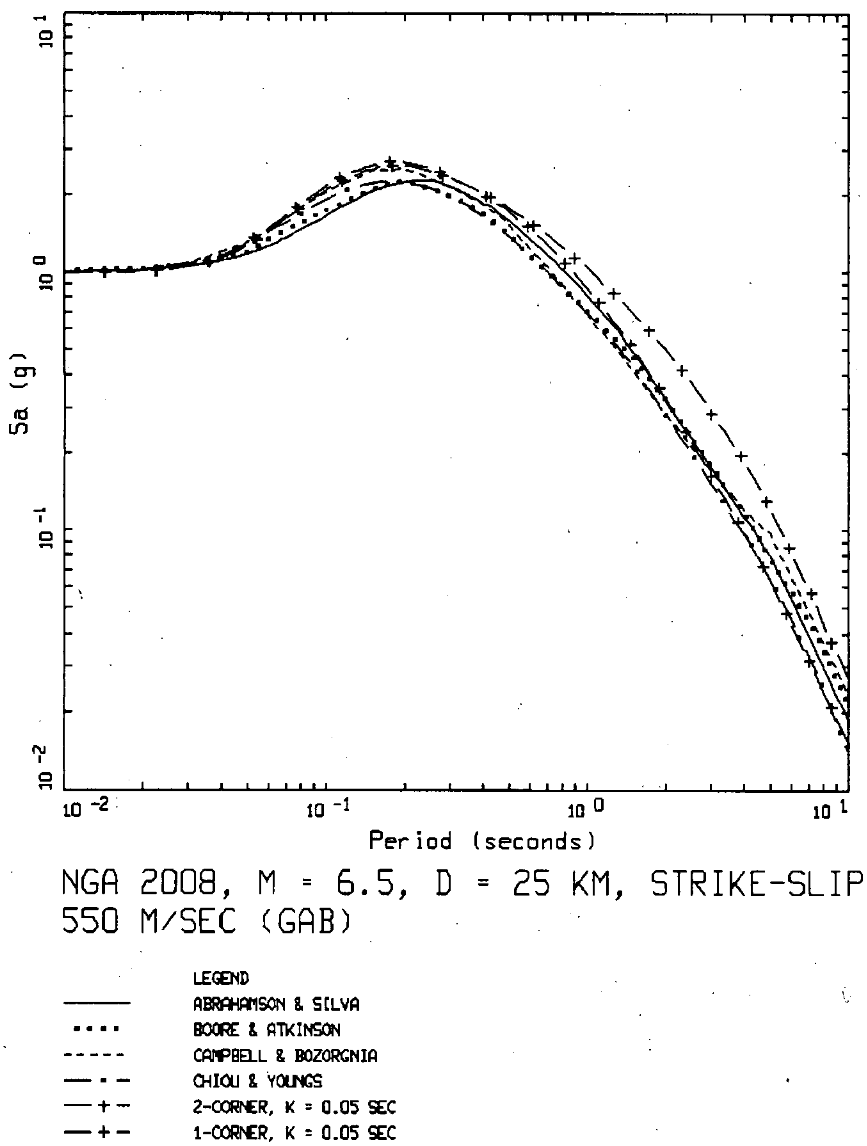



**Figure 2. Comparison of Empirical WNA Spectral Shapes (PEER, 2008 (Reference 6)) with those Computed using the Single- and Double-Corner Source Models**

Moment magnitude is 6.5 and the rupture distance is 25 km from a vertical strike-slip earthquake with the top-of-rupture at the surface. The site condition is soft rock (Geomatrix category A and B) with a $\overline{V_S}$ (30m) of 550m/sec.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-022**

**NRC RAI:**

Section 2.2.2.1 of the Enclosure 1 report discusses spectral shape effects. Please clarify if the shape of the control motion spectrum discussed in this section is applicable to the Lee site where $\overline{V_S}$ is approximately 9300 ft/sec overlaid by ~20 ft of concrete with $\overline{V_S}$ of 7500 ft/sec. Please provide additional information in regards to the nonlinear model used and how it is constrained in the linear portion as applicable at the Lee site.

**Duke Energy Response:**

For application to the Lee Nuclear Station Unit 1 Foundation Input Response Spectrum (FIRS), which consists of about 20 ft of concrete ($\overline{V_S}$ = 7500 feet per second (ft/sec)) over Central Eastern North America (CENA) hard rock ($\overline{V_S} \approx$ 9300 ft/sec), linear site response was assumed due to the material stiffness.

The shape of the control motion spectrum is appropriate for the reference site outcrop properties, and used the CENA hard rock crustal model listed in Table 2 of Reference 1. Note that Table 2 of Reference 1 is updated as part of the response to RAI 02.05.02-008 in Enclosure 3 of this letter. With a surface shear-wave velocity of about 9300 ft/sec, the transfer function is independent of the control motion due to the assumed linearity in the site response for both the concrete as well as the surface layer of the CENA crustal model.

Specifically the site response for the Lee Nuclear Station Unit 1 FIRS was performed by computing the reference site motion using a single corner-frequency point-source model with the parameters listed in the revised Table 2 of Reference 1 shown in Enclosure 3 of this letter. For the Lee Nuclear Station Unit 1 FIRS, the thin (mean thickness of 20 ft) concrete layer was simply placed on top of the crustal model. All other parameters were kept the same as those used for the reference site simulations. This includes kappa (0.006 sec) as the 20 ft of concrete, with a damping of about 0.5% (Q = 100) to 1.0% (Q = 50) would contribute at most 5 x $10^{-5}$ sec to kappa. In the site-specific analyses, the shear-wave velocity was held fixed as well as the negligible hysteretic damping.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-023**

**NRC RAI:**

Paragraph 3 of Section 2.2.2.1 of the Enclosure 1 report discusses Figure 3 of the report. The figure shows an example of median and ± 1 sigma estimates of amplification factors computed for a deep soil site in the CENA. The figure is used to illustrate the effects of control motion loading level on amplification factors. Based on the figure:

- At frequencies higher than 2 Hz amplification decreases as loading levels increase
- Deamplification reaches 0.2 at about 30 Hz

According to empirical attenuation relations available through 1997, the minimum amplification is observed at about 0.5. You chose to implement the 0.5 minimum value instead of the minimum value (0.2) shown in figure 3 of the report.

You explained the difference between the empirical and model results as possibly being the result of using equivalent-linear approximation with a single value of S-wave velocity and damping at all frequencies. However, it seems that using a fully non-linear model can result in even larger deamplification. Please provide more explanation about these differences and possibly the need to modify the model.

**Duke Energy Response:**

It is quite correct that many fully nonlinear models can result in larger deamplification at high frequency and at high loading levels than equivalent-linear analyses (NUREG/CR-6769 FSAR Reference 2.5.2-274) and EPRI ((1993) FSAR Reference 2.5.2-273). This difference is likely the result of significantly higher damping at high cyclic shear-strain in the nonlinear analysis than in the corresponding equivalent-linear analyses. Typically, fully nonlinear models are able to match a specified modulus reduction curve quite closely; however, the corresponding damping curve generally shows much larger damping at high strains (lower damping at low strains unless viscous damping is added) (Silva et al. (1986) (Reference 1); Silva et al. (2000) (FSAR Reference 2.5.2-285); NUREG/CR-6769 (FSAR Reference 2.5.2-274); and EPRI ((1993) FSAR Reference 2.5.2-273)). The lower amplification at high frequency and at high loading levels for the fully nonlinear analyses, compared to the corresponding fully equivalent-linear analyses, may reflect the higher damping. While the lower bound (water level) of 0.5 for the amplification is based on 1997 empirical Ground Motion Prediction Equations (GRMPEs) (Abrahamson and Shedlock (1997) (Reference 2)) and more recent empirical models suggest values possibly lower than 0.5 (NGA (2008) (Reference 3)), there have not been sufficient studies of sites and motions to admit lower values which are based solely on fully nonlinear modeling results. Possible equivalent-linear model modifications intended to overcome the model limitation of a lower bound amplification, perhaps through a frequency-dependent shear-wave velocity and damping (Kausel and Assimaki (2002) (Reference 4)), would also require careful study of sites which have both recorded motions over a wide range in loading levels, as well as information available on dynamic material properties (e.g., Port Island and the Kobe earthquake and aftershocks). As an alternative, for sites which reflect high loading levels in their hazard, the minimum amplification can be treated as epistemic variability (uncertainty), such as maximum magnitude. Amplification factors could then be developed reflecting multiple lower bounds (including unbounded), corresponding hazard curves developed, and relative weights applied to the resulting hazard estimates. The implementation of a lower bound of 0.5, based on available recordings through 1997, reflects a reasonably conservative approach in the absence of appropriate confirmatory observations or the reliance on fully nonlinear models.

**References:**

1. Silva, W.J., T. Turcotte and Y. Moriwaki (1986). "Soil Response to Earthquake Ground Motions." Palo Alto, Calif.: Electric Power Research Institute, EPRI Research Project RP 2556-07.
2. Abrahamson, N.A and K.M. Shedlock (1997). "Overview." Seismological Research Letters, 68(1), 9-23.
3. NGA (2008). "Special Issue on the Next Generation Attenuation Project". Technical editors, J. Stewart, R. Archuleta, M. Power, Earthquake Spectra, vol. 24(1).
4. Kausel, E., and D. Assimaki (2002). "Seismic Simulation Inelastic Soils via Frequency-dependent Moduli and Damping." Journal Engineering Mechanics, ASCE, 128(1), 34-47.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-024**

**NRC RAI:**

The discussion on Approach 3 in Section 3.1 of the Enclosure 1 report states that frequency dependent amplification factors, accounting for non-linearity in soil response, characterize site-specific amplification. Please provide additional information and justification for the nonlinear model that you used.

**Duke Energy Response:**

In Section 3.1 of the Enclosure 1 report (Reference 1), the discussion on Approaches is independent of the nonlinear soil model. The discussion in Section 3.1 is simply a presentation on the approaches to accommodate site-specific aleatory (randomness) and epistemic (uncertainty) variabilities of dynamic material properties on a probabilistically determined hazard developed for a generic (i.e., deep soil site) site condition, as illustrated in Figures 3 through 7 (Reference 1). Both fully nonlinear (NUREG/CR-6769 (FSAR Reference 2.5.2-274); Silva *et al.*, 2000 (FSAR Reference 2.5.2-285); and Bazzurro and Cornell, 2004 (FSAR Reference 2.5.2-275)), as well as equivalent-linear (NUREG/CR-6728 (FSAR Reference 2.5.2-251) models, have been used to generate amplification factors. Also, in the equivalent-linear analyses, different modulus reduction and hysteretic damping curves have been used (NUREG/CR-6728). Model justification is described in detail in EPRI (1993) (FSAR Reference 2.5.2-273) and Silva *et al* (1996) (FSAR Reference 2.5.2-288).

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-025**

**NRC RAI:**

The last paragraph of the Approach 3 discussion in Section 3.1 (Enclosure 1 report) describes two ways to implement Approach 3.

a.) Please explain why both methods of Approach 3 implementation double count site aleatory variability.

b.) Please explain the rationale for why corrections for the site component aleatory variability result in a 5-10% reduction in motion.

**Duke Energy Response:**

a.) The Ground Motion Prediction Equations (GRMPEs) for rock (as well as soil) implement natural logarithm variabilities (aleatory) of median peak amplitudes that already incorporate a site component of aleatory uncertainty. In general the total aleatory variability (variance) about median GRMPEs can be written or portioned as:

$$\sigma^2 = \sigma^2_{source} + \sigma^2_{path} + \sigma^2_{site}$$

where $\sigma^2_{source}$ refers to earthquake-to-earthquake randomness in the source (e.g., stress drop (parameter)), $\sigma^2_{path}$ reflects propagation path randomness (e.g., lateral variability in crustal structure), and $\sigma^2_{site}$ is the randomness in motions due to differences in site-conditions (velocities, nonlinear dynamic material properties, depths to rock for soil site) for a given site category (rock or soil or 30m shear wave velocity, $\overline{V_S}$ (30m)). The separate contributions are very difficult to unambiguously distinguish or even define. They are also frequency dependent, and remain largely unknown. For example, surface waves might be a site-related issue or a propagation path issue.

In developing amplification factors, provided the reference site motion (denominator) is fixed (median spectrum), the randomization of velocity, normalized shear modulus ($G/G_{max}$) and hysteretic damping curves, and depth to rock or basement material results in a variability in amplification due to the site. This variability reflects a large (if not total) component of $\sigma^2_{site}$ (Bazzurro and Cornell, 2004 (FSAR Reference 2.5.2-275)). If the control motion is also random (e.g., time histories), the issue becomes much more complex as the variability of the amplification factors now includes the reference site variability (already accommodated in the reference site hazard). One must then resort to the law of propagation of errors for ratios, which includes the covariance of the rock and soil motions to separate out the variability of the soil.

For the attenuation relation modification approach (Reference 1), an alternative to implementing the full distribution of the amplification factor is to simply use the median transfer function to modify the reference site spectral value during the hazard integration. This approach avoids the potential double counting of the site aleatory variability and is generally equivalent to the full integration followed by the approximate correction for the site aleatory variability discussed in Reference 1. It was intended to include this variant in the discussion of the attenuation relation method as a manner of implementing Approach 3 described in Reference 1.

b.) The development of the "risk equation" is described in EPRI (2004) (FSAR Reference 2.5.2-202), NUREG/CR-6728 (FSAR Reference 2.5.2-251), and NUREG/CR-6769 (FSAR Reference 2.5.2-274). These documents provide a development of the "risk equation" which, under the assumption of a hazard curve of constant slope (log-log) as well as a low annual exceedance frequency (AEF) much less than 1 (AEF<<1), may be reformulated to provide an approximate means of adjusting a mean hazard curve for a change in either aleatory or epistemic variability. The adjustment may be in either ground motion or probability and assumes the change in variability is independent of exceedance frequency. The equation for amplitude at a fixed AEF is given by:

$$A_C = A \exp 0.5 * \kappa * \left(\sigma_N^2 - \sigma_o^2\right)$$

where $A_C$ is the corrected amplitude and $\sigma_N$ and $\sigma_o$ reflect the new and original variabilities respectively. To correct for inclusion of the variability of the amplification factor $\sigma_\delta$ (i.e., approximately remove the effects of $\sigma_\delta$):

$$\sigma_N^2 = \sigma_o^2 - \sigma_\delta^2$$

resulting in:

$$\exp(-0.5 * \kappa * \sigma_\delta^2) \quad (1)$$

where $\sigma_\delta$ is the log standard deviation of the amplification function (AF) and kappa (κ) is the log-log slope of the hazard curve that is calculated at each point from the reference rock hazard curve and typically ranges from about 2 to 3 for Central Eastern North America (CENA). For maximum CENA values for these parameters of κ=3 and $\sigma_\delta$=0.3,

$$\exp(-0.5 * \kappa * \sigma_\delta^2) = 0.87 \quad (2)$$

for κ=2 and $\sigma_\delta$=0.3,

$$\exp(-0.5 * \kappa * \sigma_\delta^2) = 0.91 \quad (3)$$

and for κ=2 and $\sigma_\delta$=0.2,

$$\exp(-0.5 * \kappa * \sigma_\delta^2) = 0.96 \quad (4)$$

For the most common combinations of $\sigma_\delta$ and κ represented by (3) and (4) the scale factors correspond to about 5-10% reduction in estimated motion.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-026**

**NRC RAI:**

Paragraph 5 of Section 2.2 (Enclosure 1 report) asserts that using an RVT approach properly neglects the frequency-to-frequency and record-to-record variability and avoids double-counting of these variabilities in computed site response (relative to the time domain approach). This statement seems to be at odds with the following conclusion from Section 3.1 which describes the two methods for implementation of Approach 3:

> Both implementations result in very similar site-specific hazards (Cramer, 2003) and both will tend to double count site aleatory variability, once in the suite of transfer function realizations and again in the aleatory variability about each median attenuation relation.

Please provide a discussion that clarifies this inconsistency.

**Duke Energy Response:**

The aleatory variability about the reference site Ground Motion Prediction Equations (GRMPEs) includes frequency-to-frequency as well as record-to-record randomness. As a result, this component of the total aleatory variability is properly accommodated in the reference site hazard analyses. If time histories are used in developing amplification factors, particularly with fully nonlinear analyses, much of the frequency-to-frequency and record-to-record variability is not cancelled in taking ratios (Bazzurro and Cornell, 2004 (FSAR Reference 2.5.2-275)). Consequently this randomness contributes significantly to the site-specific parametric aleatory variability in the transfer function, which is produced with analyses of the randomly generated profiles and random nonlinear dynamic material properties.

Stated another way, the aleatory variability of the amplification factor $\sigma_{\ln\ y|x}$ (Equation 6, Reference 1) is intended to reflect only the parametric aleatory variability of site-specific dynamic material properties through multiple transfer functions computed with random realizations of profiles and random nonlinear dynamic material properties. This site-specific aleatory variability is the only component of variability that should be considered to be added in developing fully probabilistic design motions. However, in reality, the frequency-to-frequency and record-to-record component of the aleatory variability about the reference site GRMPE may properly be considered to reflect site parametric aleatory variability. If this is the case, then adding the site-specific parametric variability of the amplification factors from the randomly generated profiles and nonlinear material properties indeed double counts the aleatory variability due to site conditions: once in the hazard analysis using GRMPEs and again in applying Approach 3. If time histories are used in developing the amplification factors, the intrinsic frequency-to-frequency and record-to-record variability does not completely cancel in taking the ratios, particularly for nonlinear site response analysis, and this variability is added to the site-specific parametric aleatory variability. As a result one may consider this approach as double counting site aleatory variability twice. That is, site aleatory variability is accommodated in the reference site hazard analysis through the standard deviations of the GRMPEs, and again in applying Approach 3 using Random Vibration Theory (RVT) to develop site-specific median amplification and associated aleatory variability. If time histories are used in developing median site-specific amplification factors, the associated aleatory variability contains both site-specific parametric variability as well as frequency-to-frequency and record-to-record aleatory variability. Recommended approaches to avoid the frequency-to-frequency and record-to-record contribution to the site-specific aleatory variability is not to use time histories to drive the site-specific soil column or correct for its contribution as recommended using Equation 7 (Reference 1) with C = 0, a negative exponential, $\overline{AF_{rp}} = 1.0$, and $\sigma_\delta$ the component of aleatory desired to be removed from the hazard.

Alternatively, in implementing the modified GRMPE technique of implementing Approach 3 (Reference 1) the GRMPE can be modified with only the median amplification factor and neglect the associated aleatory variability. Either of these techniques may also be used to correct for, or not include, the site-specific parametric variability computed using RVT, thereby assuming it is sufficiently accommodated in the reference site hazard analysis in the aleatory variability about the reference site GRMPE.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-027**

**NRC RAI:**

Section 3.4.1 "Optimum Number of Realizations" of the Enclosure 1 report cites a paper by Bazzuro and Cornell (2004) which suggests that as few as 10 realizations are enough to satisfy the Approach 3 application. However, you state that Table 3 (from the report) suggests that in order to improve the accuracy in aleatory variability to 10%, 130 realizations are required at the 90% confidence level. Please provide further explanation as to why such differences exist in the number of suggested realizations, 10 by Bazzuro and Cornell to 130 as stated in your report.

**Duke Energy Response:**

Bazzurro and Cornell (2004) (FSAR Reference 2.5.2-275) consider only the direct impacts of the uncertainty (epistemic variability) in the mean (log) amplification on the site-specific hazard due principally to the uncertainty in the mean (log) control motions. Using time histories, the major contribution to the variability about the median amplification is the record-to-record variability of the rock control motions [Bazzurro and Cornell, 2004 (FSAR Reference 2.5.2-275)]. Eliminating this record-to-record control motion variability, since it is already accommodated in the reference site hazard, by using a point-source simulation power spectrum with Random Vibration Theory (RVT) site response, reduces the number of realizations to fewer than 10, about 5 for a ±10% accuracy in the mean amplification.

However, from Equation 7 in Reference 1, the aleatory variability about the median amplification can have a significant effect on the site-specific hazard. Uncertainty in the aleatory variability then results in uncertainty in the estimate of the site-specific hazard, conditional on the reference site hazard. Because many more realizations are required for a given statistical stability of the variability about the mean (standard deviation) than are required for the same stability of the mean, the $\sigma_{\ln AF(f)}$ typically control the number of realizations. Recall, for a normal distribution:

$$\sigma_{\mu} = \frac{\sigma}{\sqrt{N}} \qquad (1)$$

where $\sigma_{\mu}$ is the standard error of the mean and N is the number of samples [Tijms, 2007 (Reference 2)]. The following discussion is intended to present a clear distinction between uncertainty in the mean and uncertainty in the standard error of the mean as applied to Approach 3.

Bazzurro and Cornell (2004) (FSAR Reference 2.5.2-275) use a simple approximation to estimate the number of records, $n$, needed to keep the standard error of the mean of natural log amplification function, $\ln(AF(f))$, at any spectral acceleration level within a specified fractional accuracy, $\zeta$, which is given by:

$$n = \left[ \frac{\sigma_{\ln AF(f)}}{\zeta} \right]^2 \qquad (2)$$

where $\sigma_{\ln AF(f)}$ is the natural log standard deviation of the AF as a function of frequency, *f*. The analysis in Section 3.4.1 accounts for the additional influences of the slope of the hazard curve and the nonlinearity of the amplitude function through the exponential correction term of equation (7) of Section 3.3,

$$\exp\left(\frac{\sigma^2_{\ln AF(f)}}{2} \frac{\kappa}{1-C}\right) \qquad (3)$$

where κ is the log-log slope of the reference hazard curve that is calculated at each point from the reference rock hazard curve and typically ranges from about 2 to 3 for Central Eastern North America (CENA) and possibly as large as 6 for Western North America (WNA). *C* is the log-log slope (absolute value) of the amplification factor with respect to the reference motion that is calculated at each point from the amplification factors (AF) and is a measure of the degree of soil nonlinearity. Based on Equation 3, for a given percent accuracy in amplitude, the required accuracy in the standard deviation depends on the slope of the reference hazard curve as well as the degree of nonlinearity through the slope of the amplification factors C. Consequently, a simple estimate of the number of realizations required to achieve specific ζ based on Equation 2 from Bazzurro and Cornell (2004) (FSAR Reference 2.5.2-275) will not be accurate for all possible combinations of amplification nonlinearity and hazard curve slopes. For a selected target accuracy and confidence level Chart 9 (Reference 3) was used to find the number of realizations required to achieve the target accuracy at that confidence level. Since the accuracy also depends on k and C in Equation 3, Reference 3 was used to determine the number of realizations to achieve the required $\sigma_{\ln AF(f)}$ in Equation 3 that when combined with k and C yields the required accuracy at the required confidence level. This approach resulted in a required number of realizations of 130 for the case cited in Section 3.4.1, "Optimum Number of Realizations," of Reference 1.

For the William States Lee Unit 1 Foundation Input Response (FIRS) profile, FSAR Figure 2.5.4-252, the slope of the amplification factors has a maximum at about 0.5 and the $\sigma_{\ln AF(f)}$ averages about 0.2 or less with a hard rock hazard curve slope (log, log) near 2 so Equation 3 has a value of about 1.1. A 50% increase in $\sigma_{\ln AF(f)}$ results in an Equation 3 value of about 1.2, or a 10% change. At the 90% confidence level, fewer than 5 realizations are required (Reference 3) (30 were run for the William States Lee Unit 1 FIRS analyses), increasing to 13 at the 99% confidence level (Reference 3) and of course fewer still for estimates of the mean (Reference 1). Conversely, for a $\sigma_{\ln AF(f)}$ near 0.5, a steep hazard curve slope near 4, and over a highly nonlinear loading level with C near 0.5, Equation 3 is about 2.7. In this case a 10% increase in $\sigma_{\ln AF(f)}$ results in an Equation 3 value of about 3.4, or about a 20% increase in amplitude, which is significant. For cases such as these, to achieve a 10% accuracy in amplitude requires better than a 5% accuracy in $\sigma_{\ln AF(f)}$ and the number of samples increases from 5 to 550 at the 90% confidence level (Reference 3) to over 1,000 at the 99% confidence level (Reference 3). Thus, the difference in estimate number of required realizations needed to achieve a specified accuracy between Bazzurro and Cornell (2004) (FSAR Reference 2.5.2-275) and Section 3.4.1 of Reference 1 simply reflects a more complete accounting of the factors that affect accuracy in Equation 7 (Reference 1, Section 3.4.1) relative to Equation 2 from Bazzurro and Cornell (2004) (FSAR Reference 2.5.2-275).

For typical cases in the CENA, about 30 realizations are adequate to achieve about 10% error in the ground motion. For applications of Approach 3, guidelines on desired ground motion accuracy, % error, and confidence levels, rather than number of iterations, are encouraged as they would be more likely to ensure achievement of desired performance goals.

**References:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
2. Tijms, H., *Understanding Probability: Chance Rules in Everyday Life*, Cambridge University Press, Cambridge, pp. 159-161, 2007.
3. Crow, E.L, F.A. Davis, and M.W Maxfield, *Statistics Manual: With Examples Taken from Ordnance Development*, Courier Dover Publications, Chart 9, 1960.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-028**

**NRC RAI:**

Paragraph 2 of Section 3.4.1 (Enclosure 1 report) states the following:

> Clearly, for application of fully probabilistic approaches to developing site-specific hazard, the number of realizations should be case specific and determined with preliminary analysis.

Please provide further explanation for justifying your recommendation and explain how "case specific" realizations apply specifically to the Lee site. Does it also mean that 130 realization recommended before may not be enough in certain cases?

**Duke Energy Response:**

For the Lee Nuclear Station Unit 1, due to the small variability in velocity of the concrete and linear site response, the $\sigma_{ln}$ in Equation 1 is only about 0.1 (Reference 1). For a reference site hazard curve slope of about 2 (log-log), the exponential term is only about 1.1. Therefore to achieve a ± 10% accuracy in $Z_{rp}$, the $\sigma_{ln}$ can have a very large uncertainty. The example given in Section 3.4.1 (Reference 1) used 100% error in $\sigma_{ln}$ which results in only about a 3% change in $Z_{rp}$, far smaller than the assumed example tolerance of 10% uncertainty in site-specific design motions ($Z_{rp}$). This weak stability requirement for $\sigma_{ln}$ places the number of realizations at fewer than 5 at the 90% confidence level (Table 3 of Reference 1). An actual stability requirement of ± 10% for $Z_{rp}$ translates to a much weaker stability for $\sigma_{ln}$ than ± 100%, closer to ± 300%. For the Lee Nuclear Station Unit 1 Uniform Hazard Response Spectra (UHRS), due to the combination of linearity in site response (C = 0) as well as the uniformity of velocity the concrete fill ($\sigma_{ln} \approx 0.1$), ± 10% accuracy in design motions is achieved with an epistemic uncertainty in the site response aleatory variability of 3 (± 300%), from the chart in Table 3 of Reference 1.

In general applications of Approach 3, given specific guidelines for design accuracy in design motions as well as confidence levels, the minimum number of realizations can easily be estimated for site-specific values of $\sigma$, $\kappa$, and C. For extreme cases, large values of the exponential term in Equation 1, more than 130 realizations may be required. Using the law of propagation of errors, the following development presents an assessment of the error (fractional) in estimated motion due to epistemic uncertainty in the aleatory variability of the amplification factors.

The standard error ($\sigma_{lnAF(f)}$) of the mean of natural log amplification function, ln($AF(f)$), is site specific. The analysis in Section 3.4.1 of Reference 1 accounts for the site-specific influences of the slope of the hazard curve and the nonlinearity of the amplitude function through the exponential correction term of equation (7) of Section 3.3 (Reference 1) reproduced as Equation 1 below:

$$z_{rp} = a_{rp}\overline{AF_{rp}}\exp\left(\frac{\sigma^2_{\ln AF(f)}}{2}\frac{\kappa}{1-C}\right) \qquad (1)$$

Where:

$z_{rp}$ is soil amplitude $z$ associated with return period $r_p$;

$a_{rp}$ is the reference spectral acceleration $a$ associated with return period $r_p$,

$\overline{AF_{rp}}$ is the geometric mean (mean log) amplification factor for the reference (e.g., rock) motions with return period $r_p$,

$\kappa$ is the log-log slope of the reference hazard curve that is calculated at each point from the reference rock hazard curve and typically ranges from about 2 to 3 for Central Eastern North America (CENA) and possibly as large as 6 for Western North America (WNA),

$\sigma_{\ln AF(f)}$ is the natural log standard deviation of the AF as a function of frequency, $f$, and

$C$ is the log-log slope (absolute value) of the amplification factor with respect to the reference motion that is calculated at each point from the amplification factors, $AF_{rp}$ and is a measure of the degree of soil nonlinearity for linear site response analyses C = 0 (Reference 1).

Equation 1 can be cast in the form:

$$f = ce^{dA} \qquad (2)$$

where

$$c = a_{rp}\overline{AF_{rp}} \qquad (3)$$

$$d = \frac{0.5\times\kappa}{1-C} \qquad (4)$$

$$A = \sigma^2_{\ln AF(f)} \qquad (5)$$

Using a first-order linear expansion for relative error (Abramowitz and Stegun, 1972 (Reference 2) and the law of exponential derivatives (Dwight, 1961 (Reference 3):

$$\frac{\sigma_f}{f} \approx \frac{f'(x)}{f(x)}\Delta x = \frac{cde^{dA}}{ce^{dA}}\Delta A = d\sigma_A \qquad (6)$$

Application of Equations 1-6 yields the uncertainty in $z_{rp}$, $\sigma_{z_{rp}}$, due to amplification uncertainty through the relative uncertainty as:

$$\frac{\sigma_{z_{rp}}}{z_{rp}} \approx \frac{0.5\times\kappa}{1-C}\sigma_{\sigma^2_{\ln AF(f)}} \qquad (7)$$

where $\sigma_{\sigma^2_{\ln AF(f)}}$ is the standard deviation of $\sigma^2_{\ln AF(f)}$ which decreases as 1/sqrt($n$), where $n$ is the number of realizations (Tijms, 2007 (Reference 4). For application of fully probabilistic approaches to developing site-specific hazard, conditional on guidelines for the desired error tolerance on design motions (e.g. ± 10%) and confidence level (e.g. 90%), the number of realizations should be case specific and possibly magnitude dependent, determined with preliminary analyses. For most applications, 30 realizations would be sufficient for a reasonable stability (e.g. ≤ 10%) in site-specific design motions due to the epistemic uncertainty in the aleatory variability about the amplification factors. Similar stability in the mean amplification is typically achieved with as few as 10 realizations.

**References:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
2. Abramowitz, M. and Stegun, I. A. (Eds.), Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, 9th printing. New York: Dover, New York, p. 14 equation 3.5.7, 1972.
3. Dwight, H.B., Tables of Integrals and Other Mathematical Data, Macmillan Publishing, New York, pp. 133 equation 563.1, 1961.
4. Tijms, H., Understanding Probability: Chance Rules in Everyday Life, Cambridge University Press, Cambridge, pp. 159-161, 2007.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-029**

**NRC RAI:**

Table 2 of the Enclosure 1 report, which relates to FSAR Table 2.5.2-221, shows ranges of amplitude, magnitude and distance. Please provide additional discussion of how these ranges are developed. In particular, please explain the relationship between Table 2 of the report and the deaggregation results shown on report Figure 16 and in section 4.1 in a more transparent fashion. Why Table 2 reflects only magnitude 5.1?

**Duke Energy Response:**

The range in expected hard rock (reference site) peak acceleration from 0.01g to 1.50g is typical (Walling et al., 2008 (Reference 1) and taken to cover the range in hard rock hazard to Annual Exceedance Frequency (AEF) as low as about $10^{-7}$. The peak acceleration intervals are typically selected to be shorter below 0.5g to provide more accurate estimates of potential nonlinear amplification and V/H (vertical:horizontal) ratios over the levels of motion which generally reflect the largest contributions to the hazard. As a result, the range in reference site expected or median peak accelerations is not related to the hazard deaggregation. The magnitudes for the control motions are selected to reflect the dominant contributions (modes) to the hazard and are based on the deaggregations. Because the Lee Nuclear Station Unit 1 nuclear island is assumed to behave linearly, the site response is independent of spectral shape (magnitude). However hard rock V/H ratios depend on distance, vary little with magnitude [NUREG/CR-6728 (FSAR Reference 2.5.2-251)], and increase with decreasing distance. Since small magnitude dominates the high-frequency hazard, with magnitude (**M**) 5.1 resulting from a finer magnitude deaggregation than the 0.5 M bins shown in Figure 16 (Reference 2), **M** 5.1 was selected to conservatively represent the model driven V/H ratios for the very stiff Lee Nuclear Station Unit 1 nuclear island profile referred to as Base Case A1 (20 ft ± 3 ft of concrete over hard rock), described in FSAR Subsection 2.5.2.7 and Lee Nuclear Station Supplemental Technical Report Subsection 3.4.2.3 (Reference 2).

**References:**

1. Walling, M., W. Silva and N. Abrahamson (2008). "Nonlinear Site Amplification Factors for Constraining the NGA Models." *Earthquake Spectra,* 24(1), 243-255.
2. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-030**

**NRC RAI:**

Paragraph 2 of Section 2.2.2.1 (Enclosure 1 report) discusses the magnitude dependency of amplification factors and the guideline for discretization of reference disaggregation to ~one-half magnitude unit. This is consistent with the results shown in report Figure 16. However, the magnitude used in Table 2 is **M** 5.1 which is not consistent with report Figure 16. Please provide a discussion of the basis for **M** 5.1 vs. **M** 5.25. Also, the last sentence in this paragraph discusses the use of the mode vs. mean ("Use of the mode is clearly more appropriate than the mean, even though there is rarely a single peak over magnitude."). Please provide a discussion and rationale for this conclusion and outline how the situation with multiple nearly equal modes in the disaggregation results will be handled in the development of amplification factors using Approach 3.

**Duke Energy Response:**

The Lee Nuclear Station Unit 1 consists of 20 ft of concrete with a base-case shear-wave velocity of 7,500 feet per second (ft/sec) over hard rock with mean shear wave velocity at 9300 ft/sec ($\overline{V_S} \approx$ 9,300 ft/sec), as described in FSAR Figure 2.5.4-252. For such stiff conditions linear site response is adequate, even to loading levels of 1.50g, because of the low cyclic shear strains. For linear site response analyses, amplification factors are independent of spectral shape (e.g., effects of magnitude; see Figure 2 in Reference 1). The magnitude (**M**) 5.1 was used as it was based on a finer deaggregation than shown in Figure 16 in Reference 1.

Section 2.2.2.1, Paragraph 5, of Reference 1 states: "Use of the mode is clearly more appropriate than the mean, even though there is rarely a single peak over magnitude." Mode magnitudes are preferred over mean magnitudes as they generally more closely reflect magnitudes of actual earthquakes. For example, a bimodal magnitude distribution may have **M** 5.5 and **M** 7.5 as peaks reflecting a background source (**M** 5.5) and a large magnitude source zone (**M** 7.5, e.g., Charleston) with a mean magnitude of about 6.5. The most likely earthquake magnitudes are about 5.5 and 7.5, and amplification factors and V/H (vertical:horizontal) ratios should be developed for both magnitudes rather than a single suite for **M** 6.0. Resulting hazard curves would then reflect relative weights based on the relative peaks of the deaggregations, which would likely vary with annual exceedance frequency.

For cases of multiple nearly equal modal magnitudes, a conservative guideline for accommodation of magnitude dependencies in the reference hazard deaggregation is about 0.5 magnitude unit as described in Section 2.2.2.1.1, Paragraph 5, of Reference 1. Modal magnitudes spanning about 0.5 magnitude unit may be combined (binned) with the bin center magnitudes used in the development of amplification factors and V/H ratios.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-031**

**NRC RAI:**

Paragraph 4 of Section 4.2.1 "Site-Specific V/H Ratios" (Enclosure 1 report) discusses validation exercises relating to the 1989 Loma Prieta and 1992 Northridge earthquakes. The Northridge earthquake occurred in 1994. The Landers earthquake occurred in 1992. Please specify which earthquake is actually being discussed.

**Duke Energy Response:**

To clarify, only the 1989 **M** 6.9 Loma Prieta earthquake has a formal validation (bias and variability computed) that is presented in EPRI (1993) (FSAR Reference 2.5.2-273). The 1994 Northridge earthquake validation was performed later and is unpublished.

Section 4.2.1, Site-Specific V/H Ratios, (Reference 1) is revised to clarify the discussion of validations for the 1989 **M** 6.9 Loma Prieta earthquake presented in EPRI (1993) (FSAR Reference 2.5.2-273). Attachment 1 contains a mark-up of Section 4.2.1 that will be incorporated into a future revision of the supplemental technical report.

**Reference:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

Section 4.2.1

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachment:**

1) Revised Supplemental Technical Report, Section 4.2.1

# Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 1 to RAI 02.05.02-031

## Revised Supplemental Technical Report, Section 4.2.1

Supplemental Technical Report, "Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1," Section 4.2.1, paragraph 4, is revised as follows:

The approximations of linear analysis for the vertical component and uncoupled vertical and horizontal components have been validated in two ways. Fully nonlinear modeling using a 3-D soil model shows that the assumption of largely independent horizontal and vertical motions for loading levels up to about 0.5g (soil surface, horizontal component) for moderately stiff profiles is appropriate (EPRI, 1993). Additionally, validation exercises with recorded motions have been conducted at over 50 sites that recorded the 1989 M 6.9 Loma Prieta ~~and 1992 M 6.7 Northridge~~ earthquake~~s~~ (EPRI, 1993). These validations show the overall bias and variability is acceptably low for engineering applications but is higher than that for horizontal motions. The vertical model does not perform as well as the model for horizontal motions (EPRI, 1993; Silva, 1997). An indirect validation was also performed by comparing V/H ratios from WNA empirical attenuation relations with model predictions over a wide range in loading conditions (Silva, 1997). The results show a favorable comparison with the model exceeding the empirical V/H ratios at high frequency, particularly at high loading levels. In the V/H comparisons with empirical relations, the model also shows a small under prediction at low frequency (≤ 1 Hz) and at large distance (≥ 20 km).

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-032**

**NRC RAI:**

Paragraph 5 of Section 4.2.1 "Site-Specific V/H Ratios" (Enclosure 1 report) states that a hard rock kappa value of 0.0003 [*sic*] seconds is used for the vertical analyses. Please provide justification for using this value, including any references.

**Duke Energy Response:**

The justification for using a kappa value of 0.003 seconds is provided in the following discussion, including attached Figures 1 through 4.

For vertical analyses described in Reference 1, which are performed with linear site response, the total kappa or kappa (κ) at the surface of the profile is taken as half that of the horizontal kappa value (Anderson, 1991 (Reference 2); EPRI, 1993 (FSAR Reference 2.5.2-273); Silva et al., 1996 (Reference 2.5.2-288); Silva, 1997 (FSAR Reference 2.5.2-286); NUREG/CR-6728 (FSAR Reference 2.5.2-251)), in this case 0.003 sec. The smaller kappa value for vertical motions than horizontal motions, by about a factor of two, is a consequence of compressional waves dominating the vertical component at high-frequency (Silva, 1997 and Beresnev, et al., 2002 (Reference 3)). Kappa values at zero distance are interpreted to reflect frequency independent damping in the shallow crust (1 km to 2 km) beneath the site (Anderson and Hough, 1984 (FSAR Reference 2.5.2-278)) and are observed to be generally smaller for compressional waves than for shear waves, by about a factor of two (Anderson, 1991 (Reference 2)). This observation is consistent with the observation that kappa values, for site distances within about 50 km for Western North America (WNA) and about 100 km for Central Eastern North America (CENA), control the frequency of the peak in 5% damped response spectral shapes (Sa/a) based on Silva and Darragh, 1995 (Reference 4). Figure 1 illustrates the effect of kappa on spectral shapes for horizontal motions at a soft rock site (Geomatrix category A and B, $\overline{V_S}$ (30m) ≈ 550m/sec) computed with a single-corner frequency point-source model. For a kappa value of 0.04 sec, a typical value for WNA (Anderson and Hough, 1984; Boore and Joyner, 1997 (Reference 5); Silva and Darragh, 1995; Silva et al., 1996), the spectrum peaks at about 5 Hz, typical for empirical soft WNA rock Ground Motion Response Prediction Equations (GRMPEs) (Abrahamson and Shedlock, 1997 (Reference 6); PEER, 2008 (Reference 7)). For a kappa value of 0.02 sec, half the value for soft rock, the peak shifts to about 10 Hz (or a slightly higher frequency). For hard rock sites, Figure 1 also shows spectral shapes computed for a 100% variation about the base-case CENA hard rock value of 0.006 sec. As with the WNA soft rock comparison of kappa values (Figure 1), lower kappa values are directly reflected in a shift of the peak (maximum spectral amplification) to higher frequency. As with the vertical CENA spectra discussed below, the lowest kappa for CENA hard rock (0.003 sec) does not reflect a factor of two shift in the peak frequency compared to a kappa value of 0.006 sec due to a low-pass filter.

Considering vertical spectra, Figure 2 shows a comparison between horizontal and vertical spectra based on recordings at WNA soft rock sites. As Figure 2 illustrates, horizontal spectra peak near 5 Hz while vertical spectra peak near 10 Hz, a factor of about two higher than the horizontal frequency. This trend is seen more clearly in Figure 3 which shows the NRC WNA soft rock horizontal spectral shape along with the corresponding vertical spectra computed by applying the NRC WNA V/H ratios (NUREG/CR-6728). These spectra are largely empirical spectra (based on several empirical GRMPEs) and clearly show the difference of about a factor of two in the peak frequencies. For hard rock site conditions, Figure 4 shows a similar plot for CENA (NUREG/CR-6728). In this case, the horizontal spectra peak near 20 Hz to 30 Hz with a kappa value of 0.006 sec with the vertical spectra having peaks near 40 Hz to 50 Hz with a kappa value of 0.003 sec. The difference in frequency for the response spectral peaks for the CENA hard rock spectra appears to be less than two. This is likely due to the effect of the low-pass filter applied at 50 Hz to bring the vertical spectra close to peak acceleration near 100 Hz (NUREG/CR-6728).

In general there is consistency between the difference in kappa values between horizontal and vertical components and the differences in the response spectral peaks (Sa) between horizontal and vertical response spectral acceleration. These differences in peak frequencies are due to the different wave types dominating the motions: shear waves for horizontal motions; while for the vertical component, shear waves dominate motions at low-frequency, and compressional waves dominate at high-frequency, with the transition around 5 Hz to 10 Hz in the WNA (Silva, 1997 and Beresnev, et al., 2002). Because of the much shallower velocity gradients for shear and compressional waves at hard CENA sites, the transition frequency band for compressional-wave dominance for vertical motions is expected to be different than that for WNA soft rock site. Due to the paucity of hard rock recordings over suitable distance and magnitudes ranges, the transition frequency band remains unknown. Silva, 1997, illustrates examples of wave types controlling vertical spectra as well as development of V/H ratios. At deep soil and soft rock sites in the CENA, provided they extend to sufficient depths (≥ 1 km to 2 km), kappa values would be expected to be similar to those in WNA.

While this RAI response has used horizontal motions to illustrate the effects of kappa on spectral shape, it is clearly not appropriate to assume vertical spectra can be modeled by generating horizontal motions (Random Vibration Theory (RVT) spectra or time histories) with kappa or damping consistent with vertical motions. Vertical motions reflect a combination of incident inclined P-SV (compressional and horizontally polarized shear vertical) waves and converted waves and as such have spectral shapes similar to, but different from, horizontal motions; also, vertical motions reflect largely linear response and attenuate more rapidly with distance than horizontal motions (Abrahamson and Shedlock, 1997; Bozorgnia and Campbell, 2004 (Reference 8)).

**References:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
2. Anderson, J.G., 1991, "A Preliminary Descriptive Model for the Distance Dependence of the Spectral Decay Parameter in Southern California," Bulletin of the Seismological Society of America, 81(6), 2186-2193.

3. Beresnev, I.A, Nightengale, A.M., and Silva, W.J., 2002, "Properties of Vertical Ground Motions," Bulletin of the Seismological Society of America, 92(8), 3152-3164.
4. Silva, W.J. and R. Darragh, 1995, "Engineering Characterization of Earthquake Strong Ground Motion Recorded at Rock Sites," Electric Power Research Institute, Palo Alto, California, TR-102262.
5. Boore, D.M, and W.B. Joyner, 1997, "Site Amplifications for Generic Rock Sites," Bulletin of the Seismological Society of America, 87(2), 327-341.
6. Abrahamson, N.A and K.M. Shedlock, 1997, "Overview." Seismological Research Letters, 68 (1), 9-23.
7. Pacific Engineering Research Center (PEER), 2008, Next Generation of Ground Motion Attenuation Models (NGA), "Special Sssue on the Next Generation Attenuation Project," Technical editors, J. Stewart, R. Archuleta, M. Power, Earthquake Spectra, vol. 24(1).
8. Bozorgnia, Y. and Campbell, K., 2004, "The Vertical-to-Horizontal Response Spectral Ratio and Tentative Procedures for Developing Simplified V/H and Vertical Design Spectra." Journal of Earthquake Engineering, 8(2), 175-207.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

FSAR Subsection 2.5.2.8

**Attachments:**

1) Figure 1. Response Spectral Shapes (Sa/a, 5% Damped) Computed for a Soft Rock Site (Geomatrix Categories A and B (Abrahamson and Shedlock, 1997 (Reference 6)), $\overline{V_S}$ (30m) ≈ 550m/sec and a CENA Hard Rock Site ($\overline{V_S}$ (30m) ≈ 2830m/sec; EPRI, 1993 (FSAR Reference 2.5.2-273)) for a Suite of Kappa Values: **M** 6.5, Joyner-Boore (JB) Distance of 25 km, Source Depth 8 km
2) Figure 2. Horizontal and Vertical Response Spectral Shapes (Sa/a, 5% Damped) Computed from Recordings at WNA Soft Rock Sites (Geomatrix A and B (Abrahamson and Shedlock, 1997 (Reference 6)), $\overline{V_S}$ (30m) ≈ 550m/sec)
3) Figure 3. WNA Empirical Soft Rock Horizontal Spectral Shape and Corresponding Vertical Spectra Computed by Applying the WNA Empirical V/H Ratios (Source: Figure 4-40, NUREG/CR-6728 (FSAR Reference 2.5.2-251))
4) Figure 4. CENA Hard Rock Horizontal Spectral Shape and Corresponding Vertical Spectra Computed by Applying the CENA V/H Ratios (Source: Figure 4-41, NUREG/CR-6728 (FSAR Reference 2.5.2-251))
5) Mark-up of FSAR Subsection 2.5.2.8

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 1 to RAI 02.05.02-032**

**Figure 1. Response Spectral Shapes (Sa/a, 5% Damped) Computed for a Soft Rock Site (Geomatrix Categories A and B (Abrahamson and Shedlock, 1997 (Reference 6)), $\overline{V_S}$ (30m) ≈ 550m/sec and a CENA Hard Rock Site ($\overline{V_S}$ (30m) ≈ 2830m/sec; EPRI, 1993 (FSAR Reference 2.5.2-273)) for a Suite of Kappa Values: M 6.5, Joyner-Boore (JB) Distance of 25 km, Source Depth 8 km**

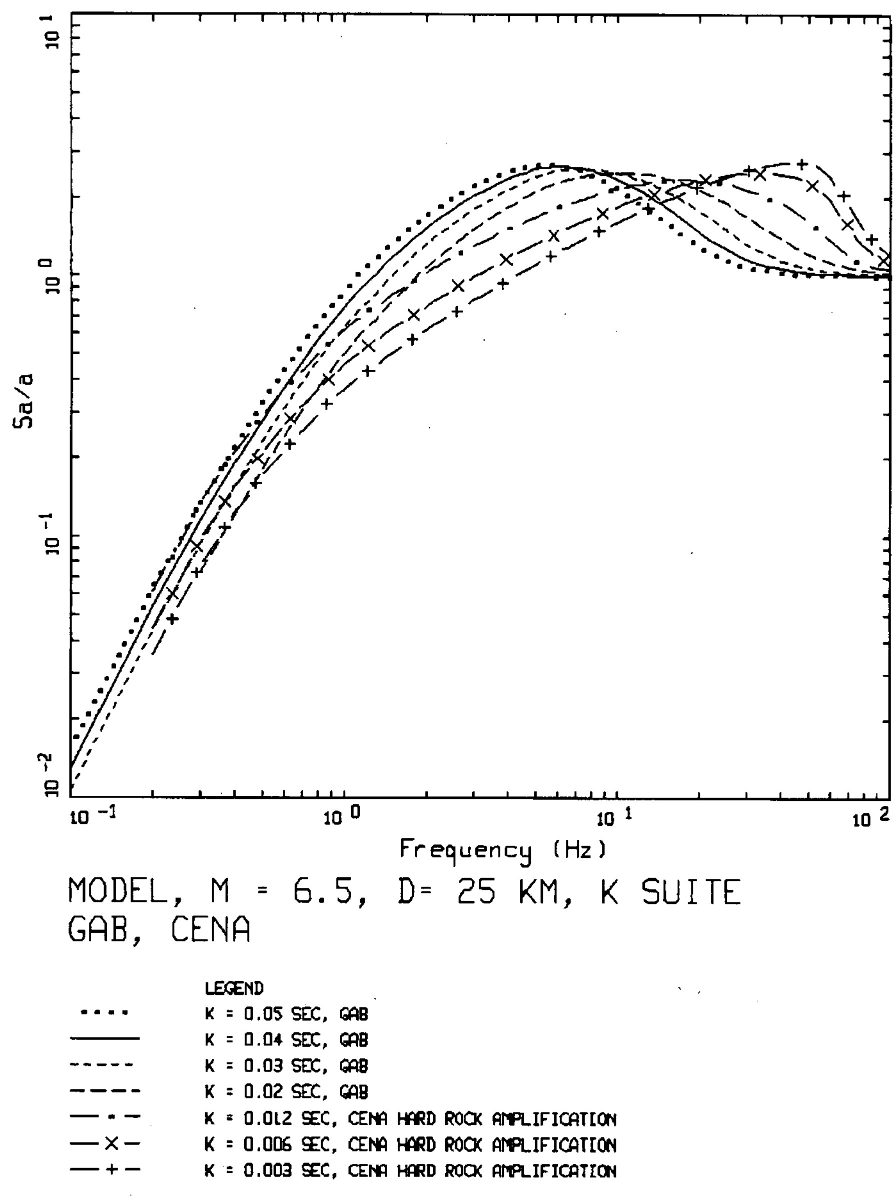



**Figure 1. Response Spectral Shapes (Sa/a, 5% Damped) Computed for a Soft Rock Site (Geomatrix Categories A and B (Abrahamson and Shedlock, 1997 (Reference 6)), $\overline{V_S}$ (30m) ≈ 550m/sec and a CENA Hard Rock Site ($\overline{V_S}$ (30m) ≈ 2830m/sec; EPRI, 1993 (FSAR Reference 2.5.2-273)) for a Suite of Kappa Values: M 6.5, Joyner-Boore (JB) Distance of 25 km, Source Depth 8 km**

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 2 to RAI 02.05.02-032**

**Figure 2. Horizontal and Vertical Response Spectral Shapes (Sa/a, 5% Damped) Computed from Recordings at WNA Soft Rock Sites (Geomatrix A and B (Abrahamson and Shedlock, 1997 (Reference 6)), $\overline{V_S}$ (30m) ≈ 550m/sec)**

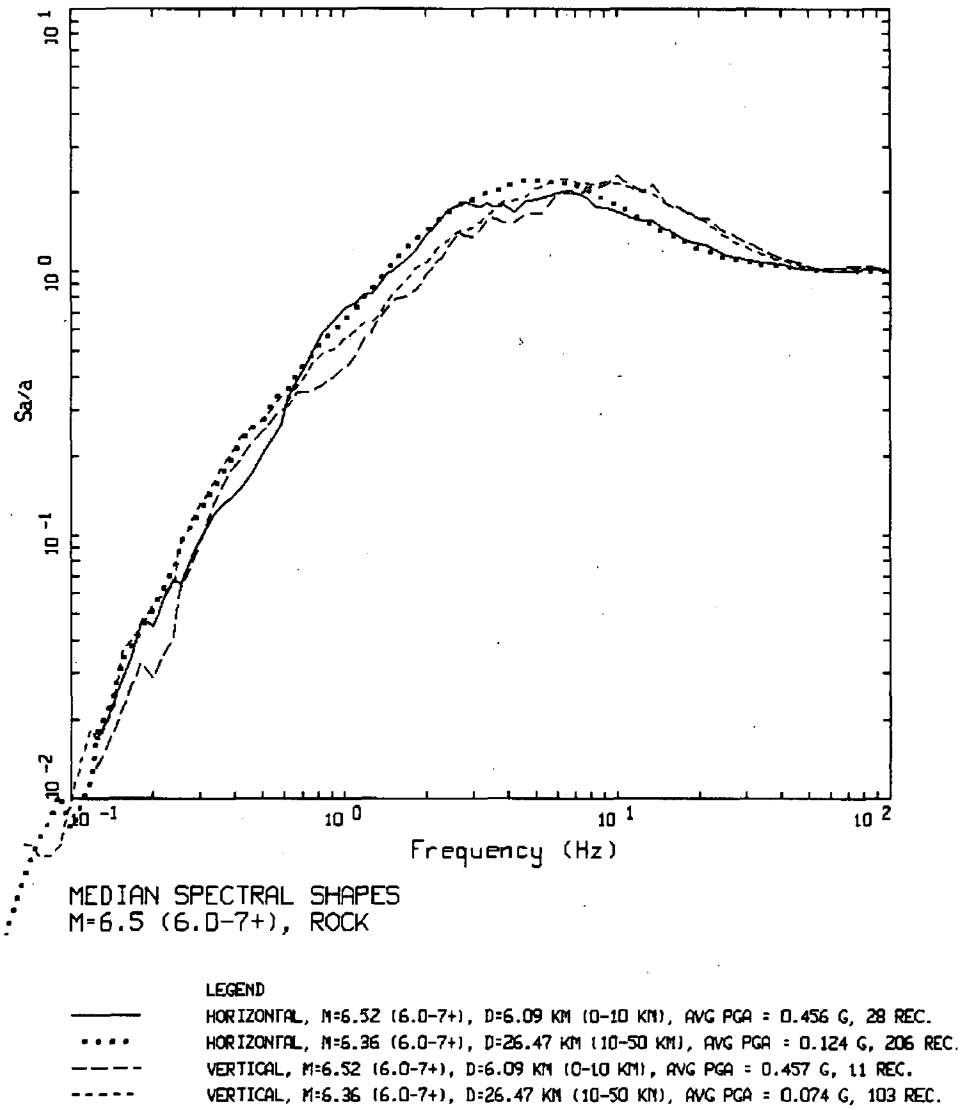



**Figure 2. Horizontal and Vertical Response Spectral Shapes (Sa/a, 5% Damped) Computed from Recordings at WNA Soft Rock Sites (Geomatrix A and B (Abrahamson and Shedlock, 1997 (Reference 6)), $\overline{V_S}$ (30m) ≈ 550m/sec)**

Mean magnitudes and mean rupture distances based on recorded data within magnitude (**M** 6 to **M** 7+) and distance (0 to 10km, 10 to 50km) bins (source: Figure 21 Silva, 1997 (FSAR Reference 2.5.2-286)).

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 3 to RAI 02.05.02-032**

**Figure 3. WNA Empirical Soft Rock Horizontal Spectral Shape and Corresponding Vertical Spectra Computed by Applying the WNA Empirical V/H Ratios (Source: Figure 4-40, NUREG/CR-6728 (FSAR Reference 2.5.2-251))**

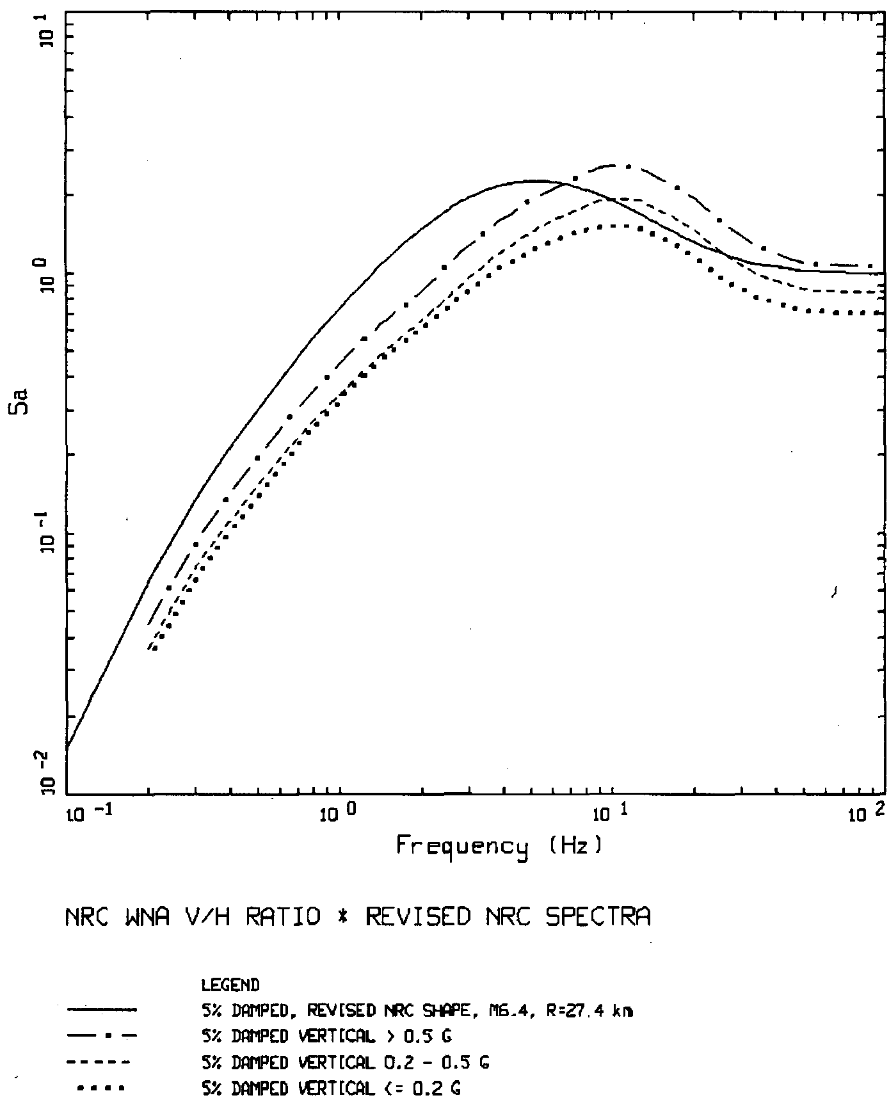



**Figure 3. WNA Empirical Soft Rock Horizontal Spectral Shape and Corresponding Vertical Spectra Computed by Applying the WNA Empirical V/H Ratios (Source: Figure 4-40, NUREG/CR-6728 (FSAR Reference 2.5.2-251))**

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 4 to RAI 02.05.02-032**

**Figure 4. CENA Hard Rock Horizontal Spectral Shape and Corresponding Vertical Spectra Computed by Applying the CENA V/H Ratios (Source: Figure 4-41, NUREG/CR-6728 (FSAR Reference 2.5.2-251))**

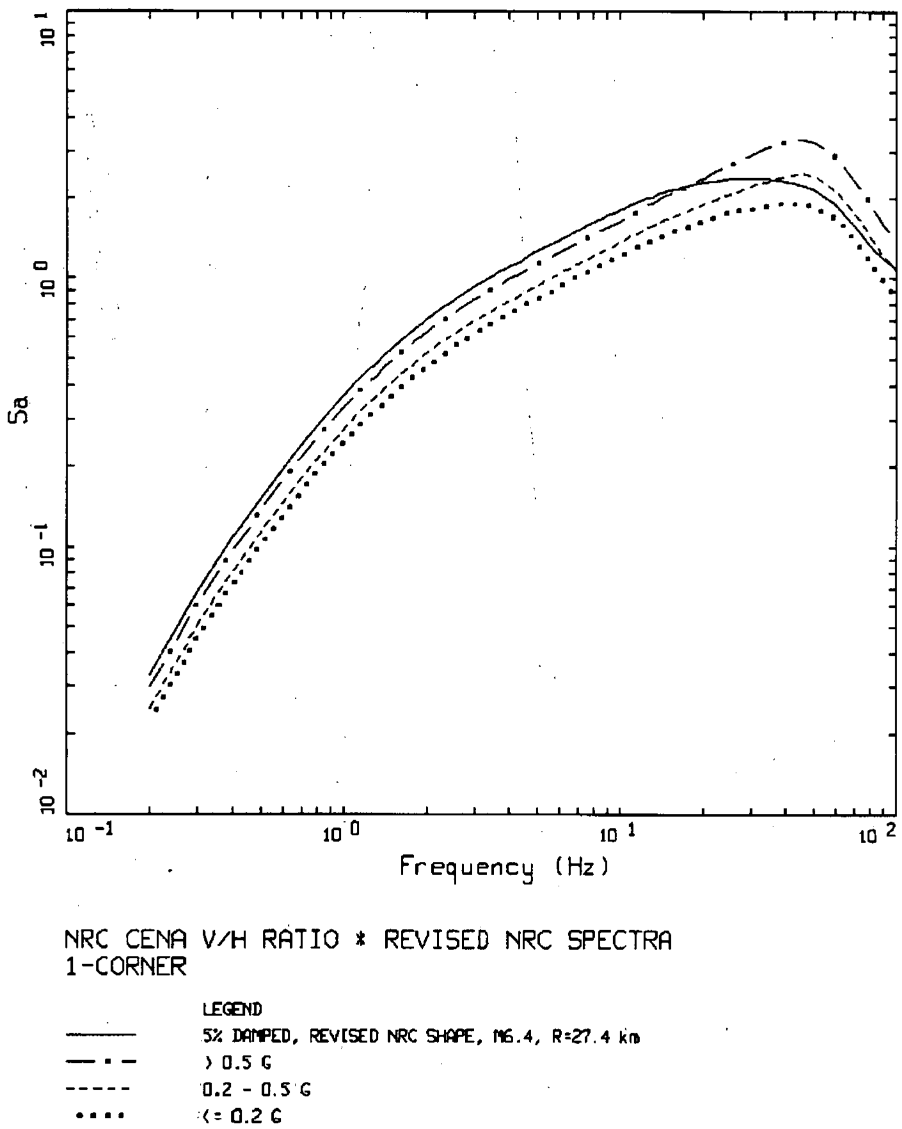



**Figure 4. CENA Hard Rock Horizontal Spectral Shape and Corresponding Vertical Spectra Computed by Applying the CENA V/H Ratios (Source: Figure 4-41, NUREG/CR-6728 (FSAR Reference 2.5.2-251))**

# Lee Nuclear Station Response to Request for Additional Information (RAI)

## Attachment 5 to RAI 02.05.02-032

## Mark-up of FSAR Subsection 2.5.2.8

COLA Part 2, FSAR Chapter 2, Subsection 2.5.2.8 will be revised as follows:

278. Anderson, J.G. and Hough, S.E., "A Model for the Shape of the Fourier Amplitude Spectrum of Acceleration at High Frequencies," *Bulletin of the Seismological Society of America* 74:~~1,343-1,373,~~<u>5; 1,969-1,993,</u> 1984.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch:** **Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s):** **RAI 02.05.02-033**

**NRC RAI:**

Paragraph 1 of Section 4.2.2 "Empirical V/H Ratios" (Enclosure 1 report) states the following:

> The relative weights listed in Table 4 reflect the assumed appropriateness of WNA soft rock empirical V/H ratios for Unit 1.

a.) Please provide rational for using soft rock V/H ratios from WNA for Unit 1.

b.) Most sites in California are characterized by much lower S-wave velocities. Please clarify what soft rock means in terms of shear-wave velocity. Is it ~760 m/sec (B-C boundary)?

**Duke Energy Response:**

Figure 1 shows median and ± 1σ (sigma) shear-wave velocity ($\overline{V_S}$) profiles for Western North America (WNA) soft rock sites [Geomatrix site categories A and B (Reference 1)]. Also shown is the Lee Nuclear Station Unit 1 Foundation Input Response Spectra (FIRS) profile, which consists of about 20 ft of concrete with mean $\overline{V_S}$ of 7500 feet per sec ($\overline{V_S}$ = 7500 ft/sec) over hard Central Eastern North America (CENA) rock with $\overline{V_S}$ ≈ 9,300 ft/sec, as described in FSAR Figure 2.5.4-252. As Figure 1 clearly indicates, the Lee Nuclear Station Unit 1 FIRS profile has significantly higher velocities than either the median or median plus 1-sigma soft rock profiles. With an average $\sigma_{ln}$ of about 0.6 (varies with depth), the Lee Unit 1 FIRS profile reflects about a median plus 2-sigma at shallow depth, over roughly the top 100 ft. At deeper depths, assuming the gradient from depths of about 100 ft to 200 ft continues with increasing depth [Silva et al., 1996 (FSAR Reference 2.5.2-288)], the Lee Nuclear Station Unit 1 hard rock velocity is at about a median plus 1-sigma above the soft rock median profile beyond depths of about 200 ft and becomes close to the hard rock velocity near a depth of about 500 ft.

To illustrate the velocities of very stiff (hard) rock sites included in WNA soft rock categories [Geomatrix site categories A and B, $\overline{V_S}$ (30m) ≈ 550m/sec], Figure 1 shows four of the stiffest known (to the applicant) recording site profiles. Interestingly, one profile (Lucerne, located in the Mojave Desert in California) has about 20 ft of weathered granite over hard granite with shear-wave velocities that slightly exceed those of the CENA hard rock. The remaining three profiles show very steep shallow gradients, rapidly approaching the CENA hard rock profile at depth, which is likely achieved at depths of 200 ft to 300 ft. These profiles suggest the CENA hard rock velocities typified by the Lee Nuclear Station Unit 1 FIRS profile are sampled by at least a small percentage of the WNA soft rock recording sites at depths exceeding from about 20 ft to about 200 ft. At the deeper depths, about 200 ft to about 500 ft, the CENA hard rock profile is about plus 1-sigma above the soft rock median, or may be expected to occur about 15% of the time at WNA soft rock sites. At shallower depths the steep velocity gradients present in the WNA soft rock profiles likely result in larger V/H ratios at high frequencies of interest

(10 Hz to 30 Hz) than CENA hard rock V/H ratios [NUREG/CR-6728 (FSAR Reference 2.5.2-251)]. At lower frequency the differences in velocity result in smaller V/H (vertical:horizontal) ratios [NUREG/CR-6728 (FSAR Reference 2.5.2-251)], which is compensated by imposing a lower bound of 0.7 (Reference 2), close to the Regulatory Guide 1.60 (Reference 3) value of 0.66.

As the preceding analyses have demonstrated, it is impractical to develop unambiguously quantitative relative weights between empirical WNA soft rock V/H ratios and CENA hard rock V/H ratios for intermediate sites. Also, contributing to this dilemma is the lack of development of realistic alternative models for computing site-specific vertical motions (Reference 1). The relative weights of 0.8 and 0.2 for site-specific versus generic WNA soft rock V/H ratio reflects subjective judgment based on the comparisons of the profiles (Figure 1). Also considered was the desire not to place full weight on a single model for developing vertical motions as it has been shown not to perform as well as the model for horizontal motions (Reference 1).

**References:**

1. Abrahamson, N.A., and K.M. Shedlock (1997): Overview, *Seismological Research Letters*, 68, 9-23.
2. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
3. Regulatory Guide 1.60, Rev. 1. "Design Response Spectra for Seismic Design of Nuclear Power Plants," U.S. Nuclear Regulatory Commission, December 1973.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachment:**

1) Figure 1. Median and $\pm$ 1$\sigma$ Shear-Wave Velocity Profiles Computed from Measured Velocities at Sites with Geomatrix Site Categories A and B

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**Attachment 1 to RAI 02.05.02-033**

**Figure 1. Median and ± 1σ Shear-Wave Velocity Profiles Computed from Measured Velocities at Sites with Geomatrix Site Categories A and B**

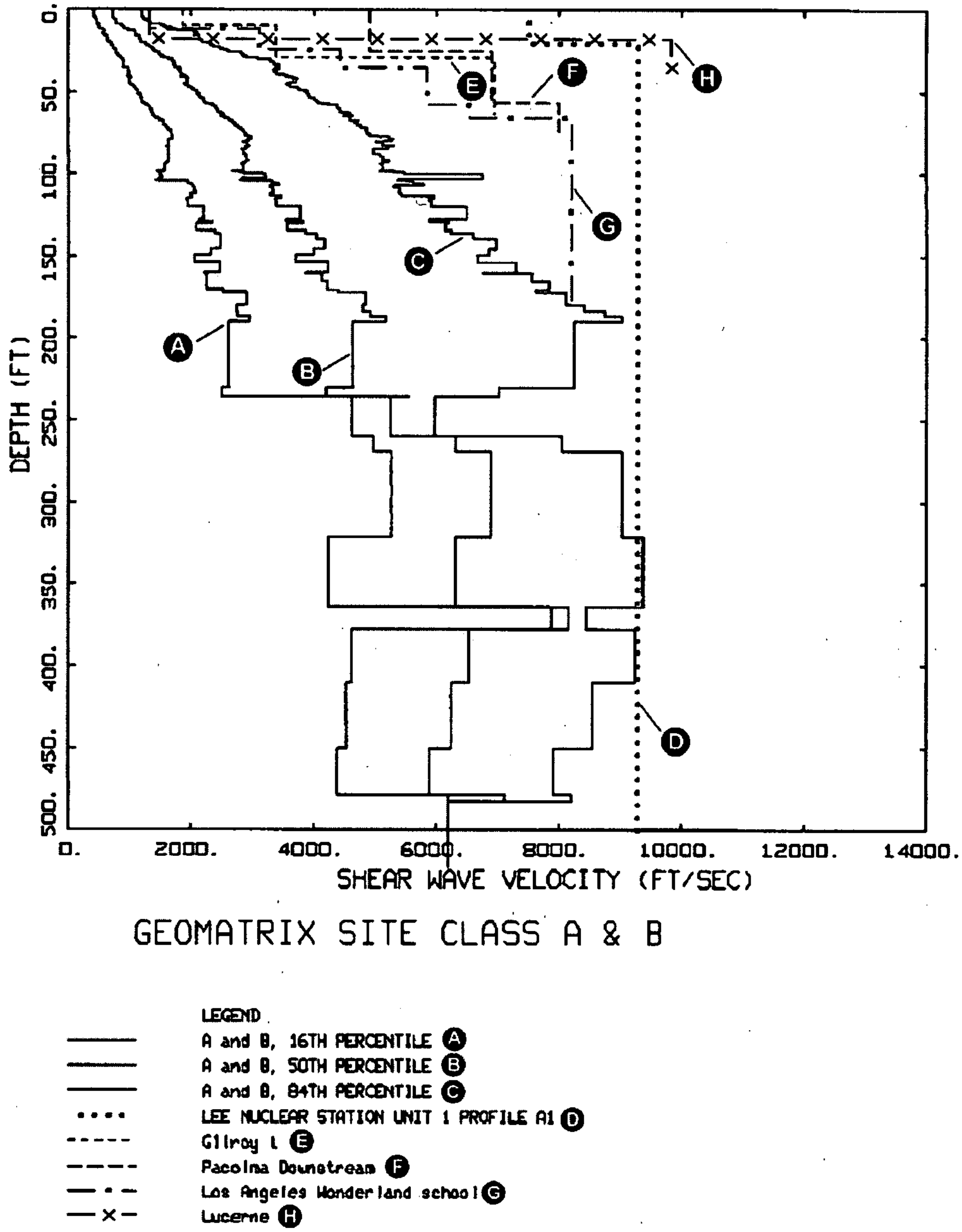



**Figure 1. Median and ± 1σ Shear-Wave Velocity Profiles Computed from Measured Velocities at Sites with Geomatrix Site Categories A and B**

Site categories A and B are considered soft rock sites, consistent with generic WNA soft rock horizontal and vertical empirical Ground Motion Response Equations (GRMPEs) [Abrahamson and Shedlock, 1997 (Reference 1)]. Also shown is the Lee Nuclear Station Unit 1 FIRS Profile 1 as well as several very stiff (hard) WNA "soft" rock profiles (Geomatrix A). The four site-specific profiles reflect currently known examples of WNA rock recording sites with extremely stiff or hard rock conditions and are shown to their respective measurement depths. Note: the increased variability in the soft rock profiles for depths below about 70 ft, reflecting a reduced number of profiles with increasing depth: about 70 above 50 ft. decreasing to only a few below 200 ft.

**Lee Nuclear Station Response to Request for Additional Information (RAI)**

**RAI Letter No. 055**

**NRC Technical Review Branch: Geosciences and Geotechnical Engineering Branch 2 (RGS2)**

**Reference NRC RAI Number(s): RAI 02.05.02-034**

**NRC RAI:**

In Table 4 of the Enclosure 1 report, the weight assignments are not clear. Nonlinearity is cited in a number of places through the report. In mean time, there are a number of different nonlinear models. Please provide graphs showing dependency of site amplification on PGA, and for a few SAs. Please provide similar graphs showing dependencies upon shear-wave velocity in order to better understand the model. Please clarify consistency of the model with known seismological data on nonlinearity which was not observed for accelerations less than 0.2g.

**Duke Energy Response:**

The weights listed on Table 4 (Reference 1) refer to V/H (vertical:horizontal) ratios. Both empirical and numerical (model) V/H ratios were used with relative class weights of 0.2 and 0.8, respectively, as listed in the lower box of Table 4. The empirical V/H ratios depend on magnitude and distance with the modal magnitude and distance changing with Annual Exceedance Frequency (AEF) as well as structural frequency, as listed in the top two boxes on Table 4. For the numerical (model) V/H ratios, since these V/H ratios depend weakly on magnitude due to the assumed linear site response, distance becomes the controlling parameter and the "model V/H Ratio weights" accommodates the modal distance dependencies based on AEF as well as structural frequency.

In response to the questions regarding nonlinearity and nonlinear models, the amplification factors shown in Figures 3 through 7 (Reference 1) were for illustration and were computed using the Random Vibration Theory (RVT) equivalent-linear approach and EPRI (1993) (Reference 2.5.2-273) modulus reduction ($G/G_{max}$) and hysteretic damping curves. Figures 3 through 7 show dependency on reference site peak ground acceleration (PGA) (e.g., Figure 3, Reference 1) as well as reference site spectral accelerations (Sa) (e.g., Figures 6 and 7, Reference 1). Dependence on shear-wave velocity is illustrated in Abrahamson et al. (2008) (Reference 2), Power et al. (2008) (Reference 3), and Walling et al. (2008) (Reference 4).

In general the equivalent-linear model, with EPRI (1993) or Peninsular Range (Walling et al., 2008) $G/G_{max}$ and hysteretic damping curves, are consistent with observations of nonlinearity as evidenced both in the empirical Next Generation Attenuation (NGA) Ground Motion Prediction Equations (GRMPEs) which use nonlinear site amplification based on the equivalent-linear model (Abrahamson and Silva, 2008 (Reference 5); Campbell and Bozorgnia, 2008 (Reference 6) as well as the model validations with specific earthquakes (EPRI, 1993); and Silva et al., 1996 (Reference 2.5.2-288). The lower limit of observed nonlinearity of about 0.2g (Silva et al., 1996, Reference 2.5.2-288) found a lower limit of about 0.3g) is probably due to low resolution as result of the intrinsic variability in the strong motion data.

**References:**

1. Bryan J. Dolan to Document Control Desk, U.S. Nuclear Regulatory Commission, Development of Horizontal and Vertical Site-Specific Hazard Consistent Uniform Hazard Response Spectra at the Lee Nuclear Station Unit 1, dated April 30, 2008, (ML081230546).
2. Abrahamson, N.A., G. Atkinson, D. Boore, Y. Bozorgnia, K. Campbell, B. Chiou, I.M. Idriss, W.J. Silva and R. Youngs (2008). "Comparisons of the NGA ground-motion relations." *Earthquake Spectra* 24(1), 45-66.
3. Power, M., B. Chiou, N. Abrahamson, Y. Bozorgnia, T. Shantz, C. Roblee (2008). "An overview of the NGA project." *Earthquake Spectra*, 24(1), 3-21.
4. Walling, M., W. Silva and N. Abrahamson (2008). "Nonlinear site amplification factors for constraining the NGA models." *Earthquake Spectra*, 24(1), 243-255.
5. Abrahamson, N.A., and W.J. Silva (2008). "Summary of the Abrahamson and Silva NGA ground-motion relations." *Earthquake Spectra* 24(1), 67-97.
6. Campbell, K. W. and Y. Bozorgnia (2008). "NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10s." *Earthquake Spectra* 24(1), 139-171.

**Associated Revision to the Lee Nuclear Station Supplemental Technical Report:**

None

**Associated Revision to the Lee Nuclear Station Final Safety Analysis Report:**

None

**Attachments:**

None