U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH

February 2005
Division 1

DRAFT REGULATORY GUIDE

Contact: T.Y. Chang,
(301) 415-6450

DRAFT REGULATORY GUIDE DG-1127

(Proposed Revision 2 of Regulatory Guide 1.92)
(Previously published as DG-1108, dated August 2001)

COMBINING MODAL RESPONSES AND SPATIAL COMPONENTS IN SEISMIC RESPONSE ANALYSIS

A. INTRODUCTION

This revised regulatory guide provides licensees and applicants with improved guidance concerning methods that the NRC staff considers acceptable for combining modal responses and spatial components in seismic response analysis of nuclear power plant structures, systems, and components (SSCs) that are important to safety.

As specified in Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," of the *Code of Federal Regulations* (10 CFR Part 50), Criterion 2, "Design Bases for Protection Against Natural Phenomena," requires, in part, that nuclear power plant SSCs important to safety must be designed to withstand the effects of natural phenomena (such as earthquakes) without loss of capability to perform their safety functions. Such SSCs must also be designed to accommodate the effects of, and be compatible with, the environmental conditions associated with normal operation and postulated accidents.

Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50 specifies, in part, requirements for implementing General Design Criterion 2 with respect to earthquakes.[1]

This guide describes methods that the NRC staff considers acceptable for complying with the NRC's regulations regarding the following aspects of seismic response analysis:

(1) combining the responses of individual modes (in the case of the response spectrum method) to a component of the three orthogonal spatial components of earthquake motion (two horizontal and one vertical), to find the representative maximum response of interest (such as displacement, acceleration, shear, moment, stress, or strain) for a given element of a nuclear power plant SSC

(2) combining the maximum responses (in the case of the time history method) or the representative maximum responses (in the case of the response spectrum method) of an SSC, when such responses are calculated either separately (for the response spectrum method or the time history method) or simultaneously (for the time history method) for each of the three orthogonal spatial components (two horizontal and one vertical) of an earthquake

Regulatory guides are issued to describe to the public methods that the NRC staff considers acceptable for use in implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations, and compliance with regulatory guides is not required. Regulatory guides are issued in draft form to solicit public comment and involve the public in developing the agency's regulatory positions. Draft regulatory guides have not received complete staff review; therefore, they do not represent official NRC staff positions.

This draft regulatory guide contains information collections that are covered by the requirements of 10 CFR Part 50, which the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number.

---

1 Appendix S to 10 CFR Part 50 applies to applicants for a design certification or combined license pursuant to 10 CFR Part 52, "Early Site Permits; Standard Design Certifications; and Combined Licenses for Nuclear Power Plants," or a construction permit or operating license pursuant to 10 CFR Part 50 after January 10, 1997. However, the earthquake engineering criteria in Section VI of Appendix A to 10 CFR Part 100 continue to apply for either an operating license applicant or holder whose construction permit was issued before January 10, 1997.

B. DISCUSSION

Background

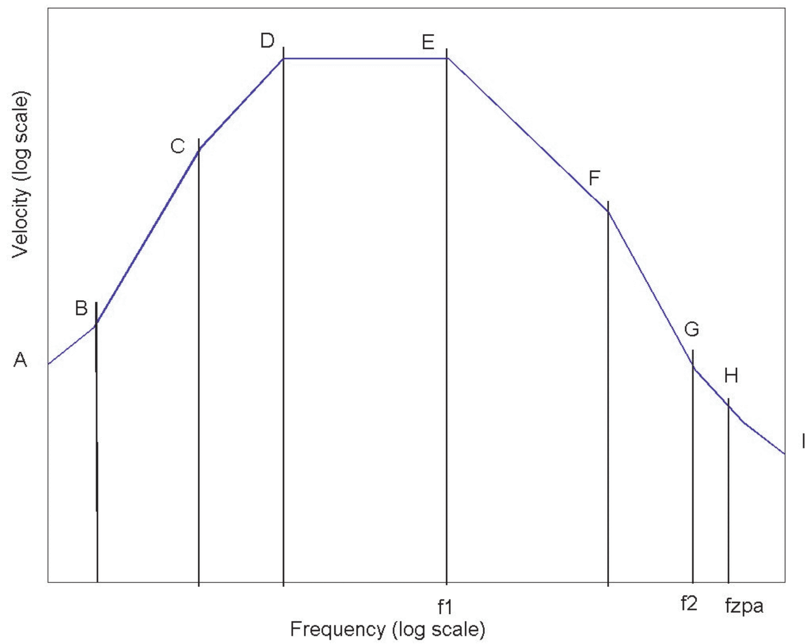
For several decades, the nuclear industry has used the response spectrum method and the time history method (described below) for the seismic analysis and design of nuclear power plant SSCs that are important to safety. In 1976, the NRC issued Revision 1 of this guide, which described then up-to-date guidance for using the response spectrum and time history methods for estimating SSC seismic response. Since that time, research in the United States has resulted in improved methods for combining modal responses and spatial components that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. This guide (Revision 2) describes methods that the NRC staff considers acceptable in view of those improvements. The more conservative methods of combining modal responses (as described in Revision 1) remain acceptable. However, the residual rigid response of the missing mass modes (as described in Sections 1.4 and 1.5 of this guide) should be addressed in analyses associated with actions requiring NRC approval that are reviewed by the NRC after the date of issuance of Revision 2 of this guide, regardless of whether a given applicant or licensee uses the methods in Revision 1 or Revision 2.

Combination of Seismic Response of Individual Modes

For the purpose of seismic design of a structure, it generally suffices to use only the maximum response values. The representative maximum response of interest for design (such as displacement, acceleration, shear, moment, stress, or strain) of a nuclear power plant SSC can be obtained by combining the corresponding maximum individual modal responses derived from the response spectrum method. (See Appendix A of this guide for a general discussion of the response spectrum method.) In general, it is unlikely that these maximum individual modal responses would occur at the same time during an earthquake. Thus, the question involves identifying the proper methods to obtain the representative maximum response of interest from the combination of these maximum individual modal responses.

All methods utilized to combine seismic responses of individual modes obtained from the response spectrum method can provide only approximate representative maximum values, which are not exact in the sense of a time history method. The goal is to develop methods that enable one to estimate the maximum responses of interest as accurately as possible for the design of nuclear SSCs. The time history method, applying either modal superposition or direct integration, has been used by researchers as a benchmark for gauging the degree of accuracy of these combination methods.

Since the issuance of Revision 1 of Regulatory Guide 1.92 in 1976, research in the United States has resulted in improved methods for combining modal responses and spatial components that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. For the purpose of discussion, the broad-banded spectrum in Figure 1 is chosen. However, this guide and the following discussion are applicable to all types of response spectra. This includes broad-banded spectra, such as a design spectrum. It also includes narrow-banded spectra (those with a single significant peak) or multiple narrow-banded spectra (those with multiple significant peaks), such as an in-structure spectrum. In Figure 1, $f1$, $f2$, and f_{zpa} are the highest significant motion frequency, rigid frequency, and zero period frequency, respectively, as defined in Section 1.3 of this guide.



KEY
AB - maximum base displacement
BC - transition from maximum base to amplified displacement
CD - amplified spectral displacement
DE - amplified spectral velocity
EF - amplified spectral acceleration
FG - transition from amplified to rigid acceleration
GH - transition from rigid to maximum base acceleration
HI - maximum base acceleration

Figure 1. Regions of a broad-banded response spectrum

For periodic modal responses (refer to Appendix A for a discussion of “periodic modal responses”) with sufficiently separated frequencies, as indicated in Revision 1 of this guide, Goodman, Rosenblueth, and Newmark (Ref. 2) showed that the Square-Root-of-the-Sum-of-the-Squares (SRSS) method is the appropriate method to combine these modal responses. When modes with closely spaced frequencies are present, several conservative methods presented in Revision 1 of this guide can be used to combine these modal responses. Research since the 1970s (e.g., Refs. 3 and 4) has shown that for periodic modal responses, the double sum equation with appropriate formulas for calculating modal correlation coefficients will more accurately combine modal responses for modes with closely spaced frequencies. For modes with sufficiently separated frequencies, this double sum equation reduces to the SRSS method.

When using the response spectrum method, in most cases, it is not practical to calculate all mode shapes and frequencies. Research since the 1980s has shown that in the regions of rigid modal responses (refer to Appendix for a discussion of "rigid modal responses"), the appropriate method to combine rigid responses is the algebraic sum method (Ref. 5). Some nuclear power plant SSCs may have a number of important modes beyond the zero period acceleration (ZPA) frequency (f_{ZPA}). As discussed in Section 1.4, the residual rigid response of the missing mass modes should be addressed (Refs. 10 and 11); otherwise, it may result in underestimation of some SSC element forces and moments in the vicinity of supports, as well as underestimation of some support forces and moments.

Research since the 1980s (e.g., Refs. 6, 7, 8, and 9) has shown that between the end of the region of amplified spectral velocity, E, and the beginning of the rigid regions, G, in Figure 1, the modal response consists of both the periodic and rigid components. Appropriate methods, as discussed in Section 1.3, should be used to separate the two components in this transition region. The combination of periodic components of responses should be treated similarly to the other periodic modal responses (Section 1.1), whereas the combination of rigid components of responses should be treated similarly to the other rigid modal responses (Section 1.2).

Finally, when modes from all regions of the response spectrum are considered, appropriate method, as discussed in Section 1.5 of this guide, should be used to combine all response components.

Combination of Spatial Components

Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants" (Ref. 12), indicated that the design of all Seismic Category 1 SSCs should be based on three orthogonal components (two horizontal and one vertical) of a prescribed design earthquake motion.

Regulatory Position 2 of this guide for the combination of spatial components has not been changed from the same position in Revision 1, except to endorse the use of a 100-40-40 percent combination rule proposed by Newmark (Ref. 13), as described in Section 2.1 of this guide, as an alternative to the SRSS method.

<u>Response Spectrum Method</u>

For response spectrum analysis when each of the three spatial components are calculated separately, Chu, Amin, and Singh (Ref. 14) concluded that for an SCC subjected to the action of the three components of an earthquake motion, the representative maximum response of interest of the SSC can be satisfactorily obtained by taking the SRSS of the corresponding representative maximum response for each of the three components calculated separately.

The SRSS procedure for combining the responses to the three components of an earthquake motion is based on the consideration that it is very unlikely that the maximum response for each of the three components of a given SSC would occur at the same time during an earthquake.

The 100-40-40 percent rule was originally proposed as a simple way to estimate the maximum expected response of a structure subject to three-directional seismic loading for response spectrum analysis, and is the only alternative method for spatial combination that has received any significant attention in the nuclear power industry. The results of the 100-40-40 spatial combination have been compared with the SRSS spatial combination. Generally, they indicate that the 100-40-40 combination method produces higher estimates of maximum response than the SRSS combination method by as much as 16 percent, while the maximum under-prediction is 1 percent.

Time History Method

In a time history method, the representative maximum response of interest, or the maximum response of interest for an SSC, can be obtained either by performing the analysis separately for each of the three components of earthquake motion, or by performing a single analysis with all three earthquake components applied simultaneously, respectively. The latter case can be used only if the three components of earthquake motion are statistically independent (e.g., Ref. 15).

C. REGULATORY POSITION

This guide (Revision 2) describes methods that the NRC staff considers acceptable to account for knowledge gained by research conducted in the United States since Revision 1 of this guide was issued in 1976. The more conservative methods of combining modal responses (as described in Revision 1) remain acceptable. However, the residual rigid response of the missing mass modes (as described in Sections 1.4 and 1.5 of this guide) should be addressed in analyses associated with actions requiring NRC approval that are reviewed by the NRC after the date of issuance of Revision 2 of this guide, regardless of whether a given applicant or licensee uses the methods in Revision 1 or Revision 2.

1. Combination of Seismic Response of Individual Modes

1.1 Combination of Periodic Modal Responses

Research since the late 1970s has shown that in the regions of amplified spectral displacement, amplified spectral velocity, and amplified spectral acceleration of a spectrum (regions CD, DE, and EF in Figure1), the periodic responses are dominant. Beyond amplified spectral velocity region DE and up to G, the modal responses consist of both the periodic and rigid components. (Refer to Appendix A for a discussion of periodic and rigid responses, as well as periodic and rigid components of responses.) The combined periodic response or periodic components of responses of interest (e.g., displacement, acceleration, shear, moment, stress, or strain) are calculated from the following double sum (sometimes termed the "complete quadratic combination," CQC) equation:

$$R_{pI} = \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_{ij} R_{p_i} R_{p_j} \right]^{1/2} \qquad (1)$$

where R_{pI} = combined periodic response of interest for the I^{th} component of seismic input motion (I = 1, 2, 3, for one vertical and two horizontal components), ε_{ij} = the modal correlation coefficient for modes i and j, R_{p_i} = periodic response or periodic component of a response of mode i, and n = number of modes considered in the combination of modal responses.

Any two modes i and j are termed correlated, uncorrelated, or partially correlated, for ε_{ij} =1, 0 and 0<ε_{ij}<1, respectively.

The modal correlation coefficients are uniquely defined, depending on the method chosen for evaluating the correlation coefficient, as follows.

1.1.1 *Square Root of the Sum of the Squares (SRSS) Method*

At the foundation of all methods for combining uncorrelated modal responses is the SRSS method. All methods for combination of periodic modal response components are equivalent to the SRSS method if the frequencies of the modes are all sufficiently separated. In this case,

□$_{ij}$ = 1.0 for $i = j$

and

□$_{ij}$ = 0.0 for i … j

and Equation 1 reduces to:

$$R_{pI} = \left[\sum_{i=1}^{n} R_{p_i}{}^{2} \right]^{1/2} \qquad (2)$$

If modes with closely spaced frequencies exist, the SRSS method is not applicable, and one of the two methods in Sections 1.1.2 and 1.1.3 below should be used instead. The definition of modes with closely spaced frequencies is a function of the critical damping ratio:

(1) For critical damping ratios #2%, modes with closely spaced frequencies are modes with frequencies that are within 10% of each other (i.e., for $f_i < f_j$, f_j # 1.1 f_i).

(2) For critical damping ratios >2%, modes with frequencies within five times the damping ratio of each other are considered modes with closely spaced frequencies (i.e., for $f_i < f_j$ and 5% damping, f_j # 1.25 f_i; for $f_i < f_j$ and 10% damping, f_j # 1.5 f_i) .

1.1.2 *Modified Rosenblueth's Correlation Coefficient*

Rosenblueth (Ref. 3) provided the first significant mathematical approach to the evaluation of modal correlation for seismic response spectrum analysis. It is based on the application of random vibration theory, utilizing a finite duration of white noise to represent seismic loading. The original Rosenblueth's formula (Ref. 3) for □$_{ij}$ was modified (Section 3.2.7, Ref. 1), as follows:

(1) A ratio of the geometric and arithmetic means of damping is multiplied to accurately account for modes with different damping ratios.

(2) The finite duration term of white noise is dropped because the duration value is often arbitrarily selected and it does not adequately account for the intended purpose of accounting for the finite duration of an input motion.

(3) The damped frequency is replaced by the undamped frequency because, for practical damping values, this simplification does not noticeably change the value of the modal correlation coefficient.

With the notations f_i = frequency (Hz) of mode i, λ_i = damping ratio of mode i, $\lambda_{ij} = (\lambda_i + \lambda_j)/2$, $\Delta f_{ij} = f_i - f_j$, and $\lambda f_{ij} = (\lambda_i f_i + \lambda_j f_j)$, the modified Rosenblueth's formula for ε_{ij} becomes:

$$\varepsilon_{ij} = \frac{\sqrt{\lambda_i \lambda_j}}{\lambda_{ij}} \left[1 + \left(\frac{\Delta f_{ij}}{\lambda f_{ij}} \right)^2 \right]^{-1} \tag{3}$$

1.1.3 *Der Kiureghian's Correlation Coefficient*

Der Kiureghian (Ref. 4) presents an expression for ε_{ij} similar to Rosenblueth's. It is also based on the application of random vibration theory, but utilizes an infinite duration of white noise to represent seismic loading. Using the same notations as Equation 3, $f_{ij} = (f_i + f_j)/2$, and $\Delta\lambda_{ij} = \lambda_i - \lambda_j$, the following formula was derived for calculation of ε_{ij}:

$$\varepsilon_{ij} = \frac{f_{ij}^2 \sqrt{\lambda_i \lambda_j} \left(4\lambda_{ij} + \Delta\lambda_{ij} \Delta f_{ij} / f_{ij} \right)}{\Delta f_{ij}^2 + 4\lambda_{ij}^2 f_{ij}^2} \tag{4}$$

1.1.4 *Observations on the Modified Rosenblueth and Der Kiureghian Equations for the Modal Correlation Coefficients*

While the form of Equation 4 differs significantly from Equation 3, the two equations produce equivalent results, as can be seen from the following observations:

(1) When frequencies of any two modes are equal,

$$f_i = f_j, \qquad \varepsilon_{ij} = \frac{\sqrt{\lambda_i \lambda_j}}{\lambda_{ij}}$$

(2) If damping ratios are also equal, then

$$\lambda_i = \lambda_j, \qquad \varepsilon_{ij} = 1.0,$$

and Equation 1 correctly gives the combined responses of the two modes as the algebraic sum.

(3) When all frequencies are far apart,

$$\frac{\Delta f_{ij}}{\lambda f_{ij}} >> 1, \quad \varepsilon_{ij} \approx 0, \text{ and equation (1) becomes } R_{pI} = \left[\sum_{i=1}^{n} R_{p_i} \right]^{1/2},$$

which is the well-known SRSS method of Equation 2.

1.2 Combination of Rigid Modal Responses

In the high frequency regions (regions GH and HI in Figure 1), the rigid responses are predominant. Also, beyond the amplified velocity region of DE and up to G in Figure 1, the modal responses consist of both the periodic and rigid components.

The rigid responses and rigid components of responses are combined algebraically, as follows:

$$R_{rI} = \sum_{i=1}^{n} R_{r_i} \tag{5}$$

where R_{rI} = combined rigid response of interest for the I^{th} component of seismic input motion, R_{r_i} = rigid response or rigid component of a response of mode *i*, and *n* = number of modes considered in the combination of modal responses.

1.3 Modes with both Periodic and Rigid Responses

Beyond the amplified velocity region of DE and up to G in Figure 1, the modal responses consist of both the periodic and rigid components. Several methods were examined for the separation of periodic and rigid response components (Ref. 16), and Gupta's method (Refs. 1, 6, 7, and 9) and Lindley-Yow's method (Ref. 8) are considered acceptable by the NRC staff, subject to the limitations discussed below. For the I^{th} component of a seismic input, the periodic components of modal responses obtained in this section should be combined with the other periodic modal responses (or periodic components of modal responses) using Equation 1. Similarly, for the I^{th} component of a seismic input, the rigid components of modal responses obtained in this section should be combined with the other rigid modal responses (or rigid components of modal responses) using Equation 5.

1.3.1 *Gupta's Method*

Gupta separated the periodic and rigid components of a response by a rigid response coefficient α_i. Using the notations of Sections 1.1 and 1.2 above, the rigid response component of a response of interest of mode *i*, R_i, is defined as follows:

$$R_{r_i} = \alpha_i R_i, \tag{6.1}$$

The periodic response component of R_i can then be expressed as follows:

$$R_{p_i} = \sqrt{1-\alpha_i^2}\, R_i, \qquad \text{where} \qquad R_i^2 = R_{p_i}^2 + R_{r_i}^2 \tag{6.2}$$

Gupta showed (Ref. 6) that the numerically-calculated rigid response coefficient can be idealized by a straight line on a semi-log graph, as follows:

$$\alpha_i = \frac{\ln\left(f_i / f1\right)}{\ln\left(f2 / f1\right)}, \qquad f1 \le f_i \le f2 \tag{7.1}$$

and

$$\alpha_i = 0 \text{ for } f_i \le f1, \qquad \alpha_i = 1 \text{ for } f_i \ge f2$$

The key frequencies *f1* and *f2* can be expressed as follows:

$$f1 = \frac{S_{a_{\max}}}{2\pi S_{v_{\max}}}, \quad \text{and } f2 = fr \tag{7.2}$$

where $S_{a_{\max}}$ = the maximum spectral acceleration, $S_{v_{\max}}$ = the maximum spectral velocity, *fr* = the rigid frequency (i.e., the lowest frequency at which the response becomes rigid). *fr* can be identified as the frequency where response spectra curves for different damping ratios converge (Point G in Figures 1 and 2), where periodic response practically becomes zero.

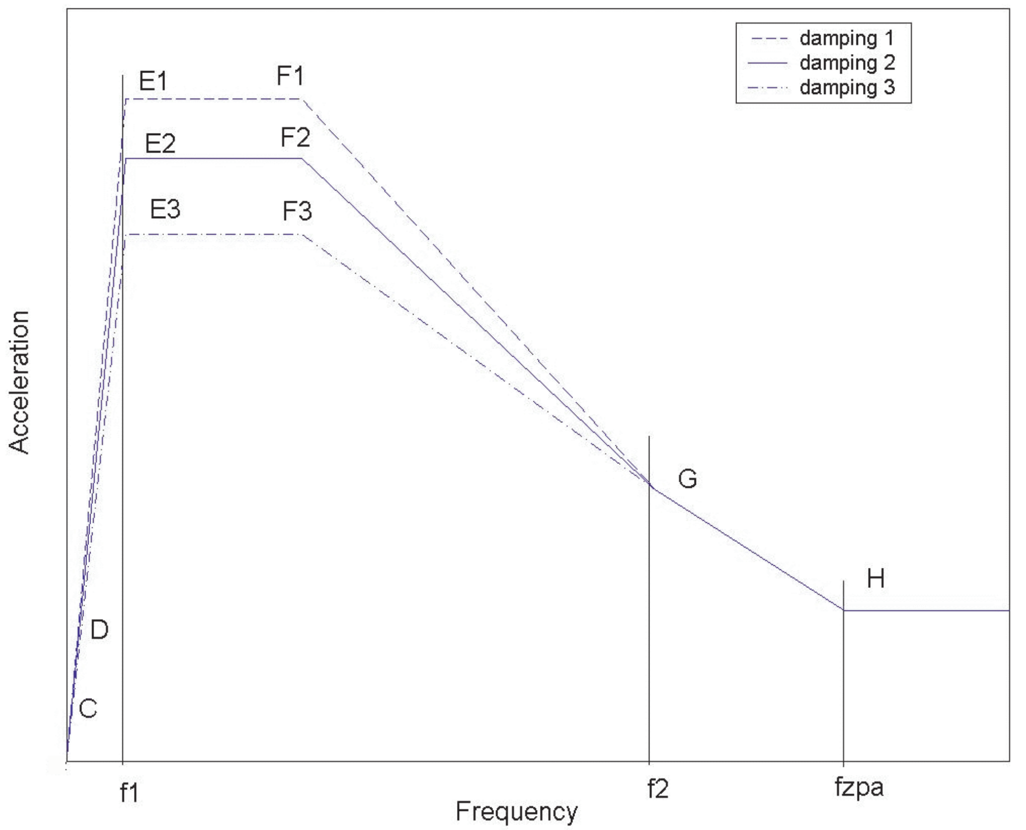


Figure 2. Response spectra with different damping ratios

The definitions of *f1* and *f2* in Equation 7.2 above are applicable to all types of response spectra (broad-banded, narrow-banded, or multiple narrow-banded). *f1* is the highest significant motion frequency. For a broad-banded design spectrum (e.g., Figure 1), *f1* is the frequency of the end point E of the amplified spectral velocity region DE, where both the spectral velocity and spectral acceleration have the maximum values.

It was found (Ref. 16) that when using Gupta's method, the results of combining modal responses are somewhat sensitive to the value of *f2* used, and there are situations that *f2* may not be uniquely determined as depicted ideally in Figure 2. In such cases, a more systematic method to determine *f2* is recommended in Appendix B of this guide, which was first proposed as Appendix F in Reference 16.

1.3.2 *Lindley-Yow's Method*

In Lindley-Yow's method (Ref. 8) separate analyses are performed for periodic and rigid response components. The periodic response component is calculated as follows:

$$R_{p_i} = R_i \left[\overline{S_{a_i}} \Big/ S_{a_i} \right] \tag{8.1}$$

Where a modified spectral acceleration is used and defined as follows:

$$\overline{S_{a_i}} = \left[S_{a_i}^2 - ZPA^2 \right]^{1/2}, \qquad \overline{S_{a_i}} \geq 0 \tag{8.2}$$

S_{a_i} = spectral acceleration of mode *i*, and *ZPA* = zero period acceleration, which is the maximum acceleration of the base input time history record.

Employing Gupta's notations, the rigid response component is calculated using the following definition for the rigid response coefficient:

$$\alpha_i = ZPA \Big/ S_{a_i}, \qquad 0 \leq \alpha_i \leq 1 \tag{9}$$

Definitions of the periodic and rigid response components then become identical to those in Gupta's method of Equation 6 above.

There is one limitation on the use of Lindley-Yow's method. Equation 9 gives $\alpha_i = 1$ when $Sa_i = ZPA$ and it continues to diminish with the decreasing frequency until the spectral acceleration reaches its peak, point F in Figures 1 and 2. However, α_i begins to increase again at lower frequencies at which the $Sa_i < Sa_{max}$. Therefore, Lindley-Yow's method should not be used for SSCs that have frequencies less than the frequency at the spectral acceleration peak.

1.4 Residual Rigid Response

Unlike tall buildings and other relatively flexible systems, some nuclear power plant SSCs may have a number of important modes beyond the ZPA frequency, f_{zpa}. In most cases, it is not practical to calculate all mode shapes and frequencies. If only modes with frequencies below f_{zpa} are included in the dynamic analysis, then the mass associated in these modes with frequencies higher than f_{zpa} is "missing" from the dynamic analysis. The residual rigid response of the missing mass modes (or the "missing mass response") can be calculated using a static analysis (Ref. 10). The combined relative displacement, $X_{missing\ I}$, of the SSC in the missing mass modes for the I^{th} component of seismic input motion is given as follows (Section 3.2 of Ref. 1):

$$K\left(X_{missing I}\right)=\overline{M}\left(ZPA_I\right), \quad \text{and} \quad \overline{M}=M\left[U_b-\sum_{i=1}^{N}\left(\Gamma_i\phi_i\right)\right]_I \qquad (10)$$

where K = stiffness matrix, $X_{missing\ I}$ = residual rigid response relative displacement vector for the I^{th} component of seismic input motion, ZPA_I = zero period acceleration for the I^{th} component of seismic input motion, M = mass matrix, U_b = influence vector, Γ_i = participation factor of mode i, ϕ_i = mode shape vector of mode i, N = number of modes with frequencies below f_{zpa}, and I = 1,2,3, the component of seismic input motion in one vertical and two horizontal directions. (Refer to Appendix A for more background information for Equation 10.)

Given $X_{missing\ I}$, one may calculate any missing mass response of interest, $R_{missing\ I}$, for the I^{th} component of seismic input motion, all of which is part of the rigid response.

It is important to account for the residual rigid response if a nuclear power plant SSC has significant frequencies higher than f_{zpa}. Ignoring the residual rigid response in these cases may result in underestimation of some SSC element forces and moments in the vicinity of supports, as well as underestimation of some support forces and moments (e.g., Ref. 11).

1.5 Combination of All Response Components

The total combined response of interest for the I^{th} component of seismic input motion (I = 1, 2, 3 for two horizontal and one vertical components) of all the modal responses is then calculated from the previous sections, as follows:

$$R_I=\left[\left(R_{rI}+R_{missing I}\right)^2+R_{pI}^2\right]^{1/2} \qquad (11)$$

2. Combining Effects Caused by Three Spatial Components of an Earthquake

Depending on which basic method is used in the seismic analysis (i.e., response spectra or time history method), the following two approaches are considered acceptable for the combination of three-dimensional earthquake effects.

2.1 Response Spectra Method

When the response spectra method is used, the representative maximum earthquake-induced response of interest in an SSC should be obtained by the SRSS combination of the maximum representative responses from the three earthquake components calculated separately as follows:

$$R = \left[\sum_{I=1}^{3} R_I^2 \right]^{1/2} \tag{12}$$

Where R = any response of interest of an SSC, R_I = combined response for the I^{th} component of seismic input motion (I = 1, 2, 3 for one vertical and two horizontal components), as obtained from Equation 11.

As an alternative, the 100-40-40 method of combination (Ref. 13) may be used in lieu of the SRSS method. The 100-40-40 procedure is as follows:

(1) Let R_1, R_2, R_3, be the maximum responses of an SSC caused by each of the three earthquake components calculated separately, such that

$$|R_1| \geq |R_2| \geq |R_3|$$

(2) The maximum seismic response, R_{max}, due to earthquake loading in three orthogonal directions is given by:

$$R_{\max} = \pm\left(1.0|R_1| + 0.4|R_2| + 0.4|R_3|\right) \tag{13}$$

2.2 Time History Method

When time history analysis method is employed for seismic analyses, two types of analyses are generally performed:

(1) For time history analysis when each of the three spatial components are calculated separately, the representative maximum response of interest of an SSC can be satisfactorily obtained by taking the SRSS of the maximum responses from the time history analysis for each of the three earthquake components:

$$R = \left[\sum_{I=1}^{3} R_I^2 \right]^{1/2} \tag{14}$$

(2) If the three components of earthquake motion are statistically independent (e.g., Ref. 13), the maximum response of interest of an SSC can be obtained by applying the algebraic sum at each time step when the three spatial components are calculated simultaneously, as follows:

$$R(t) = \sum_{I=1}^{3} R_I(t) \tag{15}$$

3. Methods Used

If the applicant has used the methods described in this guide, each applicable section of the Safety Analysis Report (SAR) should state specifically which acceptable methods were used for analyzing the SSCs covered by that section.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this draft regulatory guide. No backfitting is intended or approved in connection with the issuance of this guide.

This revision identifies improved methods that the NRC staff considers acceptable for combining modal responses and spatial components in seismic response analysis for the design of Category I SSCs. The more conservative methods for combining modal responses identified in Revision 1 of this guide also remain acceptable, with the exception that the effect of residual rigid response of the missing mass (Section 1.4 and 1.5) should also be addressed in analyses associated with actions requiring NRC approval that are reviewed by the NRC after the date of issuance of Revision 2 of this guide.

The NRC has issued this draft guide to encourage public participation in its development. Except when an applicant or licensee proposes or has previously established an acceptable alternative method for complying with specified portions of the NRC's regulations, the methods to be described in the active guide will reflect public comments and will be used in evaluating (1) submittals in connection with applications for construction permits, design certifications, operating licenses, and combined licenses, as well as (2) submittals from operating reactor licensees who voluntarily propose to initiate system modifications that have a clear nexus with this guidance.

APPENDIX A

GENERAL DISCUSSION OF THE RESPONSE SPECTRUM METHOD

A seismic response spectrum can be divided into several regions. This is true for broad-banded spectra, such as a design spectrum. It is also true for narrow-banded spectra (those with a single significant peak) or multiple narrow-banded spectra (those with multiple significant peaks), such as an in-structure spectrum. Figure 1 shows the regions of a broad-banded spectrum in a log-log plot. In order to clearly illustrate all of the regions of the spectrum, spectral velocity is plotted on the abscissa. Straight lines are used for convenience in identifying regions. These same regions are equally applicable to a curved or zig-zagged spectrum shape. Regions CD, DE, and EF represent the amplified spectral displacement region, amplified spectral velocity region, and amplified spectral acceleration region, respectively. Frequencies between D and E represent the significant frequency content of the input motion. For the purpose of discussion, the broad-banded spectrum of Figure 1 is chosen; however, the following discussion is equally applicable to narrow-banded and multiple narrow-banded spectra.

The relative displacement response of an elastic multi-degree-of-freedom SSC under seismic excitation can be represented by the following linear differential equation of motion (e.g., Section 3.2, Ref.1):

$$M\ddot{X} + C\dot{X} + KX = -M\,U_b\,\ddot{u}_g \qquad \text{(A.1)}$$

where M = mass matrix (mxm), C = damping matrix (mxm), K = stiffness matrix (mxm), X = column vector of relative displacements ($mx1$), $\dot{X}$ = column vector of relative velocities ($mx1$), $\ddot{X}$ = column vector of relative accelerations ($mx1$), U_b = influence vector; a displacement vector of the structural system when the support undergoes a unit displacement in the direction of the earthquake motion ($mx1$), m = number of dynamic degrees of freedom, and $\ddot{u}_g$ = ground acceleration.

Practically, Equation A.1 can be solved by using either the time history method or the response spectra method. Two approaches of the time history method can be used, namely the direct integration method or the modal superposition method. In the first approach, the direct integration of the equation of motion, Equation A.1, is performed using certain numerical integration methods. For the modal superposition approach, a modal analysis needs to be performed first, as described below.

In most practical cases, approximation can be used to decouple the equation of motion (Equation A.1) using the following transformation:

$$X = \Phi Y \tag{A.2}$$

where Φ = normalized mode shape matrix, $\Phi^T M \Phi = I$, I =identity matrix containing 1 along the diagonal and 0 otherwise (nxn), Y = vector of generalized coordinates ($nx1$), and n = number of modes considered.

The decoupled equation of motion for each mode then becomes:

$$\ddot{Y}_j + 2\lambda_j \omega_j \dot{Y}_j + \omega_j^2 Y_j = -\Gamma_j \ddot{u}_g \text{ , for } j = 1 \text{ to n} \tag{A.3}$$

where Y_j = generalized coordinate of mode j, λ_j = damping ratio of mode j expressed as fraction of critical damping, ω_j = circular frequency of mode j of the system, Γ_j = modal participation factor of the mode j = $\phi_j^T M U_b$; when mass is normalized so that the denominator equals 1.

The decoupled equation of motion for each mode, Equation A.3, can be solved in the time domain by integration using a proven technique. The total response can then be obtained by superposing all responses from each mode step by step in the time domain.

Alternatively, from Equation A.3, one can use the response spectra method. Using the response spectrum, the generalized response of each mode can be obtained from the following equation:

$$Y_j(\max) = \Gamma_j \left(\frac{S_{aj}}{\omega_j^2} \right) \tag{A.4}$$

where S_{aj} is the spectral acceleration of mode j corresponding to frequency ω_j.

Then, the maximum relative displacement of node i relative to the base due to mode j is as follows:

$$X_{ij}(\max) = \phi_{ij} Y_j(\max) \tag{A.5}$$

With the maximum relative displacement vector of Equation A.5, one can calculate the maximum values of any response of interest. The proper methods of combining maximum response values from various modes, and from three components of an earthquake are the subject of this guide. The technical basis for the proper methods of combining maximum response values from various modes are discussed below (Ref. 9).

Theoretically, the solution of the differential equation of motion, Equation A.1, consists of two parts, the homogeneous and the particular (in structural dynamics, the two parts are termed "transient" and "steady-state," respectively). The homogeneous solution has the frequencies of the oscillators (or individual modes), and the particular solution has the frequencies of the input motion. In modal analysis, they are sometimes termed damped-periodic (or simply "periodic") responses and "rigid" responses, respectively.

In Figure 1, the periodic (homogeneous) responses are predominant in the amplified spectral velocity region (DE) of the spectrum, namely, spectral velocity response is the prime contributor to periodic response. The predominance starts to diminish beyond E. In the other two amplified regions, CD and EF, periodic motion components are also significant. For periodic modal responses with sufficiently separated frequencies, the acceleration time histories of the oscillators (or individual modes) are generally out of phase with each other, and are also out of phase with the input motion time history. As indicated in Revision 1 of this guide, Goodman, Rosenblueth and Newmark (Ref. 2) showed that the Square-Root-of-the-Sum-of-the-Squares (SRSS) method is the appropriate method to combine these modal responses. When modes with closely spaced frequencies are present (see Section 1.1.1 for the definition of modes with closely spaced frequencies), any one of several conservative methods presented in Revision 1 of this guide can be used to combine these modal responses. Research since the 1970s (e.g., Refs. 3 and 4) has shown that for periodic modal responses, the double sum equation with appropriate formulas for calculating modal correlation coefficients will more accurately combine modal responses for modes with closely spaced frequencies. For modes with sufficiently separated frequencies, this double sum equation reduces to the SRSS method.

In the lowest frequency region (AB) and the transition region (BC), and the highest frequency region (HI) and the rigid region (GH) of the spectrum in Figure 1, the rigid (particular) responses are predominant. Most nuclear power plant SSCs do not have significant frequencies in the lowest frequency region (AB) or the transition region (BC).

In the highest frequency region (HI) and the rigid region (GH), the oscillators are very rigid so that they have the same acceleration time histories as the input motion, and, therefore, are in phase with the input motion. The relative displacement time histories of all of the oscillators in these two regions are also totally in phase with each other. The relative displacements of the oscillators can then be calculated by statically applying the inertia force opposite to the direction of the input acceleration (i.e., pseudo-static). The appropriate method to combine rigid responses in these two regions, therefore, is the algebraic sum method (Ref. 5).

The notations $f1$, $f2$ and f_{zpa} in Figure 1 are the highest significant motion frequency, the rigid frequency, and zero period acceleration frequency, respectively. They are described in more detail in Section 1.3 of this guide.

Research since the 1980s (e.g., Refs. 6, 7, 8, and 9) has shown that beyond the amplified region of DE in Figure 1 and up to point G of the spectrum, the modal response consists of both the periodic and rigid components. An appropriate method, as discussed in Section 1.3, should be used to separate the two components in these regions. The combination of periodic components of responses should be treated similarly to the other periodic modal responses (Section 1.1), whereas the combination of rigid components of responses should be treated similarly to the other rigid modal responses (Section 1.2). In addition, some nuclear power plant SSCs may have a number of important modes beyond the zero period acceleration (ZPA) frequency (f_{zpa}).

In most cases, it is not practical to calculate all mode shapes and frequencies. As discussed in Section 1.4, the residual rigid response of the missing mass modes should be addressed (Refs. 10 and 11); otherwise, it may result in underestimation of some SSC element forces and moments in the vicinity of supports, as well as underestimation of some support forces and moments.

Finally, when modes from all regions of the response spectrum are considered, an appropriate method, as discussed in Section 1.5 of this guide, should be used to combine all response components.

APPENDIX B

ALTERNATIVE METHOD FOR DETERMINATION OF THRESHOLD FREQUENCY FOR IN-PHASE MODAL RESPONSE

This alternative method for determination of the threshold frequency for rigid modal response (*f2* in Gupta's method, Section1.3.1 of this guide) was first proposed in Appendix F to Reference 16.

During the generation of a response spectrum from a ground or in-structure time history record, the complete time history of each single degree of freedom (SDOF) oscillator response is calculated and processed to identify the peak response. This peak response becomes a single point on the response spectrum plot. Each SDOF oscillator peak response has an associated time of occurrence and direction of the peak response, although this information is typically not retained because it is not needed in the generation of response spectrum. Nonetheless, valuable conclusions can be derived by comparing this information to the time and direction of the peak acceleration from the input time history record.

The lowest SDOF oscillator frequency (*f2* in Gupta's method) for which the time and direction of peak response coincide with the time and direction of the peak of the input time history represents the onset of rigid modal response that is in-phase with the input, provided that all higher-frequency SDOF oscillators exhibit the same behavior (i.e., for $f \geq f2$, all SDOF oscillator peak responses occur at the same time and in the same direction as the peak of the input time history). To further verify that rigid modal response exists, a comparison of the crossings of the acceleration equal to zero datum between the input time history and SDOF oscillator time history response should be performed for SDOF oscillator frequencies in the vicinity of *f2*.

Once *f2* is established by this procedure, it can be fully automated and made a part of the response spectrum generation algorithm.

REFERENCES

1. American Society of Civil Engineers Standard ASCE 4-98, "Seismic Analysis of Safety-Related Nuclear Structures and Commentary," ASCE, 1999.

2. L.E. Goodman, E. Rosenblueth and N.M. Newmark, "Aseismic Design of Elastic Structures Founded on Firm Ground," *Proceedings*, ASCE, November 1953.

3. E. Rosenblueth and J. Elorduy, "Responses of Linear Systems to Certain Transient Disturbances," *Proceedings of the Fourth World Conference on Earthquake Engineering*, Santiago, Chile, 1969.

4. A. Der Kiureghian, "A Response Spectrum Method for Random Vibrations," Report No. UCB/EERC-80/15, Earthquake Engineering Research Center, University of California, Berkeley, California, June 1980.

5. R.P. Kennedy, "Position Paper on Response Combinations," Report No. SMA 12211.02-R2-0, March 1984 (Published in "Report of the U.S. Regulatory Commission Piping Review Committee: Evaluation of Other Dynamic Loads and Load Combinations," NUREG-1061, Vol. 4, April 1985).[2]

6. A.K. Gupta and K. Cordero, "Combination of Modal Responses," *Proceedings of the 6th International Conference on Structural Mechanics in Reactor Technology*, Paper No. K7/15, Paris, France, August 1981.

7. A.K. Gupta and D.C. Chen, "Comparison of Modal Combination Methods," *Nuclear Engineering and Design*, Vol. 78, March 1984.

8. D.W. Lindley and T.R. Yow, "Modal Response Summation for Seismic Qualification," *Proceedings of the 2nd ASCE Conference on Civil Engineering and Nuclear Power*, Vol. VI, Paper 8-2, Knoxville, Tennessee, September 1980.

---

[2] Copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328 (telephone (202) 512-1800); or from the National Technical Information Service (NTIS) by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161; http://www.ntis.gov; telephone (703) 487-4650. Copies are available for inspection or copying for a fee from the NRC's Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email is PDR@nrc.gov.

9. Letter from A.K. Gupta to T.Y. Chang, dated September 17, 2003, with attached short paper, entitled "Comments Related to Regulatory Guide 1.92 - Draft DG 1108 Version 7/10/02 and Chang (NRC) Comments 3/12/03"; and letter from A.K. Gupta to N.C. Chokshi, dated February 26, 2003, Subject: Review of DG 1108 Version 7/10/02 (Draft for Regulatory Guide 1.92), with attached short paper, entitled "Comments Related to Regulatory Guide 1.92 - Draft DG 1108 Version 7/10/02." [3]

10. R.P. Kennedy, "Recommendations for Changes and Additions to Standard Review Plans and Regulatory Guides Dealing with Seismic Design Requirements for Structures" (part of NUREG/CR-1161, "Recommended Revisions to Nuclear Regulatory Commission Seismic Design Criteria"), Lawrence Livermore Laboratory, June 1979.

11. A.K. Gupta and J.W. Jaw, "Modal Combination in Response Spectrum Analysis of Piping Systems," *Seismic Effects in PVP Components*, PVP, Vol., 88, ASME, 1984.

12. Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants," Rev. 1, U.S. Nuclear Regulatory Commission, December 1973.[4]

13. N.M. Newmark, "Seismic Criteria for Structures and Facilities, Trans-Alaska Pipeline System," *Proceedings of the U.S. National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, June 1975.

14. S.L. Chu, M. Amin, and S. Singh, "Spectral Treatment of Actions of Three Earthquake Components on Structures," *Nuclear Engineering and Design*, Vol. 21, No. 1, 1972.

---

[3] Copies are available for inspection or copying for a fee from the NRC Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email PDR@nrc.gov. Copies can also be accessed through the NRC's public Web site (http://www.nrc.gov) under ADAMS Accession #ML041770185.

[4] Single copies of regulatory guides, both active and draft, and draft NUREG documents may be obtained free of charge by writing the Reproduction and Distribution Services, USNRC, Washington, DC 20555-0001, or by fax to (301) 415-2289, or by email to DISTRIBUTION@nrc.gov. Active guides may also be purchased from the National Technical Information Service on a standing order basis. Details on this service may be obtained by writing NTIS, 5285 Port Royal Road, Springfield, VA 22161; telephone (703) 487-4650; online at http://www.ntis.gov. Copies of active and draft guides are available for inspection or copying for a fee from the NRC's Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email PDR@nrc.gov.

15. C. Chen, "Definition of Statistically Independent Time Histories," *Journal of the Structural Division*, ASCE, February 1975.

16. R. Morante and Y. Wang, "Reevaluation of Regulatory Guidance on Modal Response Combination Methods for Seismic Response Spectrum Analysis," NUREG/CR-6645, U.S. Nuclear Regulatory Commission, December 1999.[5]

[5] Copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328 (telephone (202) 512-1800); or from the National Technical Information Service (NTIS) by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161; http://www.ntis.gov; telephone (703) 487-4650. Copies are available for inspection or copying for a fee from the NRC's Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email is PDR@nrc.gov.

REGULATORY ANALYSIS

1. Statement of the Problem

The U.S. Nuclear Regulatory Commission (NRC) issued Revision 1 of Regulatory Guide 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," in February 1976 to describe acceptable methods for complying with the NRC's regulations governing the seismic analysis and design of nuclear power plant structures, systems, and components (SSCs) that are important to safety. Since the issuance of Revision 1 of Regulatory Guide 1.92 in 1976, research in the United States has resulted in improved methods for combining modal responses and spatial components that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. This guide (Revision 2) describes methods that the NRC staff considers acceptable in view of those improvements.

2. Objectives

The objective of the regulatory action is to update the NRC's guidance in the area of seismic analysis and design of nuclear power plant SSCs in order to give licensees and applicants an opportunity to use state-of-the-art methods that are available in one document.

3. Alternatives and Consequences of the Proposed Action

3.1 <u>Alternative 1: Do Not Revise Regulatory Guide 1.92</u>

Under this alternative, the NRC would not revise Regulatory Guide 1.92 and licensees would continue to rely on the current version (Revision 1), which is based on technology developed in the 1970s. This alternative is considered the baseline or "no-action" alternative.

3.2 <u>Alternative 2: Update Regulatory Guide 1.92</u>

Under this alternative, the NRC would update Regulatory Guide 1.92 to reflect improved methods for combining modal responses and spatial components that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. The staff has identified the following consequences associated with adopting Alternative 2:

(1) Licensees would have guidance on the use of the latest technology available, with consequent improvements in the seismic analysis and design of SSCs. The more conservative methods for combining modal responses in Revision 1 of this guide would remain acceptable. However, the residual rigid response effect of the missing mass modes (as described in Sections 1.4 and 1.5 of this guide) should be addressed in analyses associated with actions requiring NRC approval that are reviewed by the NRC after the date of issuance of Revision 2 of this guide. The cost and effort to address the residual rigid effect are considered an insignificant part of the overall effort for the seismic design of an SSC, as no extensive computer calculation is expected. Previous analyses need not be repeated, since the seismic design process used for the existing operating plants, including Revision 1 of this guide, contain ample conservatism, such that the

omission of the residual response effect is not expected to raise any safety concern for the seismic design of SSCs for these plants.

(2) Regulatory efficiency would be improved by reducing uncertainty as to what is acceptable and by encouraging consistency in the seismic analysis and design of SSCs. Benefits to the industry and the NRC will accrue to the extent this occurs. NRC reviews would be facilitated because licensee submittals would be more predictable and analytically consistent.

(3) Both the NRC and the nuclear industry would realize cost savings. From the NRC's perspective, relative to the baseline, the NRC will incur one-time incremental costs to issue the revised regulatory guide. However, the NRC should also realize cost savings associated with the review of licensee submittals. In the staff's view, the ongoing cost savings associated with these reviews should more than offset the one-time cost.

On balance, the NRC staff expects that industry would realize a net savings, as their one-time incremental cost to review and comment on the revised regulatory guide would be more than compensated for by the efficiencies (e.g., reduced unnecessary conservatism, followup questions, and revisions) associated with each licensee submission.

4. Conclusion

Based on this regulatory analysis, the staff recommends that the NRC should revise Regulatory Guide 1.92. The staff concludes that the proposed action will reduce unnecessary burden on the part of both the NRC and its licensees, while improving the process for seismic analysis and design of safety-related SSCs. Furthermore, the staff sees no adverse effects associated with revising Regulatory Guide 1.92.

BACKFIT ANALYSIS

This regulatory guide gives licensees and applicants an opportunity to use state-of-the-art methods that are available in one document. As such, this draft revision of Regulatory Guide 1.92 does not require a backfit analysis as described in 10 CFR 50.109(c), because it does not impose a new or amended provision in the Commission's rules or a regulatory staff position interpreting the Commission's rules that is either new or different from a previous applicable staff position. In addition, this regulatory guide does not require modification or addition to structures, systems, components, or design of a facility or the procedures or organization required to design, construct, or operate a facility. Rather, a licensee or applicant is free to select a preferred method for achieving compliance with a license or the rules or orders of the Commission as described in 10 CFR 50.109(a)(7). The more conservative methods for combining modal responses in Revision 1 of this guide remain acceptable, with the exception that the residual rigid response effect of the missing mass modes (as described in Sections 1.4 and 1.5) should be addressed in analyses associated with actions requiring NRC approval that are reviewed by the NRC after the date of issuance of Revision 2 of this guide. It is the staff's judgment that there is ample conservatism in the seismic design process for the existing operating plants (including Revision 1 of this guide), such that the omission of the residual rigid response effect is not expected to raise any safety concern for the seismic design of SSCs for these plants.